THE EVAULATION OF TEST PROTOCOLS FOR DISPERSIVE SOIL IDENTIFICATION IN SOUTHERN AFRICA

AMRITA MAHARAJ

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DISSERTATION SUMMARY

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AMRITA MAHARAJ

Supervisor:	Professor Louis van Rooy
Co-Supervisor:	Dr Philip Paige-Green
Department:	Geology
Faculty:	Natural and Agricultural Sciences
University:	University of Pretoria
Degree:	Master of Science (Engineering & Environmental Geology)

Summary:

Dispersive soils are prevalent in many areas of South Africa and the presence of these soils has not only posed a problem in earth dam construction but has led to problems with a number of road projects. The use of dispersive soils in roadway embankments and structures can lead to serious engineering problems if the soils are not accurately identified before use and appropriate mitigation measures taken. Although the causes and consequences of soil dispersion are well understood, the consistent and positive identification of dispersive soils still remains a problem. Many identification methods have been proposed but none has been completely successful.

The current tests used for identification include the pinhole, double hydrometer, crumb and chemical tests, which are generally used in combination to obtain the most reliable outcome. These laboratory tests, however, have not always been entirely consistent, either when used in combination or individually, and it is possible that the reason lies in the actual testing procedures.

Recent investigations have shown that in many cases the identification and classification problems appear to be related to inconsistencies in the test methods and testing protocols. This has been highlighted recently at various conferences and presentations in South Africa, with a recommendation that the problem be investigated fully.

The main objective of this project was thus to carry out a detailed investigation into the current methods used for the testing and identification of dispersive soils. The test methods were thoroughly analysed and shortcomings identified. The differences in results and interpretation resulting from different test techniques are examined and solutions to overcome the problems proposed. A further objective of this study is the assessment of the interpretation of results obtained from dispersive soil chemical analysis.

A pilot study was first carried out, which recognized deficiencies in the identification process resulting from problems with the test methods. The pilot study allowed for the identification of these shortcomings in the test methods and their modification. The modified methods were used in the full study to obtain more consistent and reliable results.

The study found the pinhole test as well as the Gerber and Harmse (1987) ESP versus CEC chart to be highly unreliable. The double hydrometer and crumb tests are good indicators of dispersivity if carried out accurately and repeatably using a standard test method. The chemical analysis of the soils should be carried out using the standard methods employed by the Soil Science Society of South Africa. Final rating systems were also found to be unreliable since they put a great deal of weight on the poorly reproducible pinhole test. Emphasis is thus put on the test methods being as simple and unambiguous as possible to promote repeatability and reproducibility of the results. Recommendations are finally made proposing a suite of tests as well as a decision process which should be followed when faced with a potentially dispersive soil.

This investigation was aimed solely at the evaluation of test protocols and not the suitability or specification of limits for any rating systems. This should now be assessed using the standard test methods proposed in this thesis.

DECLARATION

I, the undersigned hereby declare that:

I understand what plagiarism is and I am aware of the University's policy in this regard;

The work contained in this dissertation is my own original work;

I did not refer to work of current or previous students, lecture notes, handbooks or any other study material without proper referencing;

Where other peoples work has been used this has been properly acknowledged and referenced;

I have not allowed anyone to copy any part of my thesis;

I have not previously in its entirety or in part submitted this thesis at any university for a degree.

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Amrita Maharaj

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Date: _______________

DEDICATION

In memory of my brother

Ashveer Maharaj

(1988 – 2012)

"Death leaves a heartache no one can heal, love leaves a memory no one can steal"

You will be forever in my heart. I love you always.

And

For my mom

Sunitha Singh

All that I am today or ever hope to be, I owe to you.

Just knowing that you are always there for me makes it easier to go on in life.

I love you most.

And

For ***Suveer Singh***

Thanks for being a good friend and an important part of our little family.

Love you…

And Last, but definitely not least,

For ***Sharmila Singh***

Friend, Confidante, Aunt and our little 'Switzerland'

Thank you for always being there… I would be lost without you.

I love you lots.

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1 Introduction

1.1 Background

Dispersive soils are prevalent in many areas of South Africa and the presence of these soils has always posed a problem on road construction sites. The use of dispersive soils in roadway embankments and structures can lead to serious engineering problems if the soils are not accurately identified before use and appropriate mitigation measures taken.

Although the causes and consequences of soil dispersion are well understood, the positive identification of dispersive soils still remains a problem. Many identification methods have been proposed but none have been completely successful. Elges (1985) stated that although dispersive clays can be utilized economically, safely and successfully in various construction projects, there are still a number of aspects that require further investigation and clarification. This is agreed upon in most of the previous literature with Bell and Maud (1994) suggesting that perhaps a rating system would offer a better prediction. It is therefore necessary to gain a better understanding of dispersive soils, thereby leading to positive identification and improved utilization.

Since the State of the Art paper on dispersive soils in 1985 (Elges, 1985), there has been some research into the complexities of dispersive soils and the difficulties they create, with the researchers coming to the same conclusions. Various rating systems have been proposed, the latest by Walker (1997); however, there still appear to be a number of problems regarding the positive identification of the soils. Dispersive soils therefore still pose a problem since no unique and precise method of classifying the soils exists.

1.2 Problem statement

The current identification methods include the pinhole, double hydrometer, crumb and chemical tests, which are commonly used in combination to obtain the most reliable outcome. These laboratory tests, however, have not always been entirely consistent, either when used in combination or individually, and it is possible that the reason lies in the actual testing procedures.

Recent investigations have shown that in many cases the identification and classification problems appear to be related to inconsistencies in the test methods and testing protocols. This has been highlighted recently at various conferences and presentations in South Africa, with a recommendation that the problem be investigated fully.

1.3 Project objectives

The main objective of this project was to carry out a detailed investigation into the current methods used for testing and identification of dispersive soils. The test methods were thoroughly analysed and shortcomings identified. The differences resulting from different test techniques are examined and solutions to overcome the problems proposed.

A further objective of this study is the assessment of the interpretation of results obtained from dispersive soil chemical analysis. Based on the findings of this study, conclusions are drawn and recommendations made to establish a standard protocol or suite of tests for the positive identification of dispersive soils.

1.4 Scope of study

This research is part of an on-going study to investigate the problems related to identification of dispersive soils and a need for standard protocols which are repeatable, reproducible and unambiguous. The study involved the collection of soil samples suspected to have dispersive characteristics. The samples were then run through the current tests recommended for dispersive soil identification.

An experimental programme was designed with the specific aim of examining the potential problems encountered when carrying out routine laboratory tests for the identification of dispersive soils. It was not the aim of this research to assess the actual dispersiveness of soils, but to concentrate on weaknesses and/or deficiencies in the test methods.

Based on the results obtained, conclusions have been drawn and recommendations made for improved test methods. For this study, emphasis was placed on the actual methods and procedures used for the tests and not the classification of the soils.

2 Literature study

2.1 Background

Dispersive soils are defined as soils which, when immersed in relatively pure and still water, will disintegrate with some particles going into suspension (Reeves et al. 2006). It is also described as the condition of slurry in which the individual clay particles do not aggregate into flocs. Dispersion occurs in those soils wherein the repulsive forces between the clay particles when saturated exceed the attractive forces. This is caused by a reduction in the concentration of cations in the pore fluids, resulting in deflocculation and dispersal of the clay particles. Therefore when the soil is in the presence of relatively pure water, the clay particles repel each other and go into suspension (Reeves et al. 2006).

Soils comprising clay minerals that have a high concentration of exchangeable sodium are usually prone to dispersion. These soils may also be highly susceptible to erosion and as a result give rise to the development of gullies and dongas. Dispersive soils are therefore often characterised in the field by the presence of surface erosion gullies and subsurface erosion tunnels. According to Brink (1985), soils that most commonly have high exchangeable sodium percentages (ESP), are those soils whose clay fraction is largely composed of smectitic clays such as montmorillonite. However, some illites with high ESP values are also known to be highly dispersive and even kaolinite clays with relatively low ESP values have been reported as having dispersive characteristics (Elges 1985).

2.2 Clay mineral chemistry and dispersivity

2.2.1 *Crystal Structure*

The crystal structure of clay minerals is the principal factor which determines their physical and chemical properties and their attraction to water. In order to identify with the concept and process of dispersion, these properties need to be examined and understood.

The atomic lattices of clay minerals comprise two structural elements. The first element consists of sheets of octahedrons made up of oxygen atoms or hydroxyl groups, with 8-coordinated aluminium, iron or magnesium atoms occurring in the interstices at equal distances from the oxygen atoms (Figure 2-1). When aluminium is present, only two-thirds of the possible positions are filled to balance the structure, which is the gibbsite structure and the formula is $Al_2(OH)_6$. When magnesium is present, all the positions are filled to balance the structure, which is the brucite structure with the formula $Mg_3(OH)_6$.

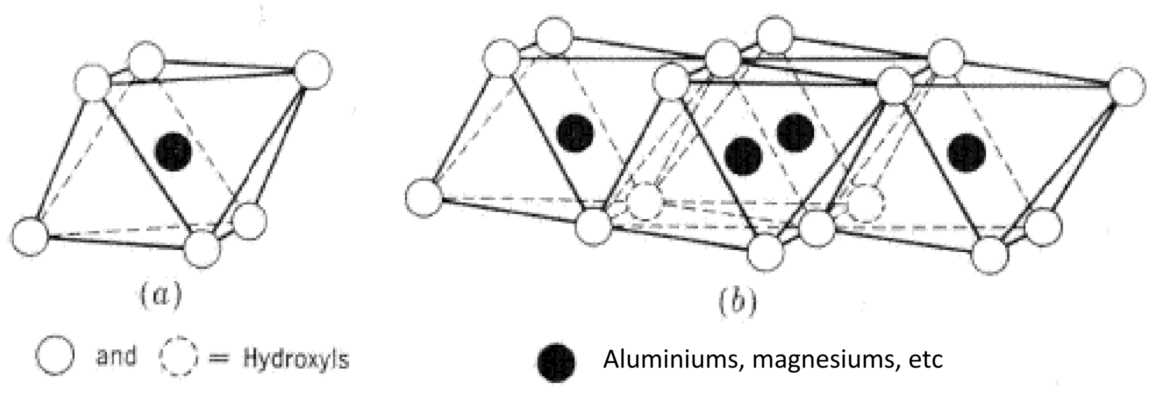


Figure 2-1: Diagrammatic sketch showing (a) single octahedral unit and (b) the sheet structure of the octahedral units (From Grim, 1962).

The second element comprises silicon-oxygen tetrahedra, where the silicon atom is equidistant from the four oxygen atoms in each tetrahedron (Figure 2-2). This is necessary to ensure lattice equilibrium. The tetrahedral silicon-oxygen groups are arranged in an infinitely repeating hexagonal lattice with sheets of composition Si_4O_6 (in some cases hydroxyl ions can replace oxygen ions). The tetrahedrons are arranged so that the tips of all of them point in the same direction, and the bases are on the same plane (Grim 1962; Ovcharenko et al. 1967).

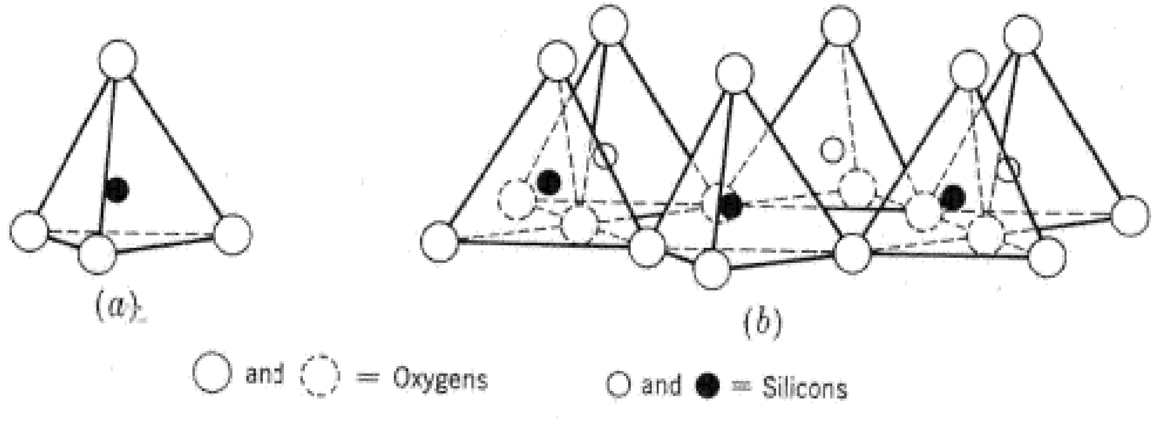


Figure 2-2: Diagrammatic sketch showing (a) single silica tetrahedron and (b) the sheet structure of silica tetrahedrons arranged hexagonal network (From Grim, 1962).

Although the aluminium-oxygen and silicon-oxygen sheets are electrically neutral, the electric fields of the two molecular sheets are adjusted such that the resulting lattice displays minimum potential energy. The ions inside the layers are bonded by electrostatic forces and the layers are held together by Van der Waals forces (Ovcharenko et al. 1967).

The chemical classification of clay minerals is based on two lattice types. The first type is a layer structure of alternating silicon-oxygen tetrahedra and aluminium-oxygen octahedra with the ratio of 1:1. Kaolinite, imperfect kaolinite and halloysite belong to this group. The second structure comprises the same elements, but with a ratio of 2:1. Examples of these are montmorillonite, hydromica and pyrophyllite.

The layered structure of kaolinite is made of alternating sheets of silicon-oxygen and aluminium-oxygen joined to form a single electrically neutral unit cell, with a structural formula of $(OH)_8Si_4\,Al_4O_{10}$. The strong bonding between the different sheets prevents hydration and adsorption from occurring in the interstices. The montmorillonite unit cell on the other hand comprises two external silicon-oxygen sheets and one intermediate aluminium-oxygen sheet. The theoretical formula of the structure is $(OH)_4Si_8Al_4O_{20}\,.nH_2O$. Each unit cell is surrounded by layers of oxygen atoms and the adjoining unit cells are held together by Van der Waals bonds, which are easily broken when polar molecules infiltrate the interstices. The polar molecules cause substantial swelling of the lattice until the individual layers are entirely separated. The degree of inter-crystalline swelling of montmorillonite clays in the presence of water is also highly dependent on the cation exchange series, which is more noticeable for sodium varieties but less evident for the calcium and hydrogen montmorillonite (Ovcharenko et al. 1967).

2.2.2 *The Diffuse Double Layer*

The internal structure of a clay mineral can have an imbalance of charges due to substitution of Si^{4+} and Al^{3+} ions by other cations of lower valence. The electro neutrality of the clay particle is then provided for by the presence of certain cations (Na^+, Ca^{2+}, K^+, Mg^{2+}, etc) on the exterior surface of the clay. These are generally referred to as 'counter' ions. The exterior cations (which are not really a part of the crystal lattice) can dissociate completely from the surface if it is in contact with water. A partial dissociation of surface ions usually takes place in an aqueous solution, imparting an electrical charge to the surface of the solid phase. In contrast to other molecular environments, the ions that detach themselves from the solid surface tend to remain in the surrounding area of the charged surface. The cause of this trend is the fixation of the surface charges to the solid phase which prevents them from spreading throughout the system. Depending on the proximity of the charges on the surface, the electric fields of the individual charges reinforce each other, giving rise to a combined electric field in the liquid layer bordering the solid surface. This field will attract any dissociated ions which will then accumulate close to the charged surface. The resulting distribution of charges (i.e.: negatively charged surface with an accumulation of positively charged ions close to it) is known as the “electric double layer” (Bolt and Bruggenwert 1978).

Since the accumulated counter ions can move freely through the solution phase, this indicates that they are subject to two opposing tendencies. They are attracted towards the clay surface by the electric field (adsorption tendency) and they have a propensity to distribute themselves uniformly throughout the solution phase by diffusion (diffusion tendency). In general, the distribution is said to endeavour towards minimum energy but also in the direction of maximum entropy of the system. The resulting (equilibrium) distribution corresponds to a minimum of the ‘Free Energy’ of the system and amounts to a ‘diffuse’ accumulation zone. These conditions are illustrated in Figure 2-3 (Bolt and Bruggenwert, 1978).

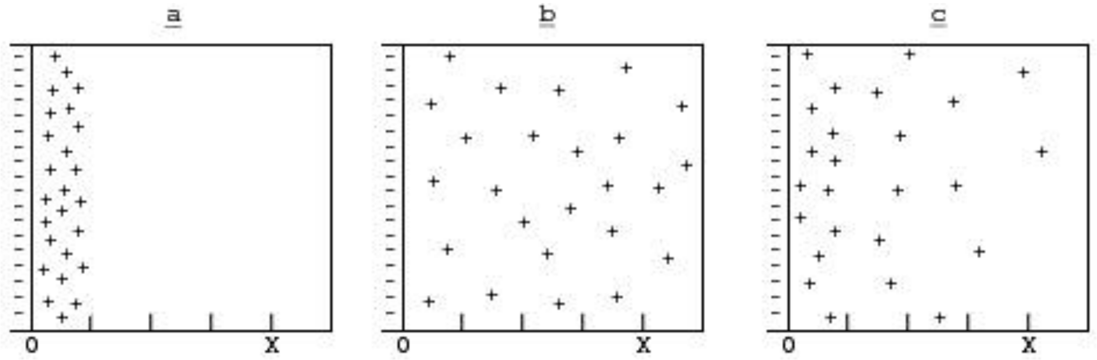


Figure 2-3: Distribution of counter ions around DDL.

a: Condition of minimum energy; b: condition of maximum entropy; c: condition of minimum Free Energy, i.e. actual distribution (Bolt and Bruggenwert, 1976).

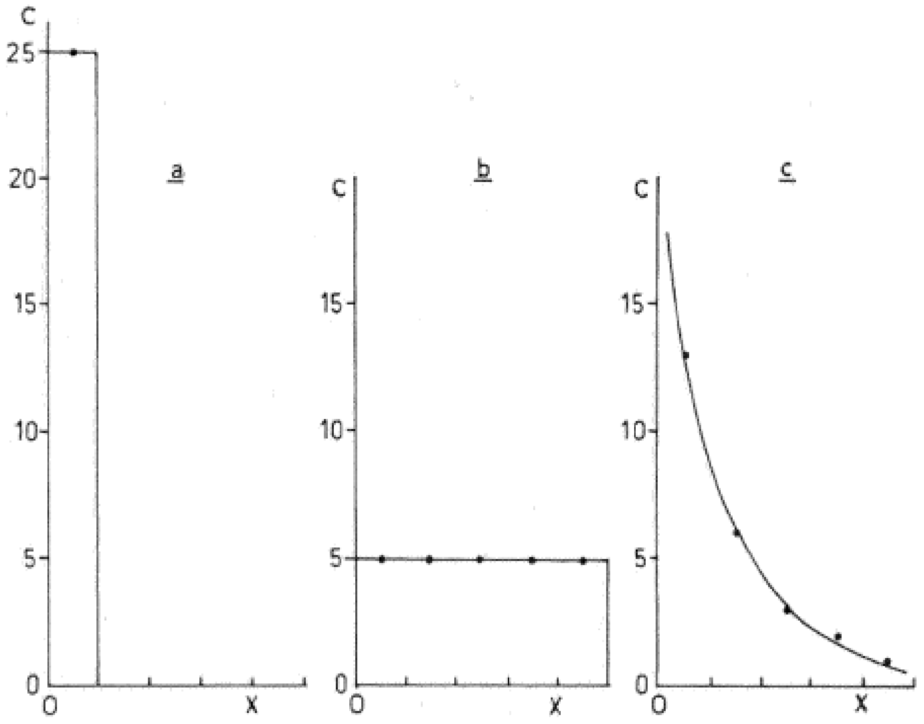


Figure 2-4: Concentration (C) of counter ions in the double layer: a, b, c is in Figure 2-3; c corresponds to the DDL (From Bolt and Bruggenwert, 1976).

The resulting arrangement of charges is defined as the diffuse (electric) double layer (DDL). The equivalent concentration (C) distribution is shown in Figure 2-4, in which the extent, x, of the DDL can be recognized. The extent of the DDL (x) is defined as the width of the region in which the electric field of the charged surface is still distinguishable, or where an obvious accumulation of counter ions is situated. According to Bolt & Bruggenwert (1978), the extent of the DDL is influenced by two main factors. These factors are the valence of the counter ions and the concentration of ions in the pore water. Divalent cations (Ca^{2+}) are attracted more strongly than monovalent cations. Therefore, the extent of the DDL will decrease with increasing valance of the counter ions. The addition of salts to the pore water inhibits the inclination of the counter ions to diffuse away from the accumulation zone and thus decreases the extent of the DDL (Bolt and Bruggenwert 1978).

It should also be noted that the ions in the DDL attract water and the quantity of water taken up by the DDL will influence the viscosity. The viscosity of the liquid in the DDL is therefore not only influenced by the quantity of electrolytes present but also by the type of ions present (Schroff and Shah, 2003).

2.2.3 *The effect of the DDL on dispersion*

The two forces that act between clay particles affecting dispersion are Van der Waal's attraction forces and the repulsive forces resulting from positively charged cations surrounding each particle. It should be noted that the influence of Van der Waal's forces is only effective over a small area, whereas repulsive forces may extend over a greater distance. The excessive amounts of sodium as opposed to calcium and potassium in dispersive soils have the effect of pushing clay particles away from each other causing the forces of repulsion to act on the clays. Ballantine and Rossouw (1989), state that the sodium cation is highly problematic in clays since it can hold 79 molecules of water, pushing the individual clay particles further away from each other. Calcium on the other hand, only holds 2 molecules of water, which keeps the clay particles close enough for the Van der Waal's forces to take effect.

Attractive and repulsive forces acting on clay particles depend on the closeness of the particles to one another. If the clay particles are in close proximity, attractive forces (Van der Waal's) will be the governing forces between the particles, and if they are further apart, they will repel each other. The major factor influencing the distance between clay particles is the thickness of the DDL. If the thickness of the DDL is small, clay particles may be close enough for Van der Waal's forces to prevail. The clay particles would therefore be attracted to one another and remain flocculated. When the DDL is large, repulsive forces predominate and the clay particles repel one another and disperse (Bolt and Bruggenwert 1978; Walker 1997).

2.3 **Dispersive Soil Characteristics**

Previous work in determining the characteristics of dispersive soils has been carried out by numerous workers and summarised by Walker (1997). The work includes the determination of various soil properties such as fabric, mineralogy, geochemistry, consistency and particle size distribution and thereafter ascertains any relationships that these factors have with dispersive soils characteristics.

2.3.1 *Fabric*

The fabric of a residual soil depends on its mineralogy, particle size distribution and the shape of the individual grains or particles. Diagenesis and weathering also play a vital role in the type of fabric that forms in a soil (Bell and Walker 2000).

Walker (1997) observed two different types of fabric present when dispersive samples were viewed under a scanning electron microscope. The fabrics were firstly, a densely packed fabric consisting primarily of clay particles and secondly, a more open fabric in which sand and silt were situated in the clay matrix. According to Walker (1997), the clay particles were closely packed and appeared to be arranged face to face to form a “turbostratic” fabric. The clay was also said to form a continuous network of small, interconnecting, regularly shaped pores; and the silt and sand were evenly distributed within the clay matrix.

Soils that have high Exchangeable Sodium Percentage (ESP) values are more prone to swelling and dispersion than soils with low ESP values. The dispersed clay particles in these dispersed soils tend to move into surrounding pore spaces and consequently reduce the sizes of the pore spaces. The sizes of the pore spaces in clays and more open fabric of dispersive soils are smaller than in non-dispersive soils. Open fabric pore spaces in dispersive soils are generally less than 30 µm and usually less than 50 µm in non-dispersive soils. Pore spaces within the clay fabric of dispersive soils generally range between 2 µm and 10 µm (Bell and Walker 2000).

Bell and Walker (2000) also noted that soils with high Total Dissolved Solids (TDS) concentrations have a different fabric to those with low TDS concentrations. Dispersive soils with low TDS concentrations are governed by a turbostratic fabric and those with high TDS concentrations have a granular fabric with no smooth clay zones. It was also observed that pore spaces in dispersive soils with high concentrations of TDS are larger than in dispersive soils with low TDS concentrations.

2.3.2 *Geochemistry and Mineralogy*

Bell and Walker (2000), state that the capacity of a soil to disperse is governed by the type of clay minerals present in the soil. High ESP values are said to exist in clays that are predominantly composed of smectites and other 2:1 clay minerals. There is the potential for high dispersivity in some illites, however, high ESP values and high dispersivity rarely occurs in clays composed mainly of kaolinite.

Whole soil XRD testing carried out by Walker (1997), found quartz to be the dominant mineral in most samples with albitic plagioclase being the second most abundant mineral. The albitic plagioclase is likely to be a source of sodium in the soil and can therefore influence dispersivity. Minor amounts of other minerals such as mica, gypsum, calcite and chlorite can also be present in the soil. Little detail regarding clay mineralogical analyses is provided.

2.3.3 *Particle Size Distribution and Consistency*

The clay fraction present in a soil does not influence the dispersivity of the soil. However, if a soil contains less than 10 per cent clay particles, there may not be enough colloids to support dispersive behaviour. On the other hand, there is no distinct difference between the clay content in dispersive and non-dispersive soils. It has also been observed that the plasticity index of a soil has no effect on the dispersivity of a soil. However, soils with plasticity indices greater than 35 per cent are likely to be self-healing, as they can swell sufficiently to seal possible flow paths before erosion can advance too far (Bell and Walker, 2000).

2.4 **Identification of dispersive soils**

Experience has shown that dispersive soils cannot be distinguished from non-dispersive soils by conventional index tests such as particle size distribution, Atterberg limits, or compaction characteristics. It should also be noted that not all materials exhibiting erosion gullies and channelling in the field are necessarily dispersive. The materials could just be highly erodible (low cohesion) or prone to slaking (Paige-Green 2008), in which cases different construction techniques and/or material treatments would be necessary.

Dispersive characteristics therefore need to be positively identified by performing various specialised tests on soil samples. Currently there are four laboratory test methods commonly used to identify dispersive soils. These tests include the pinhole test; the double hydrometer test; the crumb test and various chemical analyses of the soil and usually a combination of the results obtained from these methods is used to determine the potential of a soil to disperse.

2.4.1 *Physical tests*

2.4.1.1 *Pinhole Test*

The pinhole test was first developed in 1973 (Sherard et al. 1976a) and is considered to be one of the most reliable physical tests for the identification of dispersive soils. The test measures the erodibility/dispersivity of a compacted soil sample (37 mm long) in which water is allowed to flow through a small hole punched through the centre of the specimen (Figure 2-5). It is considered to be reliable since it simulates the action of water flowing through a pipe/crack in the soil. The pinhole, which is punched through the centre of the compacted sample, is 1 mm in diameter and water flows through the sample at heads of 50 mm, 180 mm and 380 mm during the experiment (Sherard et al.

1976a). The flow rate, effluent turbidity and size of the pinhole at the end of each test are the parameters recorded. If the effluent is highly turbid (murky) and the pinhole is enlarged, then the soil is classified as being dispersive. If the opposite is observed, i.e.: the effluent is clear and the pinhole size remains unaltered, then the soil is considered non-dispersive.

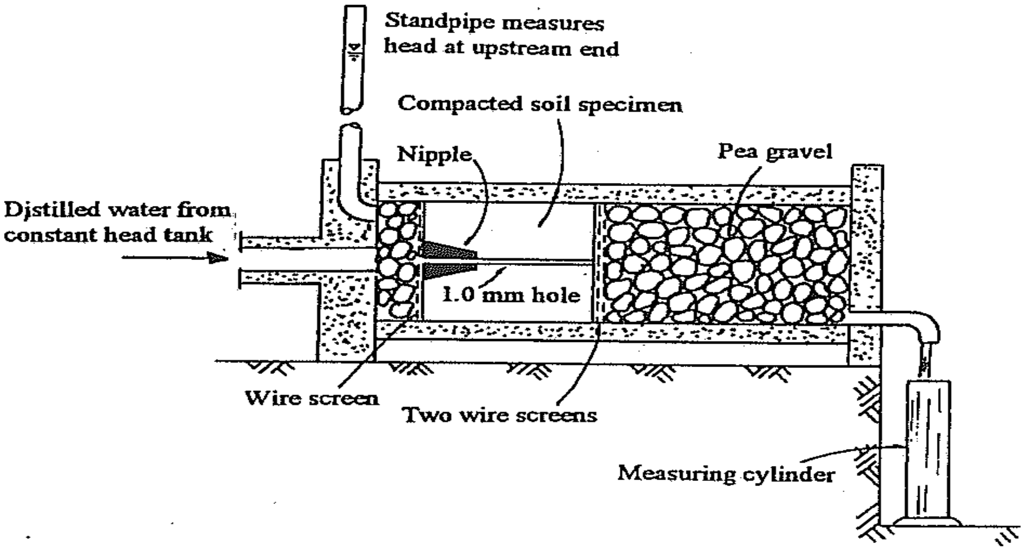


Figure 2-5: Pinhole test apparatus (Adapted from Sherard et al., 1976a)

Soils are categorized into 6 classifications (D1, D2, ND4, ND3, ND2 and ND1). Table 2-1 summarizes the criteria for evaluating pinhole test results and the classifications are described in Table 2-2.

Table 2-1: Summary of criteria for evaluating results (Adapted from Sherard et al., 1976a)

Classification	**Head (mm)**	**Time (min)**	**Final flow rate (mℓ/sec)**	**Effluent colour**	**Pinhole size after test**
D1	50	5	>1.5	Very distinct	2x
D2	50	10	>1.0	Distinct to slight	2x
ND4	50	10	<0.8	Slight but easily visible	1.5x
ND3	180-380	5	>2.5	Slight but easily visible	2x
ND2	1020	5	>3.5	Clear to barely visible	2x
ND1	1020	5	<5.0	Crystal clear	No erosion

Table 2-2: Categories of pinhole test results (Adapted from Sherard et al., 1976a)

Classification of soil	**Description of categories**
D1 and D2	Dispersive - highly dispersive soils: Fail rapidly under 50 mm head.
ND4 and ND3	Intermediate soils: Erode slowly under 50 mm or 180 mm head.
ND2 and ND1	Non-dispersive soils: No colloidal erosion under 380 mm or 1020 mm head.

Since the test aims to identify dispersive soils, it should be first noted that erodible soils are very different from dispersive soils. The pinhole test is likely to identify highly erodible soils which can be mistaken for dispersive soils. According to Bell and Walker (2000), the diameter of the pinhole at the end of the test proves to be the most reliable indicator for recognizing dispersivity. Walker (1997) also talks about a simplified pinhole test, in which the pinhole size rather than the effluent turbidity is used as the main factor for the classification of a dispersive soil. In the simplified pinhole test all samples are tested under a head of 50 mm for 5 minutes. If the pinhole of the sample enlarges to at least 2 mm after 5 minutes, then the soil is classified as dispersive. The pinhole diameters in non-dispersive soils remain unchanged and for intermediate soils, the pinhole size would range from 1 mm to 2 mm. Walker (1997) also indicated that the pinhole test showed a good correlation with the Cation Exchange Capacity (CEC) vs. ESP chart, TDS vs. %Na chart and the Sodium Adsorption Ratio (SAR) value as discussed in Section 2.4.2.

2.4.1.2 *Double Hydrometer Test*

The Soil Conservation Service (SCS) Double Hydrometer Test has also been identified as one of the most appropriate tests for classifying dispersive soils. The test evaluates the dispersivity of a soil by measuring the natural tendency of the clay fraction in the soil to go into suspension in pure water. The procedure involves the determination of the percentage of particles in the soil that are finer than 0.005 mm using the standard hydrometer test. A parallel test is carried out, in which no chemical dispersant is added and the solution is not mechanically agitated. The quantity of particles finer than 0.005 mm in the parallel test is expressed as a percentage of this fraction determined in the standard test, which is defined as the dispersion ratio or dispersivity of the soil (Walker 1997). Dispersion ratios greater than 50% are considered highly dispersive, between 30 and 50% are moderately dispersive, between 15 and 30% are slightly dispersive and less than 15% are non-dispersive (Walker, 1997)). Similar systems, but with different limits were utilised by Gerber and Harmse (1987), Elges (1985) and Walker (1997).

The dispersion test was first described by Volk (1937) as a means of determining the potential dispersivity of soils. The test has since been used extensively in this regard with minor modifications. Volk’s test compared the weight of soil grains, 0.005 mm or smaller that slaked free when air-dried lumps of soil were soaked in quiet, distilled water, with that of the entire soil. This was expressed as the percentage dispersion. Measurements of the clay in the soil-water suspension were made by the pipette method (Volk 1937).

The pipette method itself was introduced by Middleton in 1930 as a means of determining the erosion potential of a soil. The difference in the methods was that the samples collected in the pipette consisted of particles of a maximum diameter of 0.05 mm (Middleton 1930). Volk’s method was, however, preferred because studies in the southwest of the United States indicated that the dispersion of the clay fraction (< 0.005 mm diameter), was more significant in assessing the piping potential of soils (Decker and Dunnigan 1977).

The SCS involvement in earth dam construction in the United States increased in the 1940's and early 1950's. The dispersion test was employed as a routine procedure for all samples submitted to SCS Laboratories. It was during this period that the test procedure was adapted to use a hydrometer instead of a pipette (Decker and Dunnigan, 1977). The standard hydrometer test procedure is specified in ASTM standard D422-63 for Particle Size Analysis of soils (ASTM 2007a; ASTM 2007b)

With the increased use of the dispersion test and the growth of the SCS testing facilities in the 1950's and 1960's, a few inconsistencies were detected, such as, the test was not always reproducible in the same laboratory, and there appeared to be differences in the results between laboratories. Studies revealed that water quality and moisture contents of the samples were responsible for these errors and as such distilled water and in situ moisture contents were specified (Decker and Dunnigan, 1977). Since that time, there appear to have been no discussions regarding any anomalies encountered during testing in the literature.

2.4.1.3 *Crumb Test*

The crumb test, as an indicator for dispersive soils, is the simplest and easiest of the physical tests and was first described by Emerson in 1967. Emerson (1967) found the interaction of clay-sized particles in water to be a major determining factor in the stability of a soil in an agricultural context. Based on this deduction, simple physical tests were devised to qualitatively divide soils into eight different classes. Remoulded soil crumbs were also used in one of the tests to simulate the effect of cultivation on the soil. Samples from a variety of soils were tested and their chemical properties determined for comparative purposes. Figure 2-6 illustrates the flow chart developed by Emerson for the classification of soils.

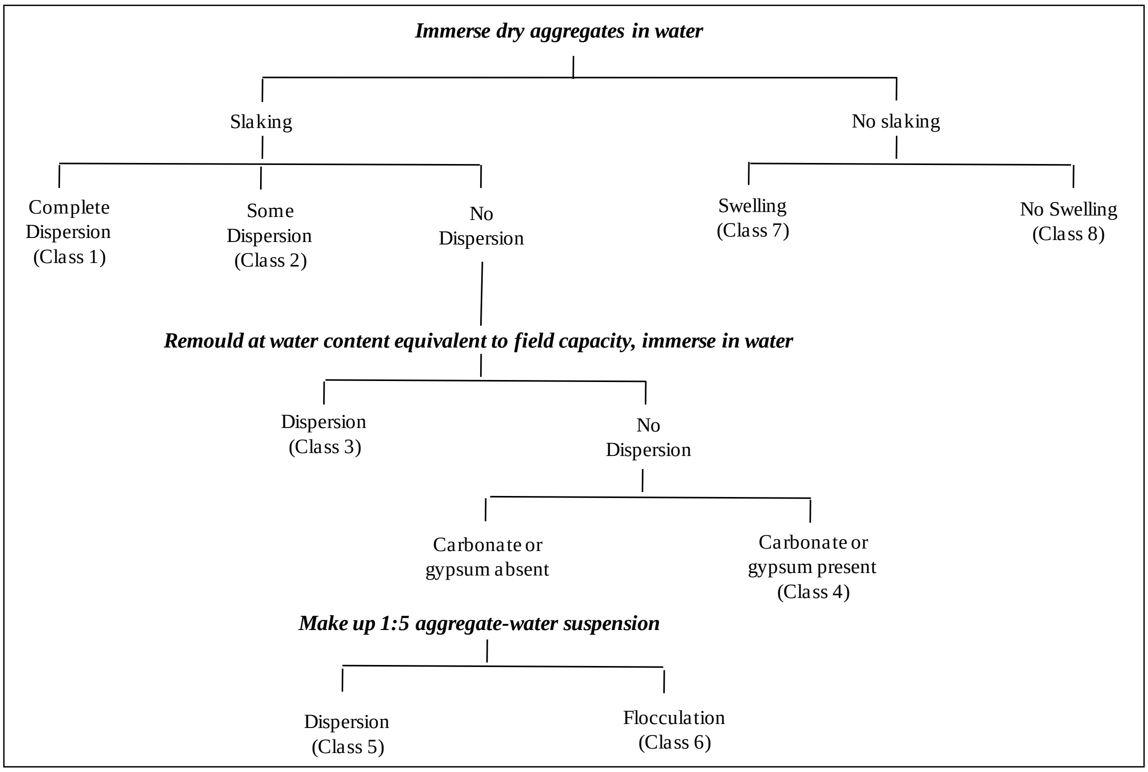


Figure 2-6: Flow chart for the classification of soil crumbs (From Emerson, 1967)

The crumb test indicates the tendency of the particles to deflocculate in solution. The test, which can also be carried out in the field, involves placing a crumb of soil (either undisturbed or remoulded) in a beaker of distilled water or very weak sodium hydroxide (NaOH) and observing the reaction as the crumb begins to hydrate (Walker 1997). The test is primarily a visual assessment of the behaviour of the soil in solution. After a certain time, the soil crumb and the solution in the beaker are observed and the soil is classified according to the quantity of colloids in suspension. Four grades can be noted ranging from no reaction to strong reaction (Table 2-3) but this interpretation can be highly subjective and operator-dependent.

Table 2-3: Description of grades for crumb test (Walker, 1997).

Grade	Reaction	Description
1	No reaction	Crumbs may slake, but no sign of cloudiness caused by colloids in suspension
2	Slight reaction	Bare hint of cloudiness in water at surface of crumb.
3	Moderate reaction	Easily recognisable cloud of colloids in suspension, usually spreading out in thin streaks on bottom of beaker.
4	Strong reaction	Colloid cloud covers nearly the whole bottom of the beaker, usually as a thick skin.

If the soil shows a dispersive reaction (grade 3 or 4), the soil is most likely dispersive. However, a reaction of grade 1 or 2 has been found to not necessarily indicate that the soil is non-dispersive. Sherard et al. (1976b) found the crumb test to be a very good indicator when carried out with distilled water, but only in one direction. In all tests where the samples were classified as dispersive (grade 3 or 4), the soils were most definitely dispersive but the converse was not true. Approximately 40% of dispersive soils showed non-dispersive reactions in the test. They also found no useful correlation when a dilute sodium hydroxide (NaOH) solution was used instead of distilled water.

2.4.2 *Chemical tests*

Chemical analyses are carried out to determine the amount of sodium relative to the other cations (calcium, magnesium, potassium) present in the soil sample and the pore water. Tests are run to determine the exchangeable cations on the clays as well as the cations in the saturation extract. Exchangeable cations are ions bonded on the surface of the clay particles, which are generally not released into water, while the saturation extract cations are those present in the pore water in the form of sodium salts. From the laboratory results, the exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), cation exchange capacity (CEC) and total dissolved salts (TDS) can be determined. These parameters are essential in determining the dispersivity of a soil using certain rating systems. Laboratory tests are also carried out to determine electrical conductivity (EC) and pH, which can aid in the analysis process (Gerber and Harmse, 1987).

The presence of exchangeable sodium on the clay particles is the main contributing factor to dispersive behaviour in soils. This is articulated in terms of the exchangeable sodium percentage (ESP) of the soil which is expressed as:

$$ESP = \frac{exchangeable\ sodium}{cation\ exchange\ capacity}\ x\,100 \qquad (1)$$

where the units are given in meq/100g clay.

The cation exchange capacity (CEC) can either be obtained by summing the amounts of the common exchangeable cations present (these are determined individually) or by a single laboratory test in which the total cation exchange capacity is determined. The difference between the two test procedures can result in significant differences in the results obtained for CEC and hence produce conflicting results and interpretations. According to Gerber and Harmse (1987), soils with an ESP value greater than 15% are considered highly dispersive and those with a low CEC (15 meq/100g clay) have been found to be completely non-dispersive at ESP values of 6% or less. Elges (1985), however, recommends a threshold ESP value of 10%, above which soils are prone to dispersion.

Another property that governs susceptibility of a soil to dispersion is the total dissolved salts (TDS) in relation to the salt content of the water affecting the structure. The higher the sodium percentages in the saturation extract relative to the TDS, the greater the susceptibility of the sodium saturated clays to disperse (Bell and Walker 2000). The percentage sodium, which is the ratio between sodium and TDS in the saturation extract, may also give an indication of dispersion potential. The percentage sodium is defined as:

$$Na\,\% = \frac{Na^{+}}{TDS}\ x\,100 \qquad (2)$$

where:

$$TDS = Na^{+} + K^{+} + Ca^{2+} + Mg^{2+} \qquad (3)$$

with all units expressed in meq/ℓ of saturation extract.

Dispersive soils contain a higher content of dissolved sodium in their pore water than other soils. The sodium adsorption ratio (SAR) is used to evaluate the role of sodium where free salts are present in the pore water. The sodium adsorption ratio is defined as:

$$SAR = \frac{Na^{+}}{\sqrt{0.5\left(Ca^{2+} + Mg^{2+}\right)}} \tag{4}$$

If no free salts are present then the use of SAR to identify a dispersive soil is not applicable. According to Bell and Maud (1994), a SAR value greater than 6 suggests that the soil is sensitive to leaching. Brink (1985) on the other hand stated that if the SAR is greater than 10, then the soil is dispersive.

2.4.3 *Rating systems*

The results from the tests and analyses are generally combined into rating systems using two or more properties to determine whether the soil is dispersive. Sherard et al. (1976b) combined two properties to develop the potential dispersivity chart in which the percentage of sodium is plotted against the TDS of a soil (Figure 2-7). Soils are classified according to where they plot in the chart. According to Elges (1985), this method of identification did not prove reliable in South Africa and the system which was adopted was the procedure by Gerber and Harmse (1987).

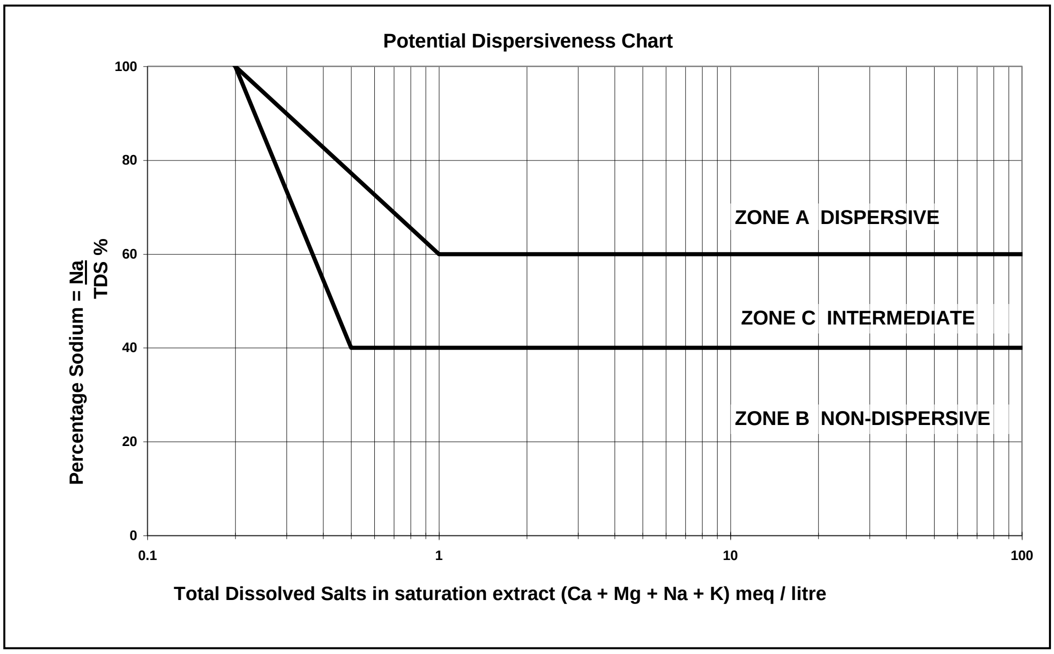


Figure 2-7: Potential dispersivity chart by Sherard et al (1976)

Gerber and Harmse (1987) developed two systems. The first is a chart plotting ESP against CEC (Figure 2-8). The degree of dispersivity of each of the soils on which the chart was derived was based on the double hydrometer test result. The second system uses a flow chart demonstrating the recommended procedure for identifying dispersive soils (Figure 2-9), in which five chemical properties and a leaching test are used to identify dispersivity.

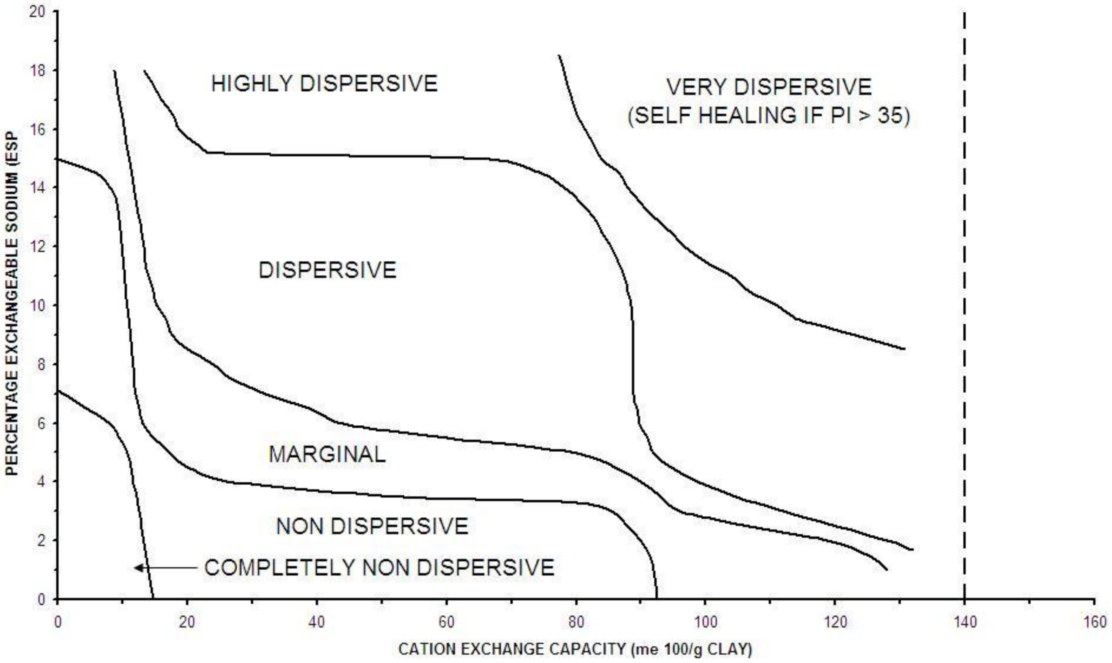


Figure 2-8: Diagram of determination of dispersion potential as a function of ESP and CEC (Gerber and Harmse, 1987)

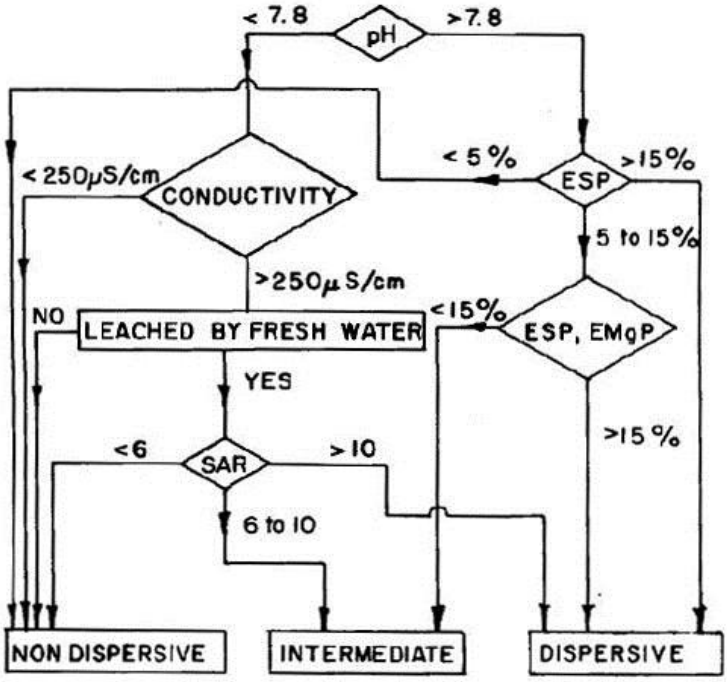


Figure 2-9: Alternative procedure for identification of dispersive soils. (Gerber and Harmse, 1987)

The ESP-CEC chart was based on a study using four methods to evaluate and define the dispersivity of 67 soil samples. These methods were the sodium concentration in a saturated paste; percentage exchangeable sodium; ESP and exchangeable magnesium percentage (EMgP) and the double hydrometer test. The double hydrometer test was chosen as the indicator test because the clay in suspension is a measure of dispersion (Gerber and Harmse, 1987). The chart was developed after test results proved 46 samples dispersive and 21 non-dispersive apparently based predominantly on the double hydrometer test.

The second procedure for the identification of dispersive soils, also developed by Gerber and Harmse (1987), takes a whole new direction with respect to the parameters used for the rating system. This system takes variables such as SAR, pH, conductivity and ESP/EMgP into account. In other words, no physical tests (pinhole, double hydrometer, etc) need be carried out to determine the dispersivity of a soil. This system is based purely on the chemical properties.

The most recent of the rating systems is the system developed by Walker (1997) and described by Bell and Walker (2000). This rating system requires results from the pinhole and crumb tests, as well as various chemical properties and the CEC-ESP relationship described by Gerber and Harmse (1987) (Table 2-4).

Table 2-4: Rating system for the identification of dispersive soils (Walker, 1997; Bell and Walker, 2000)

Test	Class & weighting	Description of dispersivity			
Pinhole test	Class	Dispersive	Moderate	Slightly	Non-dispersive
	Rating	5	3	1	0
CEC vs. ESP	Class	Highly	Dispersive	Marginal	Non-dispersive
	Rating	4	3	1	0
Crumb test	Class	Strong reaction	Moderate	Slight	No reaction
	Rating	3	2	1	0
SAR	Class	> 2	1.5 - 2.0		< 1.5
	Rating	2	1		0
TDS vs. %Na	Class	Dispersive	Intermediate		Non-dispersive
	Rating	2	1		0
Total Dispersivity Rating		Highly	Moderately	Slightly	Non-dispersive
		> 12	8 – 11	5 - 7	< 4

Bell and Walker (2000) found that the most reliable test for the identification of dispersive soils was the pinhole test. This was therefore given the highest rating in the system. It was concluded that the ESP-CEC chart (Gerber and Harmse, 1987) was also very reliable, so it is included as one of the defining parameters of the system, also with high weightings. Conspicuous by its absence in this system is the double hydrometer result.

Most of the rating systems used, currently, seems to have been based on an initial classification of the dispersivity using the double hydrometer test. Gerber and Harmse (1987) used the test as a primary parameter when developing the ESP-CEC chart. Walker (1997) included the ESP-CEC chart as a parameter in the rating system and studies carried out by Bell and Walker (2000) also make use of the double hydrometer test when originally classifying the dispersivity of the soils.

2.5 Distribution in South Africa

Dispersive soils were first identified in South Africa in the mid-1960's following the failure of several small earth dams in the, then, Orange Free State and Northern Cape province (Donaldson 1975). According to Bell and Maud (1994), these soils often occur on old pediment surfaces with gentle rolling topography and relatively flat slopes. Dispersive soils can also occur on steep hills, on which erosion channels can rapidly form (Bell and Maud, 1994).

Dispersive soils, typically associated with transported flood plain deposits, slope wash colluvium and lake bed deposits as well as residual soils, are usually found in regions which experience annual rainfall of less than 850 mm. This rainfall mostly occurs in summer as thunderstorms, with the exception of areas in the south Western Cape Province, which receives rainfall in the winter months. The areas with less than 850 mm per year rainfall are included in those regions where Weinert's climatic N-values range between 2 and 10 (Bell and Maud 1994).

Dispersive soils known to occur in South Africa have been derived from the Molteno Formation, the Beaufort Group, the Ecca Group and the Dwyka Formation of the Karoo Supergroup. They have also been derived from the Witteberg Group, Bokkeveld Group and Table Mountain Group of the Cape Supergroup, the Malmesbury Group, the Nama Group and the Kirkwood Formation and Sunday River Formation of the Uitenhage Group (Bell and Maud 1994).

In the Cape Province, many dispersive soils are derived from granites or mudrocks of the Malmesbury Formation. These derivative soils can behave in a dispersive manner even in areas where the ESP values are less than 5. A likely explanation for this could be the presence of high magnesium contents in relation to the calcium content. In areas where the sediments contain large amounts of illite, montmorillonite or vermiculite with high ESP values, dispersive soils are generally present. This is the case with soils derived from the siltstones and mudstones of the Molteno Formation and Beaufort Group, where N-values are greater than 2. Generally, kaolinitic soils that are derived from weathered granite are found to be non-dispersive. However, some soils which are derived from granites in low lying areas, under anaerobic conditions, are prone to have high ESP values and are thereby dispersive (Bell and Maud, 1994). The weatherable primary minerals from derivative rocks, such as orthoclase, albite and muscovite, can contain high concentrations of sodium and low concentrations of magnesium and calcium, which result in the development of high ESP values. In areas where Weinert's N-values are greater than 10, free salts in the soil tend to hinder the development of dispersive soils even though high SAR values are typical in the pore water. However, dispersive soils can develop in special cases where the free salts are leached out (Bell and Maud 1994). Figure 2-10 illustrates the known dispersive soil occurrences in Southern Africa according to Elges (1985).

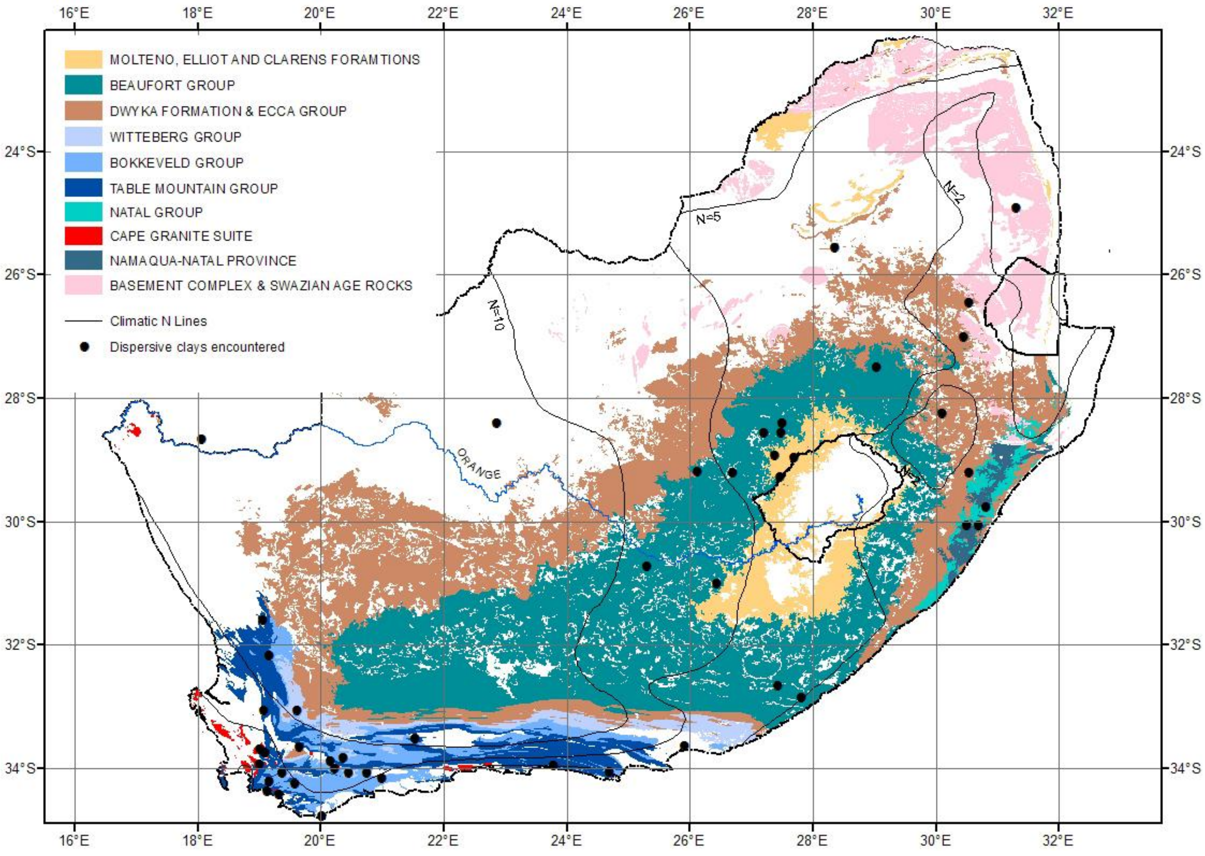


Figure 2-10: Identified dispersive soil occurrences in Southern Africa (Elges, 1985). (N.B.: Climatic N Lines = Weinert's N-values)

2.6 Problems encountered with dispersive soils

Dispersive erosion has the potential of being a serious problem in engineering and construction projects. Erosion of the soils leads to the formation of features such as gullies, dongas and pipes. Dispersive soils used in dam construction are likely to develop pipe structures if not correctly identified and carefully treated, which subsequently leads to failure of the dams. The presence of dispersive soils also poses a challenge for agricultural purposes as they have low permeability and therefore low infiltration rates.

According to Harmse and Scheurenberg in Brink (1985), dispersive soils in southern Africa are common under four conditions, many of these in line with those described in Section 2.5.:

- In low lying areas where seepage is such that the seepage water has high SAR values. The areas which are particularly susceptible are those areas where Weinert's climatic N-values range between 2 and 10. Soils derived from granitic rocks are more inclined to develop high ESP values and hence become dispersive. The weatherable primary minerals of these rocks (orthoclase, albite, and muscovite) contain low concentrations of Ca^{2+} and Mg^{2+} ions, thus facilitating the development of high SAR values (see Equation 4).

- In areas where the parent material of a transported soil contains large quantities of illite and other 2:1 clays with high ESP values. This corresponds to Cretaceous mudrocks, mudrocks of the upper Beaufort Group and the Molteno Formation of the Karoo Supergroup, where climatic N-values fall between 2 and 10. Soils in low lying areas of these formations are almost always dispersive.
- In drier regions where N-values are higher than 10. Although free salts limit the development of dispersive properties despite high SAR values within the saturation extract, dispersive soils can develop if free salts are leached out.
- Soils derived from granite or Malmesbury mudrocks in the Western Cape can display dispersive characteristics even where ESP values are less than 5. This is most likely due to the high concentration of Mg^{2+} in relation to that of Ca^{2+}.

2.6.1 *Piping Failure in earth dams*

In the conventional description of piping failure in an earth dam, the concentrated leak emerging at the downstream side is caused by water flowing through the pores of the soil. The erosion commonly begins at the discharge end of the leak, causing a local concentration of seepage and erosion forces. The erosion then travels upwards forming a tunnel-shaped passage or pipe until it eventually reaches the water source. By this time, rapid failure would have occurred in the dam. This type of failure generally occurs in cohesionless soils which have little resistance to the erosive forces of the percolating water once dispersion of the clays has formed conduits.

Unlike erosion that occurs due to the absence of cohesive bonds in the soil, erosion in dispersive soils does not occur as a result of seepage through the pores of the soil. Dispersion of the clays can occur in static water. Piping in dispersive soils is due to a deflocculation process, where water travels through a leakage channel, and the loss of material from the wall of that leakage channel occurs simultaneously along its entire length. A concentrated leak must always be present for erosion to initiate, and leakage channels are usually cracks or fissures in the soil. The initial seepage generally occurs around conduits, against concrete structures, at foundation interfaces, through desiccation cracks, cracks due to differential settlement or those due to hydraulic fracturing (Bell and Maud, 1994). Poorly compacted materials are also prone to piping failure (as is common in road fills).

The main property governing the susceptibility of a soil to dispersive piping is the amount of sodium cations present on the clay surface relative to other cations. Another important factor is that of the concentration of total dissolved salts (TDS) in the pore water. The lower the TDS of the pore water, the greater the susceptibility of the sodium saturated clays to repel each other leading to dispersion.

Indications of piping in earth dams take the form of small leakages of muddy coloured water from the earth embankment after initial filling of the reservoir. According to Bell and Maud (1994), most failures in earth dams in South Africa, have occurred on first wetting and filling of the dam. Pipes become enlarged rapidly leading to failure of the structure.

2.6.2 *Dispersive soils in roadworks*

Dispersive soils commonly occur at the top of cut slopes (in the surficial transported and/or residual soils above the less weathered in situ rock). According to Taylor and Fey (1988), since dispersive soils are often associated with perched water tables, the ingress of water is likely to cause erosion of the topsoil. This will lead to progressive steepening of the slope until a sub-vertical face angle is achieved.

Dispersive soils used for fills tend to show signs of preferential settlement. After some time, the riding quality of the road becomes undulating, camber will be disturbed and the removal of storm water will begin to pose a problem. Taylor and Fey (1988) suggest that during construction, the soil should not be allowed to dry out, "*as it will lose its ability to re-constitute itself and will therefore behave as a silt-sand combination (sic)*". Dispersive soils that are poorly compacted will form tunnels and pipes rapidly, especially in the shoulder areas that are normally compacted to lower densities than the structural layers in the road.

Care should also be taken to ensure that the material is not placed over springs or in areas of water seepage. If this is the case, piping is likely to occur resulting in a collapse of the pavement structure. Pipe and box culverts should not be placed directly on dispersive soils unless sufficient protection is provided to ensure that erosion behind the wing walls and below the invert slab cannot take place (Taylor and Fey 1988).

2.7 **Methods of stabilization of dispersive soils**

In most failures involving dispersive soils, failure of the embankment is usually the first indication of the presence of dispersive soils in the area. This illustrates the importance of early recognition and identification of dispersive soils. The problems caused by these soils can result in rapid, irreversible and catastrophic failure of structures. To avoid these problems, as well as the appropriate utilisation of available construction materials, the possible presence of dispersive soils should be considered during the early stages of investigation. This is especially important if geological and surface evidence of possible dispersive soils exists. If the presence of dispersive soils is confirmed during the site investigation phase, decisions can then be made regarding the use of alternative materials or treatment/stabilization of the dispersive soils if no other material is available.

Although dispersive soils require special treatment when used in earth dam construction, they may still constitute the most economic option for a specific situation. With regard to earth dam construction, Elges (1985) states that the permeability of the compacted material should not exceed 10^{-5} cm/sec, if piping failure due to deflocculation is to be avoided. A permeability of 10^{-6} cm/sec is taken as the lower limit of permeability but it is also possible that the limit could be 10^{-7} cm/sec for shorter drainage paths in small dams. The range of permeabilities for clay soils in dispersive conditions can therefore be 10^{-5} to 10^{-7} cm/sec (Elges 1985).

Sand filters can often seal and control leaks in dispersive clays. Sand filters act to prevent silt-sized particles from being carried along with the flow of water, which are then retained in the leakage channel and will subsequently seal off the leak. These filters, however, cannot prevent colloidal clay particles in suspension from passing through them. The filter material should also be non-cohesive in order to be effective in sealing off cracks. If the material is cohesive, it can also develop an "*open flood crack (sic)*" without collapse and therefore be unsuccessful in protecting the cracked core (Elges 1985).

Dispersive soils can be completely converted into non-dispersive soils by the addition of chemical modifiers such as hydrated lime (calcium hydroxide), gypsum (calcium sulphate) and alum (aluminium sulphate). These chemical are used as a calcium (or aluminium) source to replace sodium in the cation exchange complex reducing the distance between the clays considerably as discussed in Section 2.2.3. The application of lime, gypsum or alum increases both the soil solution electrolyte concentration and the levels of exchangeable calcium in the soil. This, in turn, reduces the inter-particle swelling pressures and hence the potential for dispersion. Lime is the most commonly used chemical modifier because it is more soluble and cost effective. Gypsum is generally more effective in reducing dispersive qualities of a soil due to its higher electrolyte content but the use of gypsum is limited because of its lower solubility and higher cost (Hardie 2009). Elges (1985) states that in a laboratory, 0.2 % of lime or gypsum by mass of clay is usually adequate. However, in construction a minimum of 2 % is generally used in order to improve mixing and allow proper/uniform distribution through the soil.

If the soil is adequately compacted at the right moisture content to the specified density and if provision is made for an effective filter drainage system, chemical stabilisation will usually not be necessary. Chemical stabilisation may, however, be required for slope protection where other treatment methods, such as grassing or gravel with necessary filter layers, are not economically feasible (Elges 1985).

Wagener et al. (1981) suggest that when considering the construction of embankment dams in areas with dispersive soils, five options of treatment should be studied. The first option is the relocation of the dam, which is not always the most practical alternative. The second option is the reconstruction of the dam by taking the dispersive soil problem into account and employing strict construction control with or without the use of a chemical stabiliser for the soil. Another alternative is upstream lining protection, with the use of membranes such as butyl rubber, polythene sheeting or bentonite. The last two choices include the chemical treatment of the basin floor and embankment sides and the water treatment option. Water treatment involves the process of increasing the electrolyte concentration of the reservoir water (with the use of chemicals such as gypsum or lime) for a limited period of time such that the dispersive behaviour of the soil is suppressed.

With regards to cuts and fills, if dispersive soils are exposed in cuts, the material would either need to be treated or removed so as to avoid erosion of the face. The soils can also be covered. Dispersive soils may also be used in the core of a fill as long as it is surrounded by better material on the sides and top, much like the construction of an embankment dam. The material should not be allowed to dry between compaction of layers as it may develop desiccation cracks (Taylor and Fey 1988). It is also possible to use sulphonated petroleum product (SPP) treatments, which will replace the sodium in the clays and “stabilize” the material (Paige-Green, 2010).

2.8 Case Histories

Historically, the construction of earth dams was carried out with basic equipment and limited field control. Failures that occurred during this period were attributed to construction deficiencies, especially poor compaction of the earth fill. The development of improved design methods, field laboratories for moisture content and density control and better equipment led to a great improvement in the standard of compaction and construction of earth dams (Donaldson, 1975).

Despite this improvement, piping failures still occurred and appeared worse than before. According to Donaldson (1975), studies of the failures of a number of dams were not very helpful since the mechanism or cause of failure could not be ascertained after the failure. At one dam project in South

Africa, close observations of the breach in the embankment floors revealed the presence of a number of smaller tunnels or pipes, which were infested with termites. This led to the conclusion that the termite channels passed through and under the embankments, forming initial leaks, which led to piping and the formation of tunnels.

At other sites, burrowing animals provided the explanation for the initial leaks. At an embankment in de Keur, investigations found a lens of sandy material at the failure zone and it was contended that the piping was initiated by seepage through the lenses. Donaldson's (1975) research revealed the mechanisms by which the failure was likely to have been initiated and which inevitably led to piping failures in dispersive soils. In this section, three cases in which dispersive soils were used in construction (local and international) have been summarised.

2.8.1 *Case history 1: Senekal Dam (Local)*

The Senekal dam was completed in 1973 and was built as an off-channel storage reservoir on the Beaufort Group of the Karoo Supergroup. The materials used for construction of the dam wall comprised alluvial silts and clays on a foundation of similar alluvium, overlying sandstone and shale at depths greater than 10m (Wagener et al. 1981).

The embankment was built according to typical small dams specifications, where the material, moisture content and density were monitored at regular intervals. The earth wall was 8m high and consisted of an inner clay core with 3m deep cut-off, silty sand flanks and rip-rap protection on the upstream face. A clay blanket approximately 20m in width continued from the clay core to reduce seepage through the foundation soils. The embankment walls were approximately 1100m long forming a reservoir of around 19 hectares and 1.4×10^6 m^3 capacity (Wagener 1980; Wagener et al. 1981). Figure 2-11 illustrates the cross section of the dam.

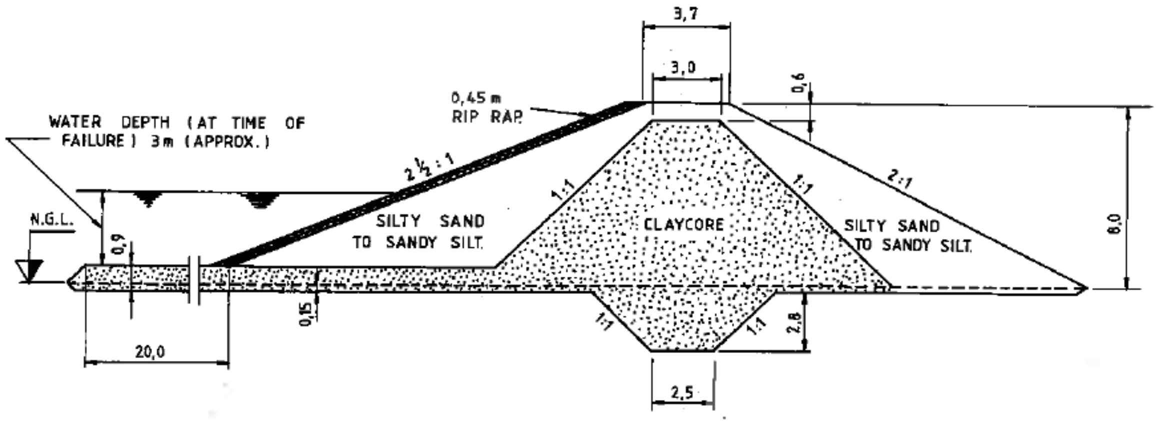


Figure 2-11: Cross section of Senekal embankment dam (From Wagener, 1980)

Filling of the reservoir began in November 1974, by pumping water from the weir, but was stopped a week later when leaks were discovered on the downstream toe of the embankment. The water level in the basin was 3m above ground level. A trench was dug at the surface where the leak was observed and two 40mm diameter holes were found at a shallow depth leading beneath the dam. The flow of water increased rapidly and the dam failed, due to piping, 4 days later (Wagener 1980).

A geotechnical investigation was then initiated in order to determine the cause of failure. The preliminary assessment found that the failure was most likely due to the presence of dispersive soils, thereafter; the investigation was focused on determining the trigger mechanism for the initial leak. The conclusion drawn from the inspection and testing of the core was that the standard work was acceptable for construction of a dam with non-dispersive material. However, it was not suitable for materials of dispersive character. Localised areas of the dam could probably display moisture contents between 2 to 4% dry of the optimum moisture content and these areas would likely be the cause of the initial leak due to their greater permeability (Wagener 1980; Wagener et al. 1981).

The foundation of the dam was also investigated and the clay materials were found to be visually similar to the core materials, with an average exchangeable sodium percentage (ESP) of 25.7. This indicated that the foundation soils were as dispersive as the core material. Eventually a total of 60 tests were conducted on various materials used in the construction of the dam, with the combined properties shown in Table 2-5. It is assumed that the grading values are percentages passing the appropriate sieve sizes.

Table 2-5: Combined properties for Senekal Dam (From Wagener, 1980).

	ESP	**INDEX PROP**		**GRADING**	
		LL	**PI**	**SILT**	**CLAY**
AVERAGE	25.3	36.5	23.1	81.4	50.0
STD. DEVIATION	10.8	13.3	9.8	9.8	13.4
COEFF. VARIATION	0.43	0.36	0.42	0.12	0.27

Wagener et al (1981) state that for the dam to have failed an initial leak would have to be present and the reason for that initial leak could be any of the following:

> *"While the dam was constructed effectively for a 'conventional" dam, it did not have sufficient compaction moisture for a dispersive material. Layers obviously existed with moisture contents as low as 4% less than optimum which may have had a potential flocculated void configuration and permeability greater than 1 × 10^{-5} cm/sec.*
> *Lapses in construction with insufficient attention to pre-treatment (scarifying and rewetting) could have led to the development of shrinkage cracks at different layers.*
> *Layers with higher permeability could have existed where borrow material with a lower PI was used.*
> *Seepage through the porous foundation soils with the presence of termite passages and rodent holes."*

The remedial measures that were considered for the dam included reconstruction; the use of upstream lining protection in the form of Butyl rubber, polythene sheeting, bentonite and a chemically treated surface layer; and finally water treatment. The water treatment approach was eventually chosen since it was considered as having a better chance of success and it was also significantly cheaper than the other methods. Water treatment involves the process of increasing the electrolyte concentration of the reservoir water for a limited period of time such that the dispersive behaviour of the soil is suppressed. In the case of the Senekal dam, gypsum ($CaSO_4.2H_2O$) was utilized. Water seepage could therefore continue to flow through the clay, inducing the swelling properties of the clay and closing small fissures. The calcium ions in the water would also replace the sodium ions in the clay lattice and thus reduce the ESP of the soil. By the time the reservoir is brought into commission, storing normal treated water, the ESP of the soil would be permanently reduced with the clay in a stable non-dispersed state (Wagener 1980).

After refilling the reservoir, water continued to seep through the foundation in a similar fashion as before, with the only exception being that the seepage water was clear. However, failure did not re-occur due to the fact that the gypsum treated water had leached the sodium ions from the soil thereby reducing its dispersive properties and the slightly saline water would have also inhibited piping, allowing the clay to swell and obstruct leakage channels with flocculated particles (Wagener et al. 1981).

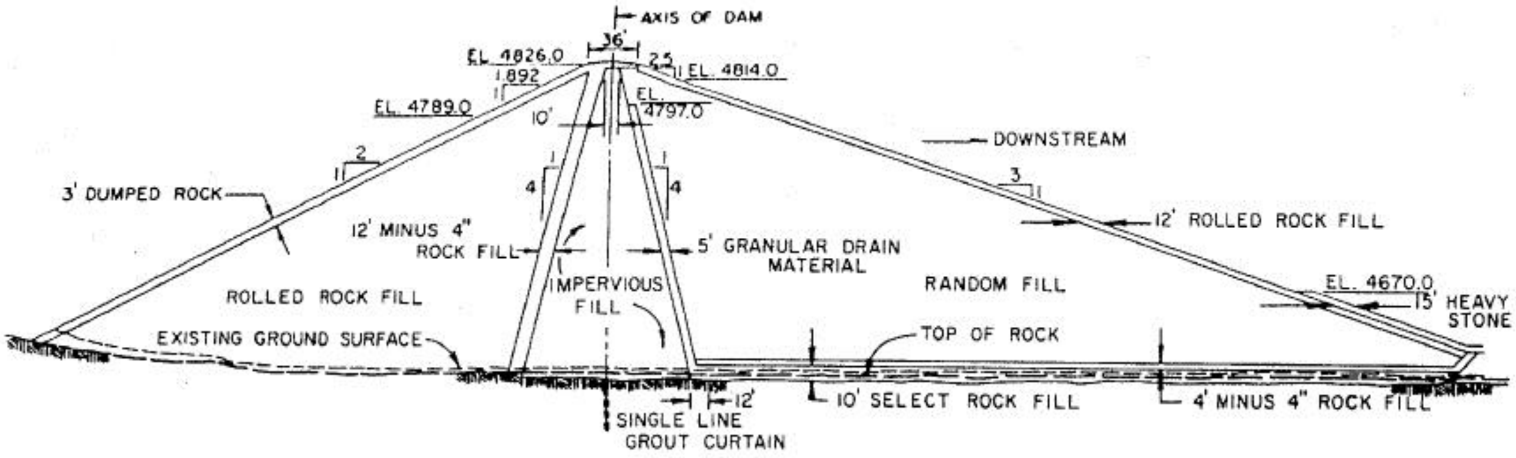
2.8.2 *Case history 2: Los Esteros Dam (International)*

Los Esteros dam is located on the Pecos River in east-central New Mexico. Construction of this dam commenced in June 1975 and was completed in 1981. In June 1976, during a joint site inspection, unusual erosion patterns were observed in a storage pond excavated in the borrow area. It was considered that the borrow material might be dispersive and three samples were taken and tested for dispersive properties.

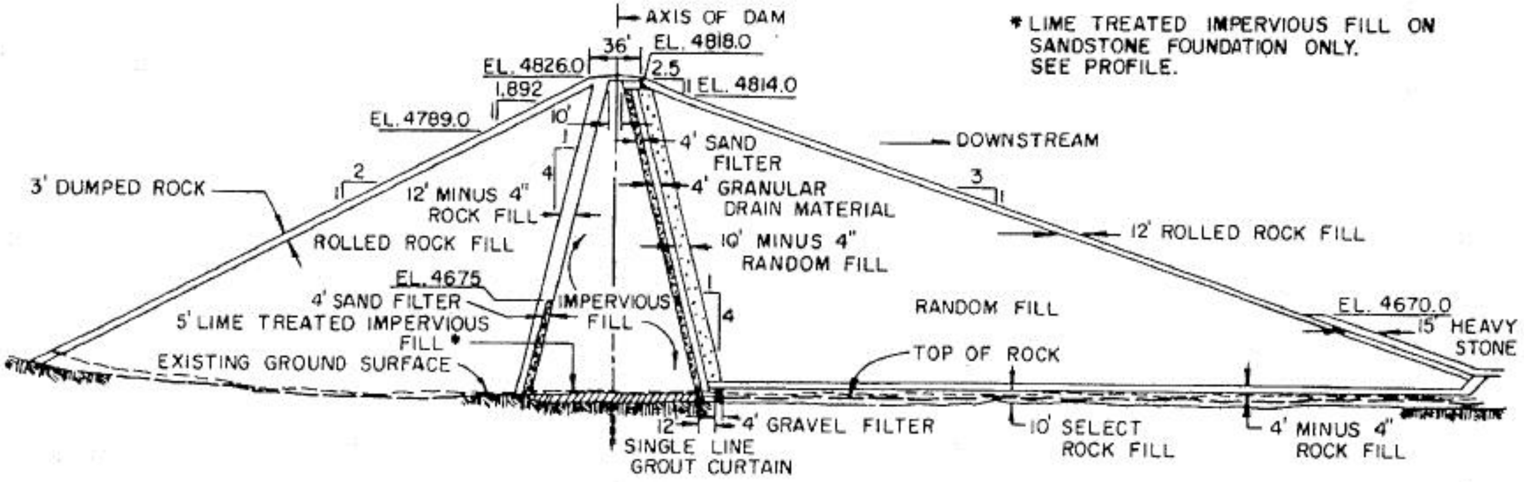
Results of the testing were found to be inconclusive due to contradicting results. Two out of the three samples showed an ESP of less than 15%, indicating that they were non-dispersive. After plotting the percentage sodium against total dissolved salts (TDS), two samples were found to be non-dispersive and one dispersive. The results were re-plotted on a revised chart, which showed all samples to be dispersive. With regard to the double hydrometer test, two tests were unsuccessful since particles remained flocculated and the clay fraction could not be determined. The third test indicated a dispersion ratio of 27% signifying a non-dispersive sample. Colour-of-flow criteria in the pinhole test showed all three samples as being dispersive, while rate-of-flow criteria showed them as intermediately dispersive (McDaniel and Decker 1979).

The site was inspected again in 1977 and a second suite of tests was run on samples. Tests were run on samples from the borrow pit as well as the sand filters and granular drain materials. The tests that were run for dispersive properties were the pinhole test, the SCS dispersion test (double hydrometer) and chemical tests. The test results indicated that the clay material in the borrow pit was highly dispersive. The tests also concluded that the erosion potential of the soil was very high within the range of salt concentration expected in the Pecos River water. Filter tests found that the suggested granular filter would not block dispersive erosion, but a sand filter used adjacent to the embankment section would successfully block it.

Based on the test results, the decision was taken to modify the contract and provide defensive design measures to rule out the possibility of dispersive erosion through the impervious core of the dam. The recommendations were to firstly treat the clay with lime to neutralize its dispersive properties and secondly, to use a sand filter to prevent dispersive erosion along any cracks or fissures that may develop. The addition of 4% (by dry mass of soil) of hydrated lime converted the dispersive soil into a non-dispersive, erosion-resistant soil. Figure 2-12 illustrates the original design of the dam and the modified design after test results concluded the soil to be dispersive (McDaniel and Decker 1979).



A. ORIGINAL DESIGN



B. MODIFIED DESIGN

Figure 2-12: Design of Los Esteros embankment dam; A: Original and B: Modified version (From McDaniel and Decker, 1979).

2.8.3 *Case history 3: Elandsjagt Dam (Local)*

The Elandsjagt Dam, situated on the Kromme River south of Humansdorp in the Eastern Cape, is a 70m high embankment dam capable of holding 100 × 10^6 m^3 of water. The geology of the site comprises massively bedded sandstones and quartzitic sandstones of the Table Mountain Group conformably overlain by sandstones, mudstones and shales of the Bokkeveld Group. The core material and earth fill for the embankment was obtained from the deeply weathered Bokkeveld shales. In the borrow pits, the weathered shales and mudstones produced silty clayey material with no surface erosion patterns that would indicate dispersive properties (Melvill and Mackellar 1980).

The probability that the material was potentially dispersive was indicated by results of hydrometer tests carried out for grading analysis of the sample. The samples were then run through a comprehensive testing programme to determine the dispersivity of the soils. Tests that were carried out included the SCS dispersion test, the crumb test, pinhole test and chemical tests.

Melvill and Mackellar (1980), found the criteria for evaluating SCS dispersion results to differ from one source to another, and for the case of the Elandsjagt dam, took values greater than 35% as an indicator of dispersivity. Values less than 15% were taken as being non-dispersive. Using these criteria, out of the 30 samples tested, 19 tests indicated dispersive behaviour and 8 indicated non-dispersive behaviour. For the crumb test, 11 out of 17 samples were classified as being dispersive. Based on the criteria for the pinhole test as described by Sherard et al. (1976a), 9 out of 17 samples tested suggested the material to be dispersive, 5 showed it to be intermediate and 3 were non-dispersive. The large diameter pinhole test was also used to evaluate the performance of a proposed fine filter material and was found to be very useful in validating the suitability of the material.

Chemical analyses were carried out on the salts in the pore water. The concentration of the cations in the saturation extract of 30 samples was determined and the results plotted on the chart proposed by Sherard et al. (1976a). All results plotted in Zone A of the chart as illustrated in Figure 2-13.

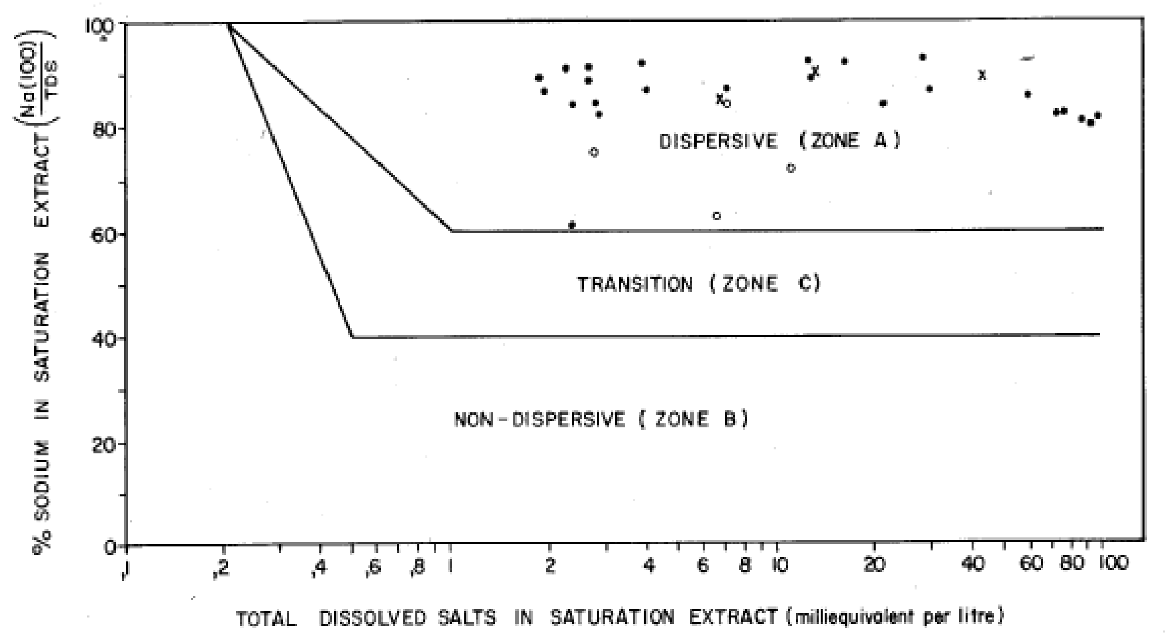


Figure 2-13: Chemical tests on pore water salt (From Melvill and Mackellar, 1980).

Results from all tests clearly indicated the dispersive potential of the soil proposed for uses as the impervious core of the embankment dam. For the stabilisation of the dispersive material, the use of hydrated lime as used at Los Esteros Dam was considered. This idea was, however, ruled out as the stabilized clay would be brittle and would be more likely to crack.

Provisions were made for the addition of a chimney drain that would act as a filter to prevent piping erosion. Other precautions were also taken to ensure the prevention of piping in the embankment. Cracks and fissures in the dam foundation were sealed off with dental concrete and slush grouting in addition to the normal prerequisite of blanket grouting. Care was also taken to minimise the formation of desiccation cracks during construction. Finally, reinforced rockfill was used on the downstream slope up to 60m high as part of the protection against flooding making the dam much more secure from the danger of catastrophic erosion (Melvill and Mackellar 1980).

2.8.4 <u>General</u>

There are various other cases in which dispersive soils have been used in construction. In some cases, the soils were not identified prior to construction, and failure had occurred, leading to investigations to determine the cause of failure. In other cases, the soils were identified during the site investigation phase, and the soils were dealt with accordingly.

In July of 1976, the American Society for Testing and Materials (ASTM) Committee held a symposium on the subject of dispersive soils. The symposium took place at the 79th annual meeting of the American Society for Testing and Materials held in Chicago, Illinois. Many cases histories can be found in the proceedings of this symposium by Sherard & Decker (1977). There is no evidence of such a conference being held since then: i.e. Conferences specifically dedicated to dispersive soils.

2.9 **Summary**

The problems related to dispersive soils were first identified in the 1960's after the failure of several earth dams. Most of the literature concentrated on in this study ranges from the 1970's (Donaldson; Sherard) to 1985, which is when the State of the Art on dispersive soils in South Africa was presented by Elges. During this period numerous failures of earth dams had occurred leading to the initiation of investigations into the problem. Work was essentially concentrated on the development of tests for the identification of dispersive soils as well as treatment methods or ways of overcoming the problem.

Since then, only limited work has been carried out on the application and use of combinations of tests to improve the predictability of dispersive soils with little or no further investigation into the actual test methods. Some authors, such as Bell and Walker (1997- 2000), converted the previous work into rating systems for the improved classification of dispersive soils. The lack of ongoing work and problems with some of the testing and interpretation were highlighted in a recent state-of-the-art document prepared as an update of Elges 1985 paper (Paige-Green, 2008).

There have, however, been noticeable contradictions in terms of some of the interpretations of results obtained from testing and the actual test methods. Due to the nature of this thesis, critical evaluations of publications analysed in this literature study, are provided in the relevant chapters. This thesis therefore concentrates on the detailed investigation of the current test methods used for the identification of dispersive soils and the correct interpretation of the results in response to the problems discussed by Paige-Green (2008). It is considered essential that standardised test methods (and interpretations) are used for the accurate and repeatable characterisation of dispersive soils in future.

The problem has been manifested by the repeated number of requests received by CSIR regarding dispersive soils and the contradictory and ambiguous results presented. These usually confirmed the problems with the test methods more than the interpretation of results.

3 Experimental Design

3.1 Introduction

Based on observations made during the literature study (Chapter 2), a test programme was developed to assess some of the deficiencies and limitations of the test methods that were identified. The experimental programme was designed with the specific aim of examining the potential problems encountered when carrying out routine laboratory tests for the identification of dispersive soils. It was not the aim of the research to assess the dispersiveness or classification of the soils, but to concentrate on weaknesses in the test methods. The aim of this chapter is thus to elucidate all aspects and activities of the experimental programme.

3.2 Pilot Study- preliminary tests

To develop an initial understanding of the problems related to the identification of dispersive soils, a limited number of samples was collected and subjected to the available standard test methods. Some modifications were made during this pilot study in order to increase the understanding of possible shortcomings in the test methods. For this study, three samples of known dispersivity were selected. The samples were considered as highly dispersive (ZT114), moderately dispersive (UM208) and non-dispersive (ND309) based on their geological and physical properties in the field, as well as past experience (Paige-Green, 2010). The recommended combinations of tests were carried out on each sample using the standard test protocols currently employed in South Africa, to identify any anomalies that could affect the results and the problems noted for future testing and modifications of the test methods.

3.3 Full Study

Based on the results obtained from the pilot study, the individual test methods were improved and fine-tuned to increase consistency, repeatability and reproducibility of the results. This entailed the testing of an additional 9 samples with the intention of identifying an optimum test protocol for each of the different types of tests.

3.4 Sampling

To carry out an investigation of this type, it is necessary to obtain a range of materials ranging from highly dispersive to totally non-dispersive. This was done on the basis of past experience with certain materials as well as visual manifestations of the exposure and erosional features in the field.

The obviously non-dispersive material (ND309) showed evidence of slaking in the field without any erosion channels. There was no evidence of piping or gullies in the material. Figure 3-1 illustrates the condition of sample ND309 in the field.

Figure 3-1: Non-dispersive sample (ND309) with no evidence of erosion, piping or gullies.

The suspected slight to moderately dispersive materials showed severe erosional features such as channelling and ridging (Figure 3-2) and the suspected highly dispersive materials showed significant piping and gully features (Figure 3-3 and Figure 3-4). Table 3-1 highlights the properties (sample location, geology, etc) of the 12 samples.

Figure 3-2: Suspected moderately dispersive sample (COED1) with erosional channels.

Figure 3-3: Sample suspected to be highly dispersive (13O3) with erosion gullies and piping structures.

Figure 3-4: Sample expected to be highly dispersive (N2S2) with piping and tunnel features.

Table 3-1: Table illustrating the location, geology/material type and expected dispersivity of samples

Sample No.	Location/ GPS coordinates	Geology/ Material Type	Expected Dispersivity (Field observations/past experience)
13O1	S 26° 00' 20.64" E 30° 27' 45.97"	Unnamed Archaean potassic granite	Dispersive
13O2	S 25° 59' 49.5" E 30° 28' 40.99"	Unnamed Archaean potassic granite	Dispersive
13O3	S 25° 54' 39.61" E 30° 35' 35.72"	Unnamed Archaean tonalitic gneiss	Highly dispersive
N2S1	S 32° 08' 13.2" E 28° 16' 32.7"	Transported material on Tarkastad Subgroup	Dispersive
N2S2	S 31° 55' 00.6" E 28° 27' 0.17"	Transported material on Adelaide Subgroup	Highly dispersive
SENJ1	S 28° 21' 11.55" E 27° 38' 22.08"	Transported material on Adelaide Subgroup	Highly dispersive
KNP1	S 24° 36' 26.18" E 31° 40' 22.34"	Unnamed Archaean potassic granite	Dispersive
UM108	S 31° 33' 18.21" E 28° 40' 24.96"	Tarkastad Subgroup mudstone	Moderately dispersive
COED1	S 29° 54' 39.40" E 30° 57' 09.05"	Dwyka Group Tillite	Moderately dispersive
ZT114	S 25° 30' 04.59" E 26° 15' 23.19"	Transported, derived from Hekpoort formation	Highly dispersive
ZB114	S 25° 30' 04.59" E 26° 15' 23.19"	Transported, derived from Hekpoort formation	Highly dispersive
ND309	S 25° 45' 13.05" E 28° 16' 44.41"	Undifferentiated diabase intrusion	Non- dispersive

All samples, after collection, were subjected to routine soil testing in the CSIR BE soils laboratory. The tests carried out included Atterberg limits (plastic limit, liquid limit and plasticity index), apparent relative density and grading analysis. The samples obtained were too small for compaction tests so densities and optimum moisture contents could not be determined. The results of the routine tests are summarized in Table 5-1 in Chapter 5.

3.5 **Methodology- pilot study**

For the pilot study, the currently recommended tests were carried out on the three samples using the existing prescribed test methods. These tests included the pinhole test (according to Sherard *et al* (1976a) and BSI 1377-5:1990); the double hydrometer test (according to BSI 1377-5:1990, ASTM D4221-99 and D422-63 and TMH1 method A6). No standard methods are specified locally for the crumb test and chemical analyses (as shown in Chapter 2) and methods adapted from descriptions in the literature were thus followed. Some modifications were made during the pilot study when faced with problems related to preparation and test methods. This helped gain a better understanding of the possible shortcomings that could occur during the testing process. The investigation into the test methods and procedures with problems encountered is discussed in chapter 4.

3.6 **Methodology- full study**

The methodology for the remainder of the project was based on the findings of the pilot study and is discussed fully in Chapter 4.

4 Investigation of current test Methods

4.1 Pilot study

Dispersive soils cannot be differentiated from non-dispersive soils by conventional soil index tests such as particle size distribution, Atterberg limits, or compaction characteristics (Elges, 1985).

Since the first occurrences of dispersive soils, many identification methods have been developed and proposed specifically for dispersive soils. The American Society for Testing and Materials (ASTM) held the first international symposium on Dispersive Clays in 1976 (Sherard and Decker, 1977). The symposium aimed to arrive at solutions to all unanswered questions related to the dispersive soil problem. In 1985, the South African Institute of Civil Engineers held the first Problem Soils conference in South Africa, where the State of the Art paper on dispersive soils by Elges (1985) was introduced. Since then, there have been a number of publications based on the primary test methods described by Sherard et al (1976b).

Dispersive characteristics therefore need to be confidently identified by performing various specialised tests on soil samples. Currently there are four test methods used in combination in South Africa to identify dispersive soils. These tests include the pinhole test; the double hydrometer test; the crumb test and the analysis of selected aspects of the soil chemistry. More often than not, a combination of the results obtained from these methods is used to determine the potential of a soil to disperse (Bell and Walker, 2000). The results from the four tests and analyses are then combined into a rating system to determine whether the soil is dispersive or not. Little work has, however, been done on the procedure, repeatability and reproducibility of the actual test methods, which in themselves may introduce a number of the problems associated with the discrimination between dispersive and non-dispersive soils.

Each of the individual test methods is discussed in detail in this chapter and the associated problems identified during this project are highlighted.

4.1.1 *Pinhole test*

The pinhole test has been considered one of the most reliable tests for classifying dispersive soils (Walker, 1997). The pinhole test measures the erodibility/dispersibility of a compacted soil sample in which water is allowed to flow through a small hole punched through the centre of the specimen. The test is generally considered in the literature to be one of the most reliable physical tests to determine the dispersibility of soils since it simulates the action of water draining through a pipe/crack in the soil. The pinhole, which is punched through the centre of the compacted sample, is 1 mm in diameter and water flows through the sample at heads of 50 mm, 180 mm, 380 mm and 1020 mm during the experiment (Sherard et al, 1976a). The flow rate, effluent turbidity and size of pinhole at the end of each test are the parameters recorded. If the effluent is highly turbid (murky) and the pinhole is enlarged, then the soil is classified as being dispersive. If the opposite is observed, i.e.: the effluent is clear and the pinhole size remains unaltered, then the soil is considered non-dispersive. In some cases, the water may be clear but the pinhole could be severely enlarged, in which case erodibility but not dispersiveness is indicated.

The pinhole test method is based on the guidelines described in a paper by Sherard et al (1976a). As stated in the paper, the test was developed for the direct measurement of the erodibility of fine grained soils, using the flow of water passing through a small hole in the specimen. The main objective was also stated as being a reliable way of identifying dispersive soils. It should, however, be noted that all dispersive soils can be erodible but not all erodible soils are necessarily dispersive (Paige-Green, 2008).

The pinhole test procedure involves separating the material finer than 2 mm and compacting it into a cylinder 100 mm in length and 34 mm in diameter. According to the guidelines and test methods, the material should be compacted at moisture contents at or close to the plastic limit of the soil. The material is compacted in the cylinder on top of pea gravel and a wire screen. After compaction, a 1 mm hole is punched through the centre of the specimen and the remainder of the cylinder is filled with pea gravel (Figure 2-5). After the specimen is prepared and the apparatus assembled, water is percolated through the pinhole under heads of 50, 180 and 380 mm for periods of 5 – 10 minutes at each head. The test was not carried out under 1020 mm constant head for the reason that it classifies the soil as non-dispersive only and this is not the purpose of the study. The quantity of flow and time at different flow volumes is measured continuously and recorded on data sheets. The turbidity of the effluent (colour of the water) during the test is also recorded.

Since the test aims to identify dispersive soils, it should be first noted that erodible soils are very different from dispersive soils. The pinhole test is likely to identify highly erodible soils which can be mistaken for dispersive soils. According to Bell and Walker (2000), the diameter of the pinhole at the end of the test proves to be the most reliable indicator for recognizing dispersivity.

This, however, should not be the only determining factor for the identification of dispersivity as the pinhole diameter of erodible soils will so increase; probably more so than for dispersive soils. The nature of the effluent plays a vital role in the test procedure, not only for the colour but also the type of sediment/material present in the water. The effluent from a soil can be highly turbid as it exits the test but not necessarily dispersive. If the soil is dispersive, the effluent should stay turbid for a prolonged period since clay particles will stay in suspension, whereas the suspension in purely erodible materials will settle out rapidly and the solution will become clear (or possibly stained if the soil contains certain elements such as iron or organic matter)..

One of the major problems associated with the pinhole test is that of preparation of the specimen in the cylinder. According to the procedure, the sample (at a moisture content at or near the plastic limit) is compacted on top of the pea gravel with the use of a Harvard Compaction apparatus. Observations during preliminary testing found that firstly, some soils appear to be excessively moist at their plastic limits. This makes the compaction process difficult, as the material shears (pore water pressure increases) under the applied load instead of compacting. This occurs because the effective strength of the material is too low. Secondly, during the compaction process the soil particles at the bottom of the cylinder tend to migrate (squeeze) through the mesh and into the voids in the pea gravel. This leads to blockages in the pea gravel and once the test starts, the water flows through the pinhole, mixes with the soil in the pea gravel and flows out as a highly turbid effluent. This then leads to misleading results.

The test method states the type of compaction (Proctor density) and an estimated target density of 95 per cent, however, it should be noted that this is just an approximation. There is no control available in the test methods to ensure that the actual target density is achieved, making the test procedure very ambiguous. This could lead to significant differences in the behaviour of the material, as almost all geotechnical properties are affected by the degree of compaction of the material. Proctor densities are most commonly utilized for dams and not for roads, which poses the question of the suitability of the test for purposes other than dam construction. Further investigations have found that no study has been carried out to determine the influence of density on the pinhole test results.

An additional component of the procedure that affects the effluent turbidity is the process of punching the pinhole. The pinhole is punched with a 1 mm steel pin after the soil is compacted on top of the pea gravel. The steel pin pushes the soil to the bottom of the specimen, but stops there since the pea gravel will not allow it go further. This, as a result, often blocks the end of the hole causing the test to fail since there will be no flow through the specimen.

All of the above problems noted during preliminary testing highlighted the various inconsistencies associated with the test procedure itself. This is probably the reason for inconclusive results obtained in past investigations when the pinhole test was used as an identification tool. It is assumed that if the problems are overcome, the test could be expected to run efficiently and be a consistent indicator of dispersivity.

4.1.2 *Double hydrometer test*

The Soil Conservation Service (SCS) double hydrometer test is one of the first methods developed to assess the dispersiveness of soils (Knodel, 1991). The test assesses the dispersivity of a soil by comparing the natural tendency of the clay fraction in the soil to go into suspension in water with an identical test in which conventional dispersants and mechanical breakdown are used. The procedure involves the determination of the percentage of particles in the soil that are finer than 0.005 mm using the standard hydrometer test for particle size distribution. A parallel test is carried out, in which no chemical dispersant is added and the sample is not mechanically agitated. The quantity of particles finer than 0.005 mm in the parallel test is expressed as a percentage of this fraction determined in the standard test, which is defined as the dispersion ratio or dispersivity of the soil (Elges, 1985). Dispersion ratios greater than 50% are considered highly dispersive, between 30 and 50% are moderately dispersive, between 15 and 30% are slightly dispersive and less than 15% are non-dispersive (Elges 1985). Other authors (Gerber and Harmse, 1987; Walker, 1997), base the categorization on different dispersion ratio limits. There is currently no standard criterion set for the dispersion ratio limits.

The test methods for hydrometer analysis currently in use locally are mainly the American standard (ASTM International, 2007), the British standard (BSI, 1990) and the South African Technical Methods for Highways - TMH1 (NITRR, 1986). Some laboratories use their own in-house modification of the methods.

Table 4-1 summarises the procedures carried out for each test standard, focusing on the main aspects of the testing procedure.

Table 4-1: Difference in testing procedures used for the determination of the clay fraction of a soil.

Property	ASTM- D422-63	BSI- BS 1377-2 & 5: 1990	TMH1- 1986 (A6)
Amount of dry soil required for the test:	Sandy: 100g Silty/Clayey: 50g	Sandy: 100g Silty: 50g Clayey: 30g	Sandy: 100g Silty/Clayey: 50g
Pre-treatment	None	With hydrogen peroxide if organic matter present.	None
Dispersant	125mℓ sodium hexametaphosphate solution at 40g/ℓ.	100ml sodium hexametaphosphate solution comprising 33g Na-hexa. + 7g Na-carbonate in distilled water to make 1 ℓ of solution.	5 mℓ each of sodium silicate and sodium oxalate solutions.
Soaking	Samples soaked for minimum of 16 hrs.	Soak in solution for min of 4hrs or overnight.	Minimum period of 2 hrs but preferably overnight.
Dispersion	Disperse for 1 minute with a mechanical stirring apparatus	Disperse sample in mechanical stirring device for at least 4 hours or overnight	Disperse for 15 minutes with a stirring apparatus
Hydrometer readings	Taken at 2min; 5min; 15min; 30min; 1h; 4h and 24h.	Taken at 8min; 30min; 2h; 8h & 24h.	Taken at 18s, 40s & 1h.
Analysis	Equations used to calculate maximum diameter of particles in suspension (Stoke's Law)	Equations used to calculate maximum diameter of particles in suspension (Stoke's Law)	Maximum particle size calculated. At 1h, max size is 0.005mm, at 40s max size is 0.05mm and at 18s, max size is 0.075mm.
Temperature	Constant temperature at or near 20°C is required.	Constant temperature bath of 25°C, to an accuracy of ± 0.5°C.	20°C when readings are taken or a temperature correction has to be applied.

Analysis of these test procedures illustrates little variation in the method of determination of the particle size of the fine fraction, except with regard to the types of dispersing agents used. The ASTM and BSI standards specify that sodium hexametaphosphate be used as a dispersing agent. However, the solution is prepared differently and at different proportions in each standard. The volume required to disperse the sample is also significantly different.

TMH1 specifies that a mixture of sodium silicate and sodium oxalate be used as the dispersing agent. A study of the past revisions of the South African standards shows that this combination was specified in the 1958 and 1986 test methods, whereas, sodium hexametaphosphate was specified as the standard dispersant in the 1970 version. No reason as to why the combination of sodium silicate and oxalate is used instead of sodium hexametaphosphate was found or why there was a change in the standard in 1970.

It should also be noted that TMH1 states that the one hour hydrometer reading indicates the percentage of the clay fraction in the sample. Analyses show that at one hour, particles in suspension in all samples are in the range of 0.006 – 0.007 mm, which is silt-sized and not clay-sized.

Preliminary tests were carried out to evaluate the effects of the different dispersing agents on the test results. For the study, the test procedures that were used as guidelines were the South African standard (TMH1) and the American Standard (ASTM), with the differing dispersing agents. The tests were carried out on three samples, one non-dispersive, one highly dispersive and a third that was considered to be moderate to slightly dispersive (based on past experience and field observations). The dispersing agents used were combinations of sodium hexametaphosphate (33g) plus sodium carbonate (7g) in a litre of water and a sodium silicate (5mℓ) plus sodium oxalate (5mℓ) solution. Samples were left to stand for approximately 16 hours after dispersion before being shaken and the hydrometer readings were taken. Time intervals for the hydrometer readings were at 1 hour, 40 seconds and 18 seconds as specified in TMH1 MethodA6. The one hour readings as well as the calculated dispersion ratios for the two dispersing agents are summarised in Table 4-2.

Table 4-2: Preliminary test results obtained from 1 hour 152H hydrometer readings and dispersion ratios.

Sample	Control	Na silicate & oxalate	Dispersion ratio %	Na Hexameta-phosphate	Dispersion ratio%
ND309	1.9	7.9	17.7	13.9	10.1
UM108	2.6	11.6	22.4	16.6	15.7
ZT114	19.9	15.9	125.2	24.9	79.9

Preliminary test results show that there is significant variation in the *apparent* clay fraction between the two dispersants. The samples that were dispersed with sodium hexametaphosphate produced more realistic dispersion ratios than those of the other samples. This could mean that these samples were not completely dispersed with this dispersing agent (sodium silicate + oxalate) or that there could be some variation in sample preparation. However, as the samples were prepared together with utmost care to ensure ideal representatives, the latter is unlikely. An additional observation is that the results obtained for the two dispersants do not correlate. Sample ND309 falls into two different categories of dispersivity based on the classification by Elges (1985). It is classified as being slightly dispersive using sodium silicate/oxalate and non-dispersive using sodium hexametaphosphate, which can lead to uncertainty regarding treatment requirements, should it be used for construction.

Another inconsistency noted is that different test methods, as well as authors, indicate different particle sizes for the clay fraction. TMH1 and ASTM use the 0.005 mm fraction as the boundary for the clay fraction, whereas BSI uses the 0.002 mm. Many authors quote the 0.005 mm fraction as the clay fraction when determining dispersivity of a soil. A Dictionary of Geology (1972) defines the clay fraction as a mineral particle having a diameter less than 0.004 mm (1/256 mm). According to Reeves *et al* (2006), the ASTM standards define the clay fraction as being less that 0.005 mm and Japan defines the fraction as less than 0.006 mm. However, a majority of the countries listed define the clay fraction as particle sizes less than 0.002 mm. Once again there is no standard definition with regards to the unit size for clay particles although a scan of the literature shows that 0.002 mm is used more widely. As the 0.002 mm fraction is also the basis for classification of South African soils according to Brink and Bruin (2002), this size fraction is taken as the upper limit of clay-sized particles for this study.

It should be noted that dispersivity is a function of the clay mineralogy and not the clay size fraction. It is possible to have a high percentage of material passing the 0.005 or 0.002 mm fraction that is entirely quartz. This would not have dispersive properties. On the other hand, if all the material passing these fractions consists of clay minerals, the dispersive behaviour would differ considerably.

The literature indicates that during studies of dispersive soils the initial indicator of dispersivity of the material is generally classified on the basis of the double hydrometer test by means of various indicator graphs/plots. Many workers (Gerber and Harmse, 1987; Bell and Maud, 1994; Walker, 1997) have then proceeded to indicate that no single test (including the double hydrometer test) can be used to identify dispersive soils, and then propose classification rating systems using a number of tests. It is postulated that many of the ambiguities (i.e., the inconsistencies of results among workers) are the result of the incorrect initial classification of the dispersivity of materials as a result of variations introduced in the double hydrometer test.

Most of the rating systems used currently in South Africa seem to have been based on the initial classification of dispersiveness by the double hydrometer test. Gerber and Harmse (1987) used the test as a primary parameter when developing the ESP-CEC chart. Walker (1997) included the ESP-CEC chart as a parameter in the rating system and studies carried out by Bell and Walker (2000) also make use of the double hydrometer test when initially classifying the dispersive soils.

This has resulted in the overlap of results within single classification bands. Although it is assumed that in these investigations, the materials have been tested following uniform and standard procedures, preliminary testing has indicated spurious results when sodium silicate/oxalate (the South African road standard) is used as the dispersant (NITRR, 1986). It is also noted that the dispersant standard in South Africa has changed over time, possibly affecting the results, if they were obtained from different laboratories over a prolonged period of time. It can thus be assumed that this would be particularly more so in projects carried out over short periods at various times related to the general use of different dispersants with time.

Problems related to the double hydrometer tests pose the potential for misleading results since the test is associated with a number of different parameters in the rating systems. Inaccurate results from the double hydrometer test can significantly affect the correlation of the final rating, particularly when this test method is used as the reference methods for the preliminary classification of the dispersivity of soils (Gerber and Harmse, 1987; Bell and Maud, 1994; Walker, 1997).

4.1.3 *Crumb test*

The crumb test is the simplest and easiest of the physical tests and is often used as a preliminary test to indicate the tendency of the particles to deflocculate in solution. The test, which can also be carried out in the field, involves placing a crumb of soil in water in a beaker and observing the reaction as the crumb begins to hydrate. The test is primarily a visual assessment of the behaviour of the soil in solution. After 10 minutes, the soil crumb and the solution in the beaker are observed and the soil is classified according to the quantity of colloids in suspension (Walker 1997). Different workers use different techniques involving the use of either undisturbed or remoulded crumbs, with some using distilled water and others a very dilute solution of sodium hydroxide (NaOH) (Sherard *et al*, 1976b; Walker, 1997).

An assessment of the literature has found that many researchers appear to misquote Emerson's (Emerson, 1964; Emerson, 1967) work and use his findings incorrectly. There have been many cases in which the method has been misinterpreted with regard to variables such as moisture content and dispersing medium (Heinzen and Arulanandan, 1977; Bell and Maud, 1994; Walker, 1997; Bell and Walker, 2000). Walker (1997), states that a densely compacted, remoulded sample is less likely to slake/ breakdown, however, as the crumb test aims to determine the dispersiveness of the sample and not the behaviour when densely compacted, it should bear no significance on the test method. An ASTM standard is also available for the crumb test (ASTM D6572-00). The standard, however, takes other variables such as temperature, which appears to have no effect on the dispersivity of a soil, into account. The standard also calls for remoulding of the sample into a specific size (irrespective of density), which again appears to have no apparent effect on the dispersivity and instead makes the preparation somewhat more laborious.

The method mostly followed currently, which can be carried out in the field or a laboratory, involves placing a crumb of soil in a beaker of solution and observing the reaction as the crumb begins to hydrate. The test is primarily used as a subjective visual assessment of the behaviour of the soil as it indicates the tendency of the particles to deflocculate and remain in suspension in the solution. After a certain time, usually 5-10 minutes, the soil crumb and the solution in the beaker are observed and the soil is classified according to the quantity of colloids in suspension (Walker, 1997; Bell and Walker, 2000).

A literature search highlighted some variations in the test methods given by various authors. It was found that there is no standard protocol available regarding which solution or crumb condition to use when carrying out the test. Tests are carried out using dilute NaOH (0.001N) or distilled water and samples can either be in their natural density and moisture state (in situ conditions) or in various combinations of natural or remoulded and air dried, oven dried or moist (Sherard et al, 1976b; Knodel, 1991, Walker, 1997). All of these variables can have significant effects on the outcome of the test and thus the classification of the soil. Figure 4-1 illustrates the variance in appearance and results when the crumb test was carried out on the same material but under different conditions. The first test was carried out on a remoulded crumb in NaOH solution (a), the second was carried out on an air dried crumb in distilled water (b) and the third on a remoulded crumb in distilled water (c).

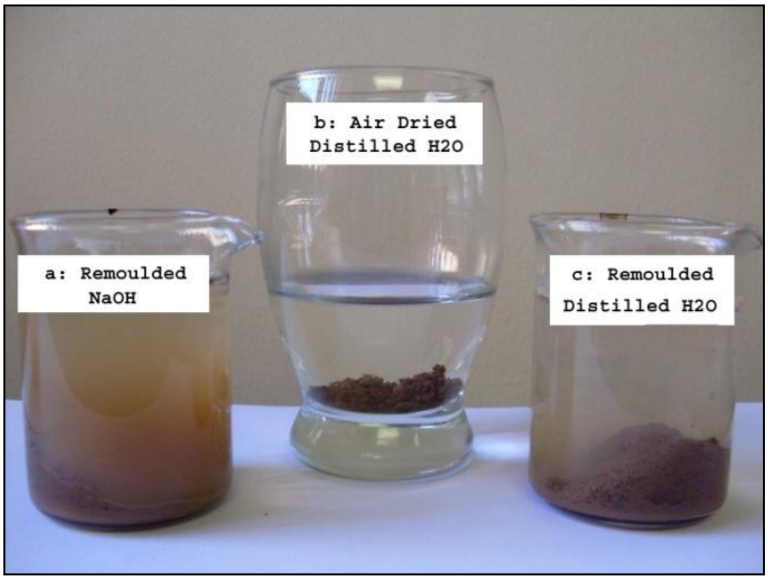


Figure 4-1: Variation in results based on different testing variables.

One of the consistent observations, however, that has come up many times is the time taken to “run” the test. It is most commonly stated that observations on the dispersivity (or suspension cloud) should be taken 5 to 10 minutes after the crumb is immersed in water (Elges, 1985; Walker, 1997). It should, however, be noted that if a soil is dispersive, the colloidal suspension will not settle and will still be present after a few hours. Figure 4-2 gives an example of what the colloidal suspension of a dispersive soil should look like after more than an hour.

Figure 4-2: Colloidal suspension of a highly dispersive soil- Grade: 4- strong reaction (Courtesy of Paige-Green, 2010).

Another observation found through discussions with various laboratories and researchers is that of the actual classification process. It should be noted that there is a significant difference between dispersive soils and erodible/ slaking soils. If, during the crumb test, the soil breaks down completely (slakes) without any colloidal suspension, then the soil will be classified as non-dispersive. The presence of colloidal suspension is the fundamental aspect of the classification process as this is the defining feature of dispersive soils (Paige-Green, 2008).

Results from preliminary testing show that after 10 minutes most of the samples observed would be classified as being dispersive to some degree. Settlement of non-dispersive particles generally begins after approximately 30 minutes and the maximum settlement is usually attained after 2 hours. Variations that could occur due to the lack of a standard protocol for testing and classifying the dispersivity of soils using the crumb test can lead to differences in classifications.

Table 4-3: Results obtained for crumb test under different variables.

Medium	Crumb condition	Time	Sample		
			ZT114	UM108	ND309
Distilled Water	Air dried	10 min	4	1	2
		2 hrs	4	1	1
		16 hrs	4	1	1
	Oven dried	10 min	4	2	1
		2 hrs	4	1	1
		16 hrs	4	1	1
	Remoulded	10 min	4	4	2
		2 hrs	4	4	1
		16 hrs	4	2	1
0.001N NaOH	Air dried	10 min	3	1	1
		2 hrs	4	1	1
		16 hrs	4	1	1
	Oven dried	10 min	1	2	1
		2 hrs	3	2	1
		16 hrs	3	1	1
	Remoulded	10 min	4	4	2
		2 hrs	4	4	1
		16 hrs	4	3	1

4.1.4 *Chemical Analyses*

The main problem noted during this research with the chemical analyses of soils is the inconsistency of the interpretation of results and the use of a range of test methods to determine any single property. Typically the chemical analysis tests are carried out by commercial laboratories (mostly agricultural) and investigations into the operation of a number of local laboratories has found many variations in the actual test methods and data interpretation used. Discussions with local laboratories also indicated that no standard protocol regarding test methods is employed countrywide.

Some of the discrepancies in results are due to variations in the way a property is measured. Cation exchange capacity (CEC), for example, is defined as the sum of extractable cations. Discussions with different laboratories found that some use a CEC that has been determined independently by summing the values for each of the individual cations while others use the total cation exchange capacity as determined by a single laboratory test. Investigations into the determination of CEC show that the results obtained from the summation of extractable cations is usually significantly different from that of the total CEC obtained from a single laboratory test. Different chemicals are also used to extract the exchangeable cations by different laboratories. These differences pose a problem when using the results to evaluate dispersivity since CEC is apparently related to other variables such as Exchangeable Sodium Percentage (ESP) and Exchangeable Magnesium Percentage (EMgP) (See Chapter 2). The routine provision of CEC results by laboratories seldom indicates which method was followed.

It has also been noted in various reports that the chemical properties (e.g., CEC, ESP, etc) are sometimes expressed as meq/100 g of dry soil and other times as meq/100g of clay (Gerber and Harmse, 1987; Elges, 1985; Walker, 1997). If the material consists of pure clay (i.e., 100% finer than 0.005/ 0.002 mm and 100% consisting of clay minerals) the results should be identical. However, very few natural soils have as fine a particle size distribution as this, and the test is usually conducted on material passing the 0.425 mm sieve. The results from these two sample fractions would differ significantly. Many laboratory reports do not state the units and even if stated, in general, workers (particularly with engineering and not soil science backgrounds) receiving these results would not question the difference or calculate the clay equivalent. To compound the problem, various laboratories present the results in terms of units such as meq/ℓ, cmol(+)/kg, meq/100g, mg/kg and mg/ℓ, which further requires conversion factors and complicates the interpretation of the results. Although 1 meq/100g = 1 cmol(+)/kg, calculations indicate that these units do not necessarily correlate directly with the other measurement units used.

Many of the commercial laboratories also calculate and provide derived properties such as Sodium Adsorption Ratio (SAR) and ESP, so as to make it easier for the customer to analysis these properties. However, it should be noted that the basis of these calculations might not always be consistent. Experience, during this study, has found the results for the same samples from two different laboratories to be very different. Investigation into the reasons for these variations in results (by means of interviews), found the specific equations used for calculations to be dissimilar. Table 4-4 shows the equations used by two laboratories for the determination of SAR as well as the correct equation for SAR determination.

Table 4-4: Variation in determination of SAR from two laboratories

Correct Equation	Equation used by Lab1	Equation used by Lab2
$SAR = \frac{Na^+}{\sqrt{0.5\left(Ca^{2+} + Mg^{2+}\right)}}$	$SAR = \frac{CEC}{\sqrt{0.5\left(Ca^{2+} + Mg^{2+}\right)}}$	$SAR = \frac{Na^+}{CEC} \times 100$

Table 4-5 and Table 4-6 illustrate the significant difference in results obtained from two laboratories.

Table 4-5: Difference in test results obtained from two laboratories (pH & CEC)

Sample #	pH			CEC		
	LAB1	LAB2	Difference	LAB1 cmol(+)/kg	LAB2 meq/100g	Difference
ZT114	9.44	9.05	0.39	14.80	11.47	3.33
UM108	4.88	4.16	0.72	7.81	6.07	1.74
ND309	6.51	6.07	0.44	15.78	18.50	2.73
Avg			**0.52**			**2.60**
Max			**0.72**			**3.33**
Min			**0.39**			**1.74**

Table 4-6: Difference in calculated results obtained from two laboratories (SAR & ESP)

Sample #	SAR			ESP (%)		
	LAB1	LAB2	Difference	LAB1	LAB2	Difference
ZT114	91.09	16.80	74.29	57.72	8.02	49.70
UM108	4.56	3.07	1.49	1.34	1.17	0.17
ND309	0.43	2.54	2.11	0.67	1.14	0.47
Avg			**25.96**			**16.78**
Max			**74.29**			**49.70**
Min			**1.49**			**0.47**

The calculated results obtained show differences of up to 50% for the ESP results and 74 for SAR values. The ZT114 sample has ESP values of 58% and 8% from the two laboratories, which are relatively significant considering that one result classifies the soil as being dispersive and the other as non-dispersive. It should also be noted that the units for the properties (meq/100g soil or clay) is not clearly stated with the test results. Discussions with some laboratories found that they are not even sure what the correct units are. Analysis of the test methods from the Soil Society of South Africa found that it is likely the units are in meq/100g soil (Loock, 1990) and would require conversion to meq/100g clay.

One of the laboratories presented the SAR values (calculated by the laboratory), along with the rest of the results and the values were found to be completely incorrect. The laboratory SAR value for sample ZT114 was given as 2.36 and the value obtained by calculation using the correct equation in Table 4-4 is 16.80, resulting in a significant difference in the result. It is, therefore, clear that the actual results of properties obtained directly by laboratory testing show significant differences from those calculated by means of equations.

4.1.5 *Summary*

The four principal tests used for the identification of dispersive soils have been methodically analysed and investigated. The investigations have highlighted some of the differences that can be obtained from a single soil, as a function of variations in test procedures. This is due to the numerous variables in the test procedures resulting in different interpretations of the test methods, and consequently non-comparable results. The number of ambiguities in the test procedures which can be interpreted differently by different laboratories and investigators has also been presented. A variety of factors affects the dispersive behaviour of soils resulting in contradictory results, which are likely to pose a problem when faced with the task of treating the soil for construction purposes. Owing to the problems encountered due to ambiguities and misinterpretations, difficulties related to repeatability and reproducibility are likely to arise. The individual tests themselves, if done correctly and consistently, may themselves be adequate indicators of dispersivity.

4.2 **Full Study**

Based on results obtained from the pilot study, the test methods were modified where necessary to eliminate the ambiguities, problems and deficiencies noted. The intention was to develop standard protocols that will produce repeatable and consistent results.

4.2.1 *Pinhole test*

The main problem identified during the pilot study was the sample preparation in terms of compaction to achieve a target density and moisture content. These components are loosely defined and if one has to carry out the test according to the methods available, it would be very difficult to obtain consistent results. The second problem is that of the actual procedure carried out during the test. These problems are discussed in details below.

4.2.1.1 *Density*

The test method, according to Sherard et al (1976a), states that the sample should be compacted using a Harvard Miniature compaction device to *approximately* 95% of Standard Proctor maximum dry density (MDD). During the preliminary tests, preparation of the sample using the Harvard miniature compaction device was extremely difficult. The compaction device does produce a consistent compaction effort through the cylinder, especially with the pea gravel below, which moves around when the load is applied. There is also no definite means of ensuring that 95% of Standard Proctor MDD is achieved.

Under normal circumstances, the quantity of sample generally supplied for preliminary testing is insufficient to allow complete routine testing. As a result, the compaction characteristics are one of the properties that cannot always be determined with the limited quantity of material. This poses the question: how does one ensure that a consistent density is achieved for the pinhole test specimen? Investigation into this matter found research that was carried out to predict the maximum dry density (MDD) and optimum moisture content (OMC) using Atterberg limits and apparent relative density (ARD) of the sample (Haupt, 1980; Semmelink, 1991).

Based on Semmelink's work (1991), the MDD (given as per cent solid density (%SD)) and OMC of a soil can be calculated as follows:

$$MDD\ (mod.AASHTO)(\%SD) = k_6.(GF)^{0.85} + k_7.C + k_8.(LS) + k_9.C^3 + k_{10} \qquad (1)$$

$$OMC\ (mod.AASHTO)(\%) = k_{16}.(GF)^{0.85} + k_{17}.C + k_{18}.(LS) + k_{19}.C^3 + k_{20} \qquad (2)$$

Where GF = Grading factor as defined in Equation (3)

C = (% passing the 0.425 mm sieve/100). (LL/100)$^{0.1}$

LL = Liquid limit

LS = Linear shrinkage (assumed as 0.5*(PI) for the purpose of this study)

K_n = Regression coefficient (Table 4-7)

GF = Σ (percentage passing sieve size/normal sieve size (mm))/100
(for the 75 mm, 63 mm, 53 mm, 37.5 mm, 26.5 mm, 19 mm, 13.2 mm,, 4.75 mm, 2.00 mm sieve sizes) (3)

Table 4-7 shows the regression coefficients needed for Equations (1) and (2).

Table 4-7: Regression coefficients by Semmelink (1991)

k_6	k_7	k_8	k_9	k_{10}	k_{16}	k_{17}	k_{18}	k_{19}	k_{20}
-33.7346	19.27655	-1.20764	-12.3063	99.93611	7.175719	0.346294	0.555493	2.861833	0.800098

Using the apparent relative density (ARD) of the soil sample, the MDD in kg/m^3 is then calculated as:

$$\text{MDD (kg/m3)} = (\%\text{SD} / 100) \times \text{ARD} \qquad (4)$$

The research carried out by Semmelink (1991) concentrated on the moisture-density relationship when prepared and compacted at the modified AASHTO compaction effort. The majority of investigations into dispersive soils relate to dam construction while little work has been carried out on the use of dispersive soils in road construction, particularly when used as subgrades and fills. The major difference in these two applications is the specified densities, which are typically 95% of Standard Proctor MDD for dams and 90-95% of modified AASHTO MDD for roads. In order to minimize dispersive problems it is suggested that compaction be as high as possible (Elges, 1985).

The test procedure by Sherard *et al* (1976a) calls for 95% of Standard Proctor MDD, which as discussed above, is suitable for dam construction. A study was carried out by Haupt (1980) in which a correlation between moisture-density relationships of the modified AASHTO and Standard Proctor compaction efforts was established. Based on Haupt's work, the following equations were used to determine the MDD and OMC for Standard Proctor compaction effort:

$$\text{MDD}_P = 1.2\,(\text{MDD}_M) - 533 \qquad (5)$$

$$\text{OMC}_P = 1.25\,(\text{OMC}_M) - 0.5 \qquad (6)$$

where MDD_P = Proctor maximum dry density

MDD_M = modified AASHTO maximum dry density

OMC_P = Proctor optimum moisture content

OMC_M = modified AASHTO optimum moisture content

For this study, samples were compacted at 95% of Standard Proctor MDD, in conformance with conventional testing of dispersive soils. However, five comparative tests were carried out at 95% of modified AASHTO MDD to assess the impact of density on the results.

Attempts to compact the samples using the Harvard Miniature Compaction Device were unsuccessful for various reasons (as discussed previously). For this reason and to minimise variability, it was decided that all samples for this investigation would be statically compacted to the target densities.

4.2.1.2 *Moisture content*

According to the test method, the moisture content of specimens for testing should be at or near plastic limit (Sherard *et al*, 1976a). As discussed in Chapter 3, all samples were run through routine soil analysis after collection. The results found most of the plastic limits to be very high leaving the samples excessively moist. This made the compaction process very difficult, as the material sheared (pore water pressure increases) under the applied load instead of being compacted. The predicted optimum moisture contents of the samples were significantly lower than the plastic limits. The results for the plastic limits and optimum moisture content are presented graphically in Figure 4-3 to illustrate the significant difference between the two properties. The plastic limits for some samples are as high as 34 % with the corresponding OMC of 14 %. Based on trial and error, it was found that a moisture content equivalent to OMC+3.5% appeared to be most successful in achieving samples suitable for compaction and testing. This moisture content was thus used for the preparation of all samples.

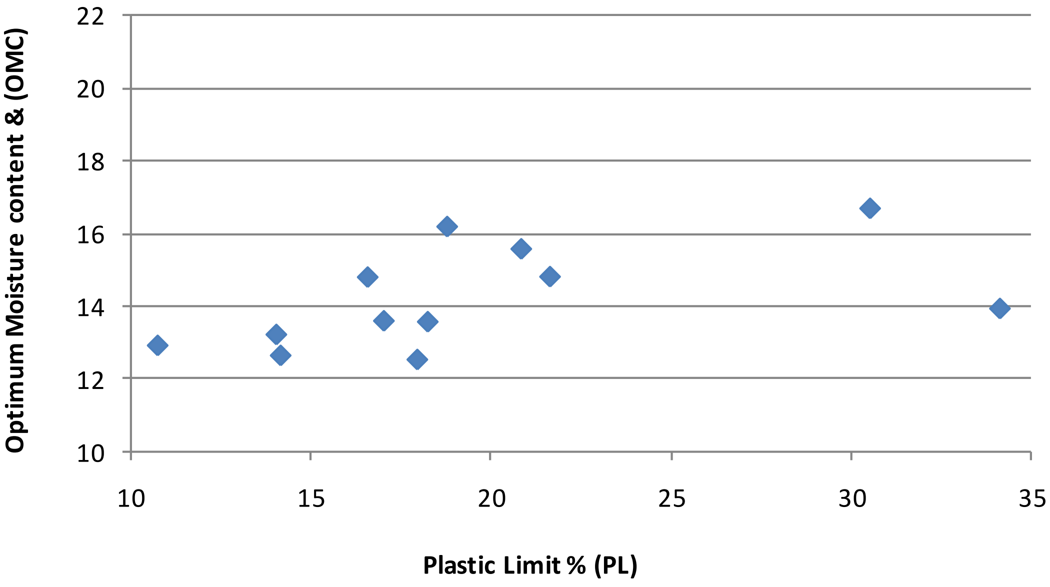


Figure 4-3: Picture showing comparison of plastic limits with optimum moisture contents.

4.2.1.3 *Test procedure*

For the test procedure, the correct proportions (air dried soil and distilled water) were accurately weighed out to produce the required final moisture content and thoroughly mixed. Samples were then left to equilibrate/cure overnight. After curing, samples were statically compacted to produce

38 mm specimens in a 100 mm long cylinder. A steel nipple was pushed through the compacted specimen and the hole was punched using the nipple as a guide with a 1.0 mm diameter steel needle.

Wire screens and pea gravel were placed in the cylinder on either side of the compacted specimen as illustrated in Figure 2-5. The cylinder was assembled and set up in the constant head apparatus. Distilled water was then percolated through the specimen under heads of 50 mm, 180 mm and 360 mm. Observations were made and the results are tabled in the following chapter.

4.2.2 *Double hydrometer test*

Since the preliminary test results showed significant variations in the clay fraction between the two dispersants and the samples that were dispersed with sodium hexametaphosphate produced more realistic dispersion ratios, the full study involved the use of sodium hexametaphosphate as the dispersing agent. The British Standard (BS 1377-5: 1990) and the proposed SANS method (SANS 3001-GR3) both used sodium hexametaphosphate as the dispersant. The test method that was used was based on the British Standard (BS 1377-5: 1990), with some minor modifications. It should be noted that all hydrometers are not exactly alike even though they meet the standard requirements (152H). There will always be differences with regard to the length of the bulb, volume of the bulb or the individual markings on the stem with all hydrometers. For this reason, every hydrometer that was used for this study was individually calibrated as specified in the British Standard Method (BS 1377-2:1990).

For the experimental study, samples were air dried and passed through a 0.425 mm sieve. Duplicate samples were soaked (one in distilled water and the other in dispersant) for a period of approximately 16 hours. The sample that was soaked with the dispersant was mechanically agitated for 20 minutes and then both samples transferred to cylinders and placed in a temperature controlled water bath to attain equilibrium temperatures. Once equilibrium temperatures were reached (20°C), the cylinders were agitated again (by hand) before being placed back in the water bath and readings taken. Hydrometer readings were taken at 30 seconds, 2 minutes, 5 minutes, 10 minutes, 1 hour, 2 hours, 4 hours and 20 hours and particle diameters were calculated to be plotted on a grading curve. The percentages finer than 0.002 mm was obtained from the plot and the dispersion ratio was calculated.

4.2.3 *Crumb test*

Since the preliminary results did not produce significantly conclusive results, all 12 samples were run through the crumb test with all variations. Crumbs were immersed in distilled water and dilute sodium hydroxide (0.001 N NaOH). The samples were tested with different conditions of crumbs. The crumbs were air dried, oven dried and remoulded. Observations were made at 10 minutes, 1 hour, 2 hours and 16 hours (overnight). The samples were then classified based on the grading system as discussed in Chapter 2.

4.2.4 *Chemical analyses*

The 12 samples were sent to three different commercial laboratories for determination of the soil chemical properties. The laboratories chosen are commonly used South African laboratories for soil chemical analysis by contractors/consultants and industry. Two of the laboratories specialise in soil testing for agricultural purposes while the third specialises in testing for civil engineering purposes. Chemical analyses included the determination of exchangeable cations, cations in the saturation extract, cation exchange capacity (CEC), pH and electrical conductivity. As part of their test reports, these laboratories also calculate parameters such as sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP) and total dissolved salts (TDS) (see Chapter 2). In order to assess the accuracy of the individual laboratory results, the parameters were all recalculated for comparative purposes. The 12 samples were also sent to a different laboratory for X-ray diffraction analysis to determine the clay components of the soils.

5 Results

5.1 Introduction

Testing of the 12 samples was carried out according to modified protocols based on the pilot study and the results obtained are summarised as follows. The full results are provided in Appendix A.

5.2 Routine classification tests

The results for Atterberg limits (PL, LL, PI, and LS), grading analyses and apparent relative density are shown in Table 5-1. The X-ray diffraction (XRD) results showing the mineral composition of the samples is presented in Table 5-2.

Table 5-1: Table showing results for Atterberg limits, grading analysis and apparent relative density.

Sample	Atterberg Limits				Grading analysis			ARD
	LL	PL	PI	LS	% passing 2.00 mm	% passing 0.425 mm	% passing 0.075 mm	
13O1	39.7	34.2	5.6	4.0	98.0	86.0	40.7	2.77
13O2	44.2	30.5	13.7	9.3	91.4	75.7	54.0	2.67
13O3	23.5	17.0	6.5	5.9	88.5	61.2	32.7	2.64
N2S1	31.7	20.8	10.9	6.0	96.2	93.7	63.3	2.79
N2S2	33.6	21.6	11.9	6.2	92.4	82.4	69.4	2.69
SENJ1	20.0	14.2	5.9	3.2	91.8	85.1	40.7	2.66
KNP1	27.1	18.2	8.9	4.5	97.3	78.1	40.1	2.65
UM108	15.4	10.7	4.7	2.5	98.1	96.0	45.8	2.61
COED1	25.5	16.6	8.9	4.7	99.1	95.5	57.9	2.63
ZT114	20.7	14.0	6.6	3.5	95.8	88.1	60.3	2.76
ZB114	26.0	18.0	8.1	4.0	94.8	87.2	63.5	2.84
ND309	27.8	18.8	9.0	8.8	90.8	59.0	20.0	2.80

Table 5-2: XRD results showing mineral composition of samples.

Minerals	Sample Number											
	13O1	13O2	13O3	N2S1	N2S2	SENJ1	KNP1	UM108	COED1	ZT114	ZB114	ND309
Andalusite										7.6	7.6	
Goethite								2.3		5.2	5.6	
Calcite				0.2	4.0							
Diopside	2.0	1.7	0.1			1.5	2.5		2.5			0.3
Enstatite						1.6	1.5					0.6
Hematite	0.4	0.3	0.1		0.1	0.1	0.2			0.2	0.3	3.8
Kaolinite	**51.9**	**47.2**	**24.6**	**28.9**	**36.8**	**9.0**	**12.9**	**1.7**	**31.1**	**41.8**	**42.7**	**23.8**
Microcline	3.3	9.7	1.6	4.4	3.4	6.4	15.4	1.2	13.5			8.0
Muscovite	7.7	7.3	3.7	6.8	8.0	6.3	5.9	3.0	4.9	7.3	8.0	1.6
Plagioclase	1.2	1.1	3.2	4.9	8.2	5.6	22.8	1.7	18.0			19.1
Quartz	33.5	32.7	66.8	54.7	39.5	69.4	38.9	90.1	30.1	37.9	35.8	23.5
Smectite												**19.3**
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

5.3 Pinhole Test

Results obtained from the pinhole tests are summarized in Table 5-3.

Table 5-3: Summary of pinhole test results.

95% Standard Proctor compaction effort

Sample	**Final Head (mm)**	**Final Flow rate (ml/s)**	**Colour**	**Pinhole size**	**Effluent after 1 hour**	**Classification**
13O1	----	----	----	----	----	----
13O2	180	0.8	Clear	x 1	----	**Non-dispersive**
13O3	180	0.02	Clear	----	----	**Non-dispersive**
N2S1	50	0.6	Medium	x 4	Slight	***Intermediate (<0.8ml/s) & dispersive (hole>x 2)***
N2S2	50	0.6	Dark	x 3	Medium	***Intermediate (<0.8ml/s) & dispersive (hole>x 2)***
SENJ1	50	0.5	Dark	x 3	Cloudy	**Dispersive**
KNP1	50 180	0.4 0.9	Slight Slight	x 1 x 1	Slight Slight	**Intermediate** ***??***
UM108	----	----	----	----	----	----
COED1	50	0.7	Dark	x 5	Medium	***Intermediate (<0.8ml/s) & dispersive (hole>x 2)***
ZT114	50	0.3	Dark	x 2	Dark/Cloudy	**Dispersive**
ZB114	50	0.2	Dark	x 2	Dark/Cloudy	**Dispersive**
ND309	180	0.8	Clear	x 1	----	**Non-dispersive**

95% Modified AASHTO compaction effort

Sample	**Final Head (mm)**	**Final Flow rate (ml/s)**	**Colour**	**Pinhole size**	**Effluent after 1 hour**	**Classification**
13O1	50	0.1	Clear	----	----	**Non-dispersive**
13O2	180	1.04	Clear	x 1	----	**Non-dispersive**
KNP1	50 180	0.03 0.9	Slight Slight	---- x 2	---- Slight	***Intermediate??*** ***??***
KNP1	50 180	0.3 0.7	Slight Slight	---- x 2	---- Slight	***Intermediate??*** ***??***
COED1	50	0.3	Medium	----	Slight	***Dispersive?? (Flow < 0.8ml/s)***
ZB114	50	0.5	Dark	x 2	Dark/Cloudy	***Intermediate (<0.8ml/s) & dispersive (hole>x 2)***

5.4 Double Hydrometer

The results for the modified double hydrometer test are shown in Table 5-4.

Table 5-4: Summary of the double hydrometer test results.

Sample #	Percentage passing 0.002 mm (% clay)		Dispersion ratio (%)
	Standard hydrometer	Double hydrometer	
13O1	15.0	5.8	39
13O2	59.0	0.0	0
13O3	26.3	3.0	11
N2S1	56.4	3.4	6
N2S2	65.2	4.1	6
SENJ1	29.5	27.7	94
KNP1	22.8	0.6	3
UM108	24.6	1.0	4
COED1	27.6	18.0	65
ZT114	31.6	43.8	**139**
ZB114	47.9	58.5	**122**
ND309	24.0	0.0	0

5.5 Crumb Test

The results obtained for the crumb tests are tabulated below. Table 5-5 shows the results obtained when distilled water was used as the immersion medium and Table 5-6 shows the results when dilute sodium hydroxide (0.001N NaOH) was used.

Table 5-5: Results for crumb tests with distilled water as the immersion medium.

Sample #	Distilled Water									Overall Class-H_2O
	Air Dried			Oven Dried			Remoulded			
	10 min	2 hrs	16 hrs	10 min	2 hrs	16 hrs	10 min	2 hrs	16 hrs	
13O1	1	1	1	1	1	1	1	1	1	***1***
13O2	1	1	1	1	1	1	1	1	1	***1***
13O3	3	1	1	2	1	1	1	1	1	***1***
N2S1	1	1	1	3	2	1	1	2	2	***2***
N2S2	1	1	1	3	2	2	3	2	1	***2***
SENJ1	4	4	4	4	4	4	4	4	4	***4***
KNP1	1	1	1	1	1	1	3	3	2	***2***
UM108	1	1	1	2	1	1	4	4	2	***2***
COED1	2	2	1	3	1	1	3	2	2	***2***
ZT114	4	4	4	4	4	4	4	4	4	***4***
ZB114	3	4	4	2	4	4	4	4	4	***4***
ND309	2	1	1	1	1	1	2	1	1	***1***

Table 5-6: Results for crumb tests with dilute sodium hydroxide (0.001N NaOH) as the immersion medium.

Sample #	0.001N NaOH									Overall Class-NaOH
	Air Dried			Oven Dried			Remoulded			
	10 min	2 hrs	16 hrs	10 min	2 hrs	16 hrs	10 min	2 hrs	16 hrs	
13O1	2	1	1	3	2	1	3	2	1	***2***
13O2	1	1	1	1	1	1	1	1	1	***1***
13O3	2	1	1	3	3	1	4	3	2	***2***
N2S1	1	1	1	2	1	1	3	4	3	***1***
N2S2	2	1	1	1	1	1	3	3	2	***1***
SENJ1	4	4	4	2	3	3	4	4	4	***4***
KNP1	2	1	1	2	1	1	2	1	1	***1***
UM108	1	1	1	2	2	1	4	4	3	***2***
COED1	3	2	1	2	2	1	3	2	2	***2***
ZT114	3	4	4	1	3	3	4	4	4	***4***
ZB114	2	4	4	3	3	3	4	4	4	***4***
ND309	1	1	1	1	1	1	2	1	1	***1***

5.6 Chemical analysis

The chemical analyses were carried out by three different laboratories. The results are summarized in Tables 5-7 and 5-8. Table 5-7 shows the chemical properties based on the exchangeable cations in the soil samples and the properties based on the cations in the saturation extract are presented in Table 5-8.

Table 5-7: Chemical properties based on exchangeable cations obtained from 3 laboratories.

LAB 1

Sample #	pH	Clay %	CEC (meq/100g soil)	CEC* (meq/100g clay)	Exch. Na^+ (meq/100g clay)	ESP 1 (meq/100g soil)	ESP 2 (meq/100g clay)
13O1	5.37	15	4.39	29.27	0.16	3.67	0.55
13O2	5.40	59	9.98	16.91	0.09	0.87	0.51
13O3	6.21	26	2.75	10.56	0.11	3.90	1.01
N2S1	8.06	66	16.12	24.61	0.67	4.16	2.72
N2S2	8.67	56	16.23	28.99	3.22	19.86	11.12
SENJ1	8.96	30	11.71	39.71	2.62	22.33	6.59
KNP1	8.24	23	14.94	66.38	25.71	172.14	38.73
UM108	4.88	25	7.81	31.88	0.43	5.48	1.34
COED1	6.12	28	13.05	47.45	1.19	9.09	2.50
ZT114	9.44	32	14.80	46.24	8.54	57.72	18.47
ZB114	9.65	48	15.96	33.24	10.56	66.20	31.78
ND309	6.51	24	15.78	65.73	0.11	0.67	0.16

LAB 2

Sample #	pH	Clay %	CEC (meq/100g soil)	CEC* (meq/100g clay)	Exch. Na^+ (meq/100g clay)	ESP 1 (meq/100g soil)	ESP 2 (meq/100g clay)
13O1	4.94	15	6.21	41.40	0.20	3.22	0.48
13O2	5.13	59	5.45	9.24	0.20	3.67	2.17
13O3	5.83	26	4.02	15.46	0.16	3.98	1.03
N2S1	6.99	66	12.94	19.76	0.84	6.49	4.25
N2S2	7.92	56	13.40	23.93	0.91	6.79	3.80
SENJ1	8.08	30	11.05	37.46	0.91	8.24	2.43
KNP1	8.02	23	13.10	58.22	0.90	6.87	1.55
UM108	4.16	25	6.07	24.78	0.29	4.78	1.17
COED1	5.50	28	14.66	53.31	0.90	6.14	1.69
ZT114	9.05	32	11.47	35.84	0.92	8.02	2.57
ZB114	9.42	48	13.48	28.08	0.91	6.75	3.24
ND309	6.07	24	18.50	77.08	0.21	1.14	0.27

LAB 3

Sample #	pH	Clay %	CEC (meq/100g soil)	CEC* (meq/100g clay)	Exch. Na^+ (meq/100g clay)	ESP 1 (meq/100g soil)	ESP 2 (meq/100g clay)
13O1	4.99	15	3.20	21.33	0.23	7.19	1.08
13O2	5.17	59	2.20	3.73	0.15	6.82	4.02
13O3	5.97	26	5.70	21.92	0.29	5.09	1.32
N2S1	7.44	66	15.10	23.05	1.01	6.69	4.38
N2S2	8.58	56	22.40	40.00	5.48	24.46	13.70
SENJ1	8.53	30	12.60	42.71	3.87	30.71	9.06
KNP1	8.47	23	18.10	80.44	22.70	125.41	28.22
UM108	4.65	25	2.40	9.80	0.32	13.33	3.27
COED1	6.16	28	14.60	53.09	1.77	12.12	3.33
ZT114	9.21	32	8.50	26.56	11.57	136.12	43.56
ZB114	9.45	48	15.90	33.13	14.70	92.45	44.38
ND309	6.47	24	15.90	66.25	0.28	1.76	0.42

Table 5-8: Chemical properties based on cations in the saturation extract obtained from 3 laboratories.

LAB 1				
Sample #	**Na^+ (meg/ℓ)**	**TDS (meg/ℓ)**	**% Na**	**SAR**
13O1	0.95	1.5	62.7	2.0
13O2	0.28	0.5	58.9	1.1
13O3	0.45	0.6	75.7	2.0
N2S1	3.10	4.6	66.9	3.6
N2S2	24.09	27.5	87.5	18.5
SENJ1	6.16	6.5	94.4	16.2
KNP1	266.33	308.0	86.5	58.9
UM108	5.86	9.3	63.3	4.6
COED1	9.90	13.7	72.0	7.2
ZT114	50.72	51.4	98.6	91.1
ZB114	74.38	74.9	99.2	147.3
ND309	0.37	1.9	19.3	0.4
LAB 2				
Sample #	**Na^+ (meg/ℓ)**	**TDS (meg/ℓ)**	**% Na**	**SAR**
13O1	1.60	2.3	69.6	3.2
13O2	1.30	1.6	81.3	4.1
13O3	1.30	1.6	81.3	4.1
N2S1	7.20	8.7	82.8	8.9
N2S2	9.00	12.7	70.9	7.0
SENJ1	9.10	10.0	91.0	18.2
KNP1	9.10	13.5	67.4	7.0
UM108	4.00	7.7	51.9	3.1
COED1	8.60	9.9	86.9	12.2
ZT114	9.20	10.2	90.2	16.8
ZB114	9.10	10.6	85.8	13.6
ND309	2.90	5.8	50.0	2.5
LAB 3				
Sample #	**Na^+ (meg/ℓ)**	**TDS (meg/ℓ)**	**% Na**	**SAR**
13O1	0.74	1.2	59.7	1.5
13O2	0.31	0.6	48.4	0.8
13O3	0.64	0.8	78.0	2.1
N2S1	3.01	4.3	69.8	3.7
N2S2	23.60	26.4	89.6	20.1
SENJ1	7.51	9.0	83.3	8.6
KNP1	264.30	286.2	92.3	79.8
UM108	3.14	6.4	49.4	2.5
COED1	9.90	13.7	72.0	7.2
ZT114	182.90	191.9	95.3	86.3
ZB114	62.10	63.5	97.8	74.8
ND309	6.54	8.2	79.5	7.1

5.7 **Summary**

This chapter presents a comprehensive array of test data that has been collected through testing of the 12 samples. The implications and interpretations of the results are discussed in the following chapter.

6 Discussion

6.1 Introduction

Based on the literature study, laboratory investigations and test results, the following discussion related to each test method is presented. In order to relate the individual tests to the dispersivity, each sample has been designated a classification (expected dispersivity) based on observations made in the field and past experience and testing in some cases. The expected dispersivity of the samples as adapted from Table 3-1 is presented in Table 6-1. This is only a preliminary classification carried out in order to get a feel for the interpretation of the test results obtained during the laboratory investigation. This classification in no way biased the actual interpretation or analysis of the test methods.

Table 6-1: Dispersive classification designated to each sample based on past experience and field behaviour.

Expected Dispersivity	Sample											
	13O1	13O2	13O3	N2S1	N2S2	SENJ1	KNP1	UM108	COED1	ZT114	ZB114	ND309
Highly dispersive			x		x	x				x	x	
Dispersive	x	x		x			x					
Moderately dispersive								x	x			
Non-dispersive												x

6.2 Pinhole test

Results obtained from the pinhole tests prove the test to be unreliable when identifying dispersive soils. The test is based on a sound principle; however it appears to be more adequate at identifying erodible soils through the inspection of the pinhole and is only useful for dispersiveness in terms of the effluent analysis, mostly being done incorrectly at present. Observations during testing found that the test itself can be unduly time consuming. Sherard et al (1976a) states that the principal differentiation between dispersive and non-dispersive soils is given by the test results under 50 mm of head, giving the impression that there is no need to run the test through to 1020 mm head of flow. If a soil does not proved to be dispersive under 50 mm head of flow, then one can increase the head to 180 mm to verify that assumption. Increasing the head any further will result in the classification of erodible soils, which is not the primary objective of the test.

Walker (1997) states that soils which test highly dispersive (D1) and moderately dispersive (D2) in the pinhole test will be problematic and will erode by dispersive piping. Those soils classified as intermediate (ND4) will erode slowly and intermediate soils (ND3) will erode very slowly under high heads. The question one must ask now is: how does one differentiate between slowly and very slowly? Walker (1997) also states that soils classified as non-dispersive (ND2 and ND1) in the pinhole test will not erode through dispersive piping. It should be noted that an erodible soil, which has no dispersive properties, will still erode in the pinhole test and particles will fall into the cylinder. The particles will settle after some time but as the experiment classifies the soil during the test, it is likely that the erodible soil will be incorrectly classified as dispersive to some extent.

Observations made while carrying out the pinhole test found that the test is essentially an empirical test based on subjective evaluation. The results presented in Table 5-3 show that the use of the pinhole test to evaluate the dispersiveness of a soil is ambiguous and obscure. Based on the classification provided by Sherard et al (1976a), four of the samples tested could not be categorized into a dispersive class (N2S1, N2S2, KNP1 and COED1). According to the test method developed by Sherard et al (1976a), if the rate of flow at the end of 10 minutes under 50 mm of head does not exceed 0.8 mℓ/s and the hole diameter does not exceed 1.5 needle diameters, then the soil is classified as intermediate (ND4). If the flow rate at the end of 10 minutes exceeds 1.0 mℓ/s and the pinhole diameter exceeds 2 needle diameters, classify the soil as dispersive (D1). Results from this study (Table 5-3) found 4 samples which could not be classified based on the combination of flow rate and pinhole size after the test. Samples N2S1, N2S2 and COED1 all had final flow rates below 0.8 mℓ/s but the pinhole sizes all exceeded 1.5 needle diameters. Sample KNP1 could not be classified either because the results did not fall within any of the proposed categories.

Data was not obtained for two samples (13O1 and UM108) because the test could not be completed. Sample UM108 proved to be excessively moist during the preparation stage. Three different samples were prepared on different days but all gave the same result. The sample was compacted into the cylinder; however, it continuously collapsed into the cylinder making it impossible to punch a pinhole through the specimen. Another difficulty faced was that the nipple persistently collapsed into the specimen because the sample was excessively soft and moist. Figure 6-1 illustrates the difficulty faced when attempting to compact the sample into the cylinder and Figure 6-2 demonstrates the collapse of the nipple into the specimen. The sample specimen appeared too wet, even though it was at the specified moisture content.

Figure 6-1: Photograph illustrating the collapse of sample UM108 into the cylinder.

Figure 6-2: Photograph demonstrating the collapse of the nipple into the specimen.

The inability to complete the test for sample 13O1 was due to the fact that the sample was impermeable. Firstly, during the compaction process, the sample appeared to be dry (even though it was at the correct moisture content). After compaction, the specimen was excessively hard and punching of the pinhole was difficult. Once the test began, no flow was observed so the apparatus was dismantled and the cylinder opened to re-punch the pinhole. It was assumed that the hole was blocked. Once opened, it was found that the distilled water did not flow/soak through the sample. The punched pinhole was in perfect condition but water would not flow. Figure 6-3 shows accumulation of water in the pea gravel on top of the compacted specimen. Once the pea gravel was removed, the top of the specimen showed signs of erosion on the surface (Figure 6-4). The bottom end of the specimen was completely dry.

Figure 6-3: Photograph showing the accumulation of water in the pea gravel on top of the compacted specimen.

Figure 6-4: Photograph showing erosion of sample at the top end of the compacted specimen.

Five samples were tested at a different density to that required in the current method. The samples were compacted at 95% of modified AASHTO MDD. This was carried out to determine if the density has any influence on the results for the identification of dispersive soils. The results, also presented in Table 5-3, found that the classification is not strongly influenced by the density of the compacted test specimen. Results were similar, yet still somewhat ambiguous.

6.3 Double hydrometer test

Since the introduction of the Technical Methods for Highways (TMH1), the majority of soil testing for roads and construction in South Africa has been carried out using this standard. Hydrometer tests have been carried out using the method A6 as stated in TMH1. Investigations into the use of the method (by means of interviews) has shown that some laboratories use the hydrometer test method A6 (TMH1) as the standard test and modify the same method for the parallel test for use in the double hydrometer test.

A thorough investigation into the test method (TMH1 Method A6) has found many inconsistencies, which can have a significant effect on the results for dispersive soil identification. The hydrometer reading taken at the one hour time interval was taken to be the percentage of the clay fraction (0.005 mm) as specified in TMH1. This, however, was found to be incorrect. Using the equations based on Stoke's Law, the time for recording of the 0.005 mm fraction can be calculated to be within the 2 hour range and the time for the 0.002 mm fraction would be between the 5 hour and 20 hour range using the modified test method. Table 6-2 illustrates the results obtained from two different samples, with emphasis on the one hour time interval and the corresponding particle diameter. Results clearly show that the hydrometer reading obtained at the one hour interval gives particle sizes in the 0.006 mm range, which, by definition is classified as silt-sized particles and probably does not consist of individual clay minerals (perhaps agglomerations or quartz particles).

Table 6-2: Calculated diameters of particles in suspension at different time intervals using Stoke's Law- with emphasis on the 1 hour readings.

Sample ND309 with dispersant							
Elapsed time *t* (min)	Temperature *T* (°C)	Reading *Rh'*	*Rh'* + *Cm* = *Rh*	Effective depth *Hr* (mm)	Particle Diameter *D* (mm)	*Rh'* - *Ro'* = *Rd*	Percentage finer than *D* *K* (%)
0.53	20	26	27	126.65	0.0636	20.5	63.78
1.03	20	24	25	129.94	0.0463	18.5	57.56
2.02	20	21.5	22.5	134.05	0.0336	16.0	49.78
3.00	20	20.5	21.5	135.69	0.0278	15.0	46.67
5.10	20	19.5	20.5	137.34	0.0214	14.0	43.56
10.00	20	18	19	139.80	0.0154	12.5	38.89
57.00	20	16.5	17.5	142.27	0.0065	11.0	34.22
127.00	20	15	16	144.74	0.0044	9.5	29.56
295.00	20	14	15	146.38	0.0029	8.5	26.44
1263.00	20	12.5	13.5	148.85	0.0014	7.0	21.78
Sample COED1 with dispersant							
Elapsed time *t* (min)	Temperature *T* (°C)	Reading *Rh'*	*Rh'* + *Cm* = *Rh*	Effective depth *Hr* (mm)	Particle Diameter *D* (mm)	*Rh'* - *Ro'* = *Rd*	Percentage finer than *D* *K* (%)
0.68	20	36.0	37.0	110.21	0.0551	30.5	98.42
1.20	20	34.0	35.0	113.50	0.0422	28.5	91.97
2.00	20	32.0	33.0	116.79	0.0331	26.5	85.52
3.00	20	30.5	31.5	119.25	0.0273	25.0	80.67
5.07	20	29.0	30.0	121.72	0.0213	23.5	75.83
10.00	20	27.0	28.0	125.01	0.0153	21.5	69.38
60.00	20	21.5	22.5	134.05	0.0065	16.0	51.63
120.00	20	19.0	20.0	138.16	0.0047	13.5	43.56
240.00	20	17.0	18.0	141.45	0.0033	11.5	37.11
1200.00	20	12.5	13.5	148.85	0.0015	7.0	22.59

The results obtained from the modified test were compared with TMH1 Method A6 results from preliminary tests. According to TMH1, the 1 hour hydrometer reading gives the 0.005 mm fraction. The 18 second reading gives the percentage passing 0.075 mm and the 40 second reading is the silt-sized fraction (0.050 mm). These values were plotted along with the values obtained for the modified test, in which the particle diameters were calculated using equations based on Stoke's Law and more hydrometer readings were taken at more frequent time intervals. Figure 6-5 illustrates the variation in particle size distribution (PSD) curves for two samples. There is a significant variation in the PSD curves with the 0.005 mm fraction ranging from approximately 10 % to 32 % for ND309 and 22 % to 45 % for COED1. It is thus clear that the TMH1 method does not produce the correct results.

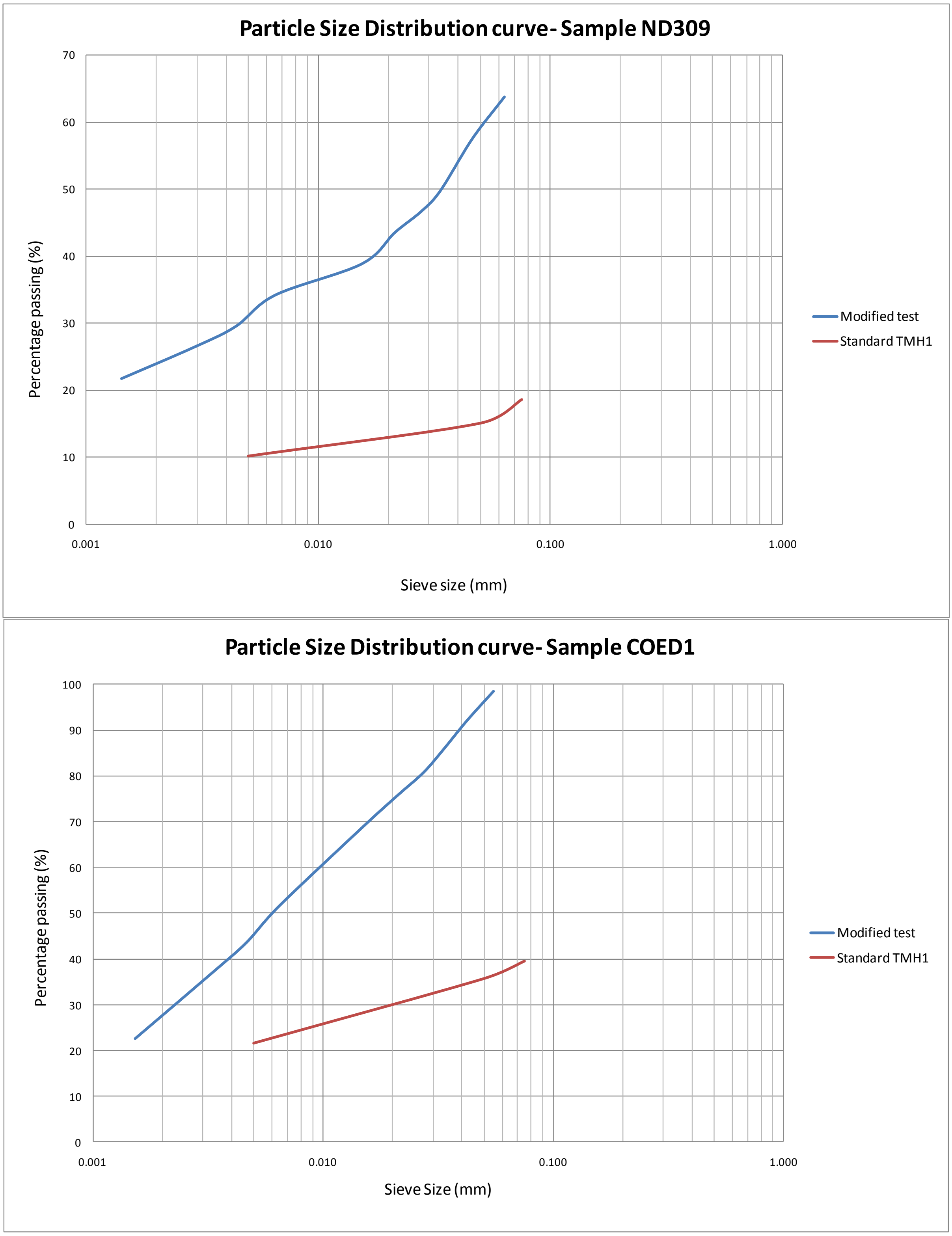


Figure 6-5: Comparison between the modified and TMH1 particle size distribution curves for two samples (ND309 and COED1).

The second discrepancy noted (as described in section 4.1.2) is the variation in the definition of the clay fraction. TMH1 and ASTM use 0.005 mm as the boundary for the clay fraction, whereas BSI uses 0.002 mm. Many authors quote the 0.005 mm fraction as the clay fraction when determining dispersivity of a soil. By definition, clay mineral particles are colloids with a maximum diameter of 0.002 mm (Reeves et al, 2006) and cation exchange activities will predominantly occur on this fraction. Therefore, the 0.002 mm fraction should be ideally used in dispersive soil identification analyses.

Figure 6-6 shows dispersion ratios for the 0.005 mm and the 0.002 mm fraction using the TMH1 and modified test methods respectively (Y-axis), compared with that of the dispersion ratio for the 0.005 mm fraction using the modified test method (X-axis).

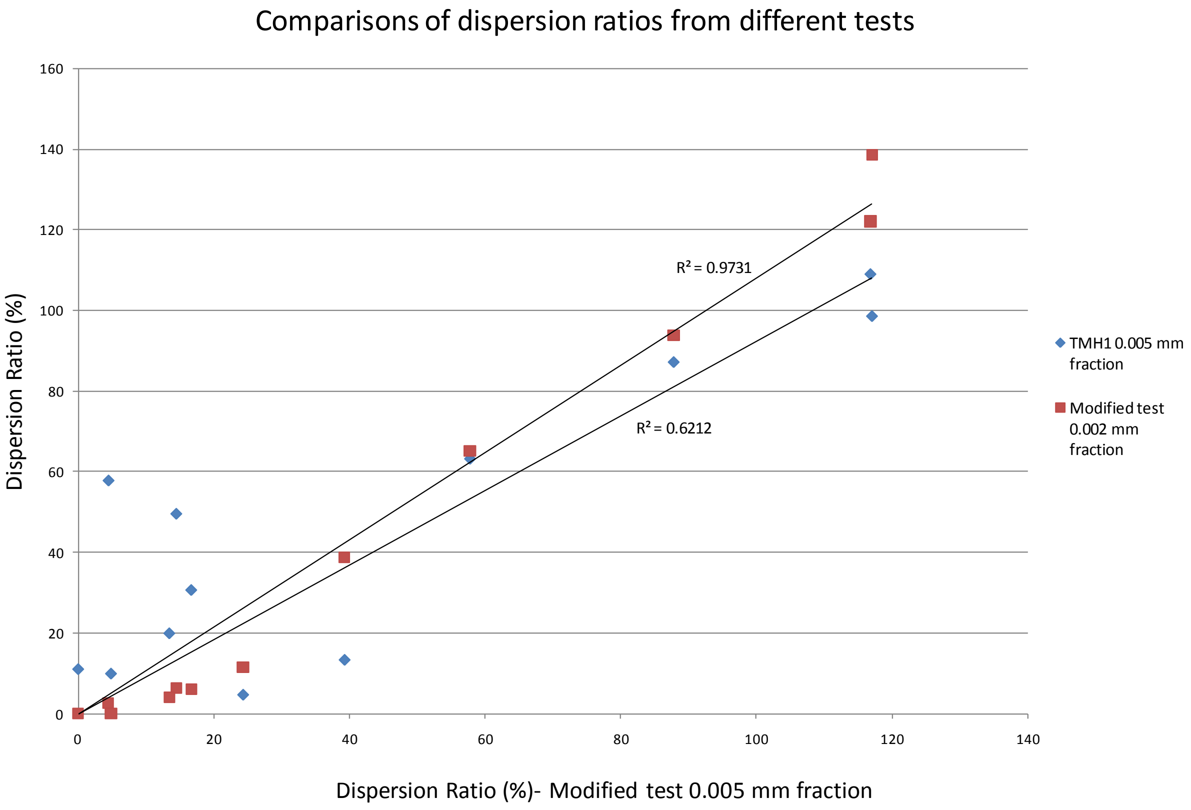


Figure 6-6: Comparison of dispersion ratios obtained using the modified test method and TMH1 method.

Regression coefficients obtained for both plots show that there is a better correlation between the dispersion ratio of 0.002 mm and 0.005 mm fraction for the modified test method compared with that of the dispersion ratio for the 0.005 mm fraction using the TMH1 method. The biggest discrepancies occur with dispersion ratios smaller than 60 % (20 – 60 %), which is mostly in the critical zone used for classification.

Based on the above mentioned shortcomings identified with the TMH1 Method A6 test standard, it is concluded that, while the TMH1 standard is probably suitable for gravel or aggregate testing with low active clay content, it should not be used for dispersive soil identification as it requires greater care and understanding. With regards to the ASTM standards, it is recommended that the definition of the clay-sized fraction be re-analysed and a standard definition used, which should correspond to other available standards.

With reference to the categories of dispersive classification based on results obtained from the double hydrometer test, the classifications from the literature study were found to be highly inconsistent. According to the State of the Art on Dispersive soils by Elges (1985), a soil would be classified as dispersive if the dispersion ratio is greater than 35 %. Other authors, however, describe a more specific classification whereby the soil can be classed as non-dispersive, slightly dispersive, moderately dispersive or highly dispersive based on the dispersion ratio (Bell and Maud, 1994; Bell and Walker, 2000; Knodel, 1991; Walker, 1997). Table 6-3 shows the different ranges of dispersion ratio for classification found in previous literature.

Table 6-3: Variation in dispersion ratio ranges found in previous literature.

Author/s	Dispersion ratio ranges for classification				
	Highly dispersive	Dispersive	Intermediate/ Moderately dispersive	Slightly dispersive	Non dispersive
Elges (1985)		> 30 %			< 30 %
Knodel (1991)		> 50 %	30 % to 50 %		< 30 %
Bell and Maud (1994)	> 50 %		30 % to 50 %	30 % to 15 %	< 15 %
Walker (1997) - MSc Thesis		> 30 %	30 % to 15 %		< 15 %
Bell and Walker (2000)	> 50 %		30 % to 50 %	30 % to 15 %	< 15 %

The results obtained for the 12 samples using the modified test method are graphically presented in Figure 6-7. The figure shows the expected dispersivity as described in the field versus the dispersion ratio from the hydrometer test related to two classification systems based on work by Elges (1985) and Bell and Walker (2000). The plot proves that the expected dispersivity as observed in the field does not necessarily relate to the classification based on the dispersion ratio. Erosion patterns and piping observed in the field are not primary indicators of dispersivity.

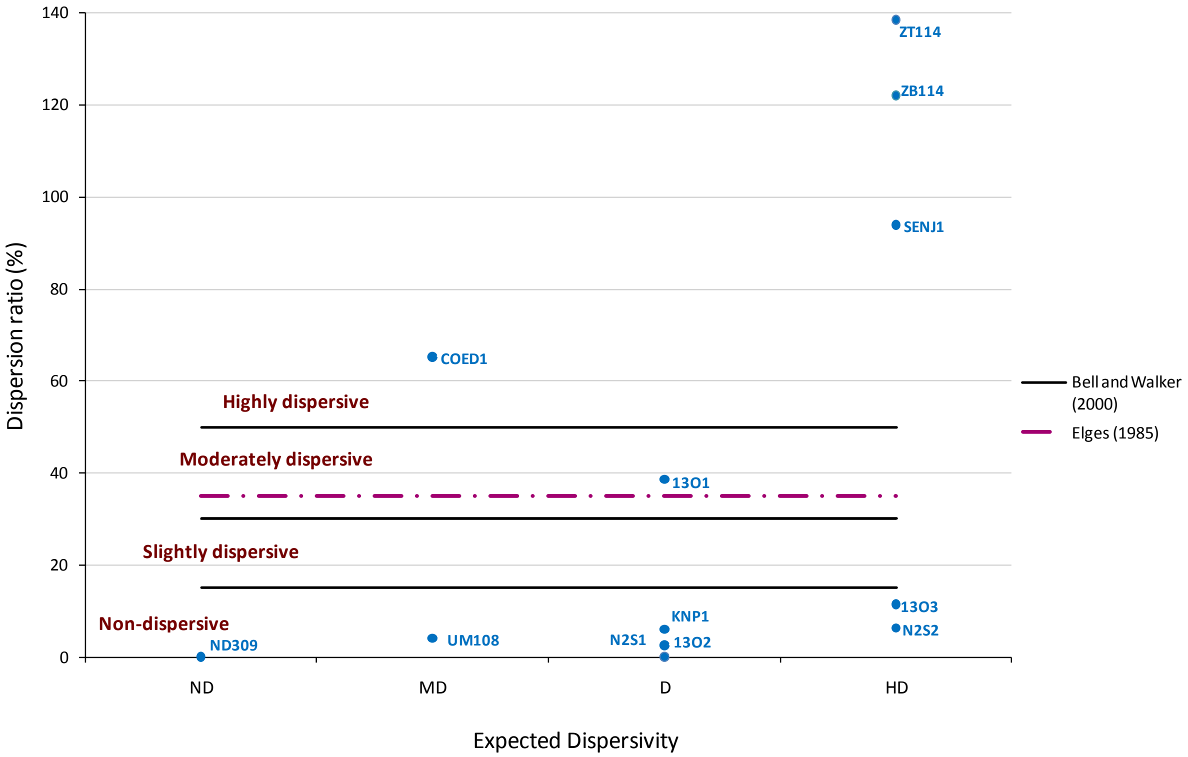


Figure 6-7: Plot of dispersion ratio versus expected dispersivity related to two classification systems.

Three of the samples showed dispersion ratios greater than 100 %, which indicated that the natural dispersion was greater than the mechanical/chemical dispersion. It is not understandable as to why this had occurred, however it was noted that the dispersion greater than 100 % were only present in the highly dispersive samples. It is probable that the dispersing agent caused some kind of flocculation in the highly dispersive soils. The high dispersion ratios could also be owing to some interaction between the dispersant and the clay particles with high sodium content. Another explanation could be that Na- hexametaphosphate is not as effective and does not simulate the natural dispersion in highly dispersive soils. This is a possible area for additional research in chemistry. Since, the high dispersion ratios occur in the highly dispersive soils only, and it does not affect the identification, it is not a major concern.

With regards to the classification systems, based on the limited testing of the 12 samples carried out, it is suggested that the classification proposed by Elges (1985) be used as a standard. However, it is also suggested that a larger number of samples be tested using the proposed test methods to confirm that this is, in fact, the most suitable/ appropriate classification system. It is also considered only necessary to determine if a soil is dispersive or not and not the degree of dispersiveness and is discussed in detail later (Section 6.6). This is probably the area where inconsistencies and misleading results occur. This may now be overcome with the adoption of the new proposed SANS 3001-GR3 hydrometer test method. During the hydrometer testing for this project, various aspects related to the new test method were discussed with the developer of the new SANS method and some important aspects identified during this research have now been incorporated into the new method.

6.4 **Crumb test**

Crumb test results found there to be no significant differences in results with either distilled water or 0.001N NaOH when the soil is dispersive. However, if the soil is not dispersive, different results were obtained based on the type of immersion medium. The use of 0.001N NaOH gives a good indication of dispersive soils if the soil is in fact dispersive. However, the risk of falsely classifying non-dispersive soils as dispersive is greatly increased as well. Observations during testing found the presence of staining in the solution after 2 hours. Since the test is essentially a visual indication of dispersiveness, it can be highly subjective. It is possible that a non-dispersive soil could be classified as being dispersive due to the staining in the solution and not resulting from fines in suspension. Sodium hydroxide solutions are known to stain (discolour) in the presence of organic matter (SANS 5832, 2006)

With regards to the condition of the crumb, the oven dried crumbs gave the worst indication of dispersivity. This is likely due to the fact that high temperatures can change the nature of certain clays in the soil, thereby hindering their dispersive properties.

Based on results obtained and observations made during the study, it recommended that in order to acquire repeatable and consistent results, the crumb test should be carried out as follows:

- Condition of crumb: Remoulded (air dried or *in situ* moisture content)
- Immersion Medium: Distilled water
- Observation conditions: Described using current categories but readings taken after 1 and 2 hours.

6.5 **Chemical analyses**

For evaluating the results of the chemical analyses, a basis for comparison is required from the three laboratories. Results show the chemical properties obtained from the 3 laboratories to be significantly inconsistent (Table 5-7 and Table 5-8). The laboratories were interviewed, and it was found that only one of the laboratories used a standard protocol for the testing programme (Lab 1). Labs 2 and 3 carried out the chemical tests without any standard test method. The methods were carried out based on past experience or ‘experienced’ technicians who did not need protocols and instead carried out the tests from memory. The results from Labs 2 and 3 were thus plotted against the results from Lab 1 to determine any correlation/relationship. Figure 6-8 and Figure 6-9 illustrate the relationship between the laboratories based on SAR and ESP testing respectively. The regression analyses of SAR for Lab 2 and Lab 3 versus Lab 1 show R^2 values of 0.03 and 0.97 respectively. This implies that there is a better correlation between the SAR values from Lab 3 and Lab 1. The results from Lab 2 are significantly variable and don’t show any similarity to the other laboratories. The same pattern is evident in Figure 6-9 with the R^2 value for Lab 3 being 0.96 and 0.0009 for Lab 2. It should be noted that Lab 1 and 3 are agricultural laboratories and therefore generally carry out testing of the more sensitive nature. Lab 2 is a civil engineering laboratory, where dispersive soil identification testing is not a regular occurrence, therefore making the tests more sporadic.

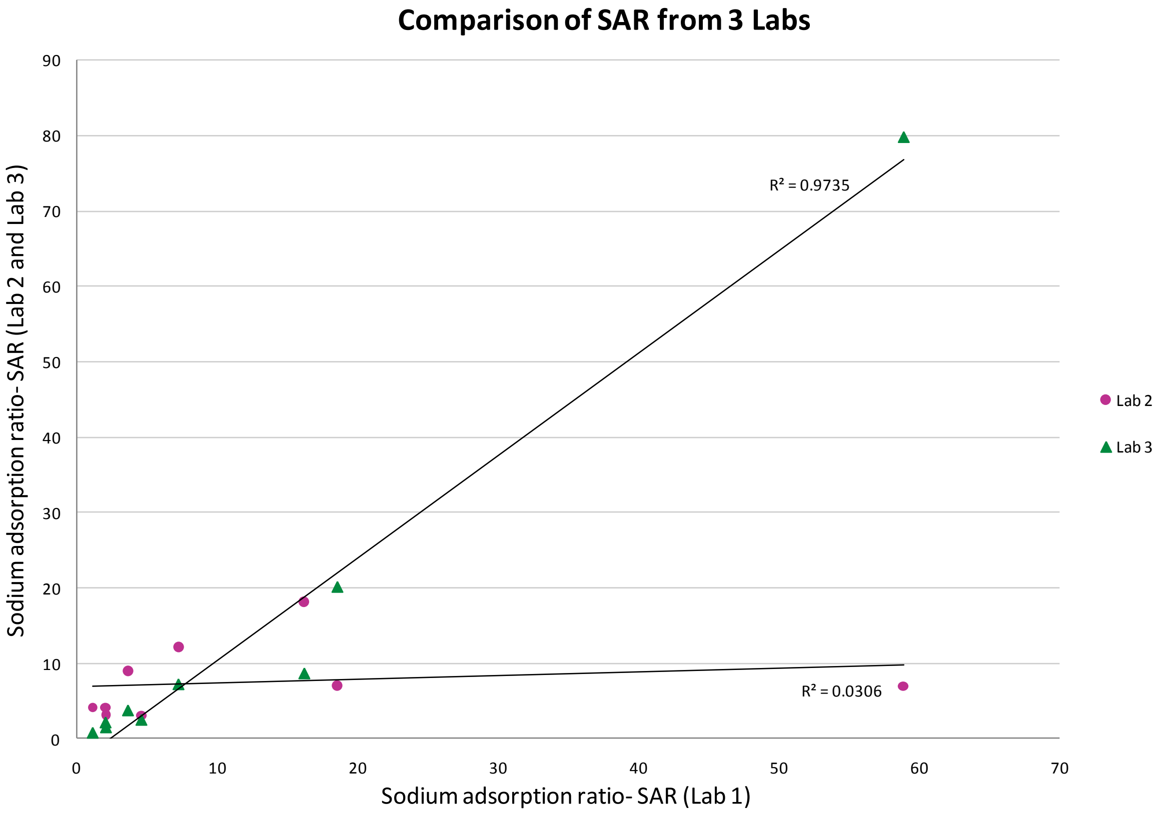


Figure 6-8: Comparison of Sodium Adsorption Ratio from 3 laboratories.

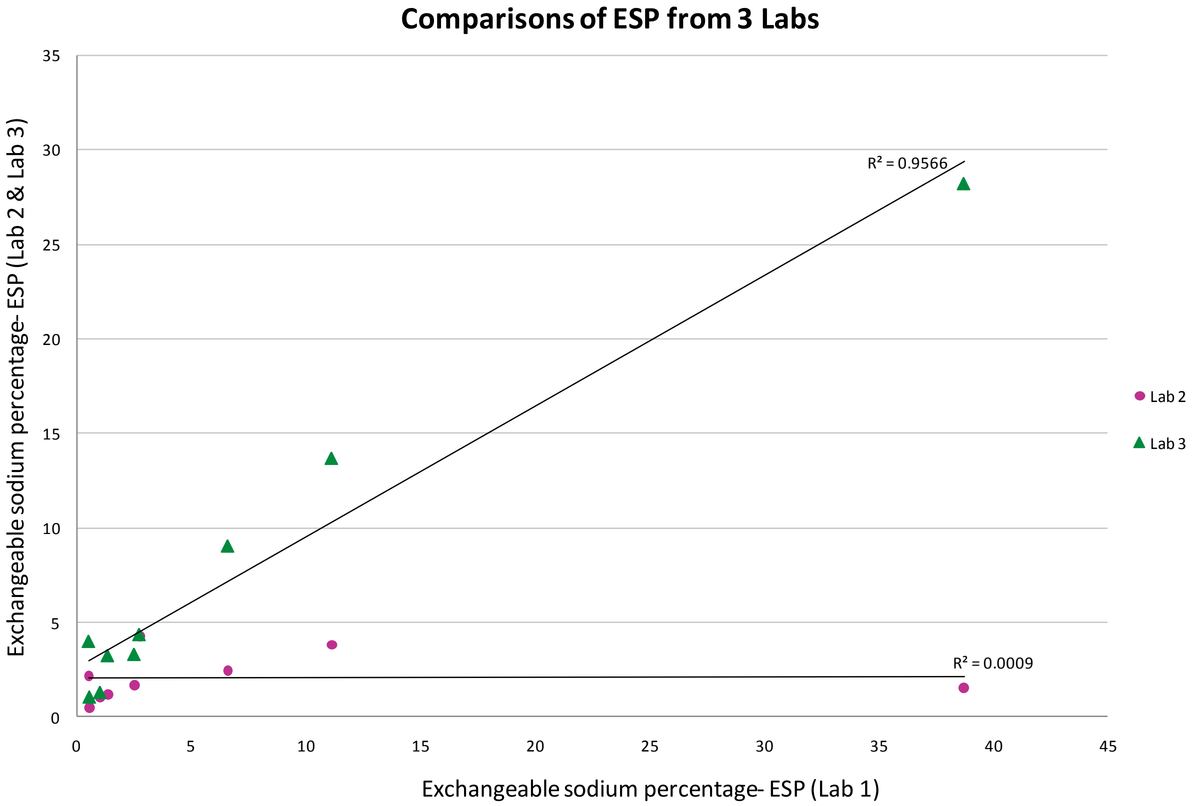


Figure 6-9: Comparisons of Exchangeable Sodium Percentage from 3 laboratories.

Comparison of results obtained from the 3 laboratories show some correlation between Labs 1 and 3, and no correlation between Labs 1 and 2. This is likely due to the difference in methods used for testing or interpretation of the results obtained from testing. Generally, if a client receives data/ test results from a commercial laboratory, those results will not be queried or verified and since the laboratories do not follow one standard national protocol, the results will definitely vary. The results for the 12 samples used for this study, show that some samples are classified as both non-dispersive and dispersive due to variations in the different laboratory results. This can lead to significant structural problems if a dispersive soil is not categorised and correctly treated before use. Results from the chemical analyses of soils are also used in the various ratings systems available for classification. If the results are incorrectly interpreted or calculated (incorrect measurement units, equations, etc), the final classification in the rating system, will be affected. Once again this will lead to inaccurate classifications.

6.6 Rating systems

The results from the testing of the 12 samples were used to determine the dispersivity of the samples based on the various rating systems available. Figure 6-10 and Figure 6-11 show the samples plotted in the Gerber and Harmse (1987) ESP vs. CEC chart. In Figure 6-10, the CEC for the samples was calculated as meq/ 100g clay, where the results obtained from the laboratories were converted to the clay equivalent. The CEC values used in Figure 6-11 are those results obtained from the laboratories and no changes were made to them.

Figure 6-10 shows that the results for Lab 2 all plot in the same area with very little variation. All 12 samples tested by Lab 2 lie in the non-dispersive section, which is completely incorrect. Results from Lab 1 and 3 look more promising with a good scatter. It should also be noted that the known dispersive samples plot in the correct area for Lab 1 and 3 results. However, some values plot outside the diagram, which poses a significant problem, which can lead to the incorrect classification of the soil. Those results which plot outside the area of the graph have very high ESP’s and CEC in the range of 30 – 40 meq/100 g clay and would require extrapolation of the zones of high ESP to be classified..

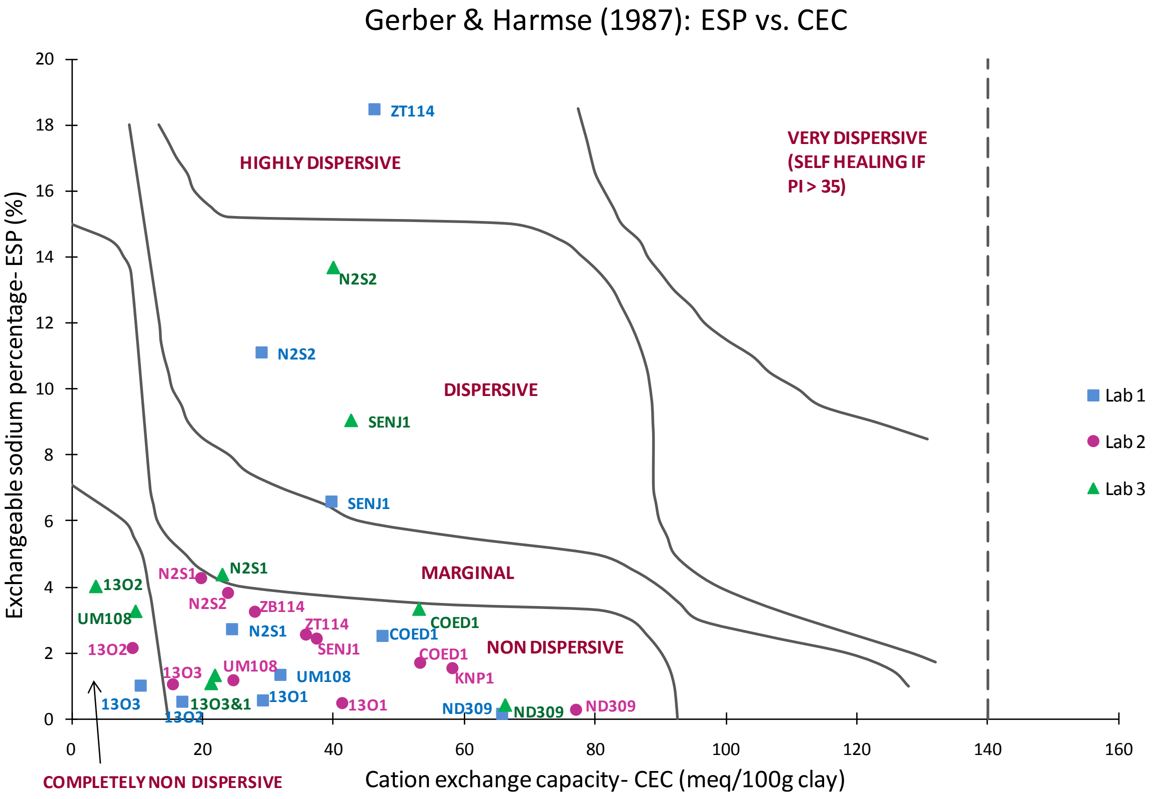


Figure 6-10: Results of chemical analysis from 3 laboratories plotted as ESP (%) vs. CEC (meq/100g clay).

Figure 6-11 shows all results from the 3 laboratories plotted in a small area of the graph. There is no scatter or pattern showing the correct classification of the samples. The known dispersive samples lie in the non-dispersive section.

It should be noted that Gerber and Harmse (1987), created the ESP versus CEC chart from test results of 67 samples based on four tests, one of them being the double hydrometer test. However, according to the paper by Gerber and Harmse (1987), the double hydrometer results obtained for their samples was only categorised into 'dispersive' and 'non-dispersive' soils. This poses the question: where do the marginal, highly dispersive and completely non-dispersive categories come from? Also 'completely non-dispersive' and 'non-dispersive' should logically be the same class. A non-dispersive soil will not be a problem whether classified as completely non-dispersive or just non-dispersive. Similarly, no different degrees of treatment are specified for different categories of dispersive soils and the in-out classification of Elges (1985) would suffice.

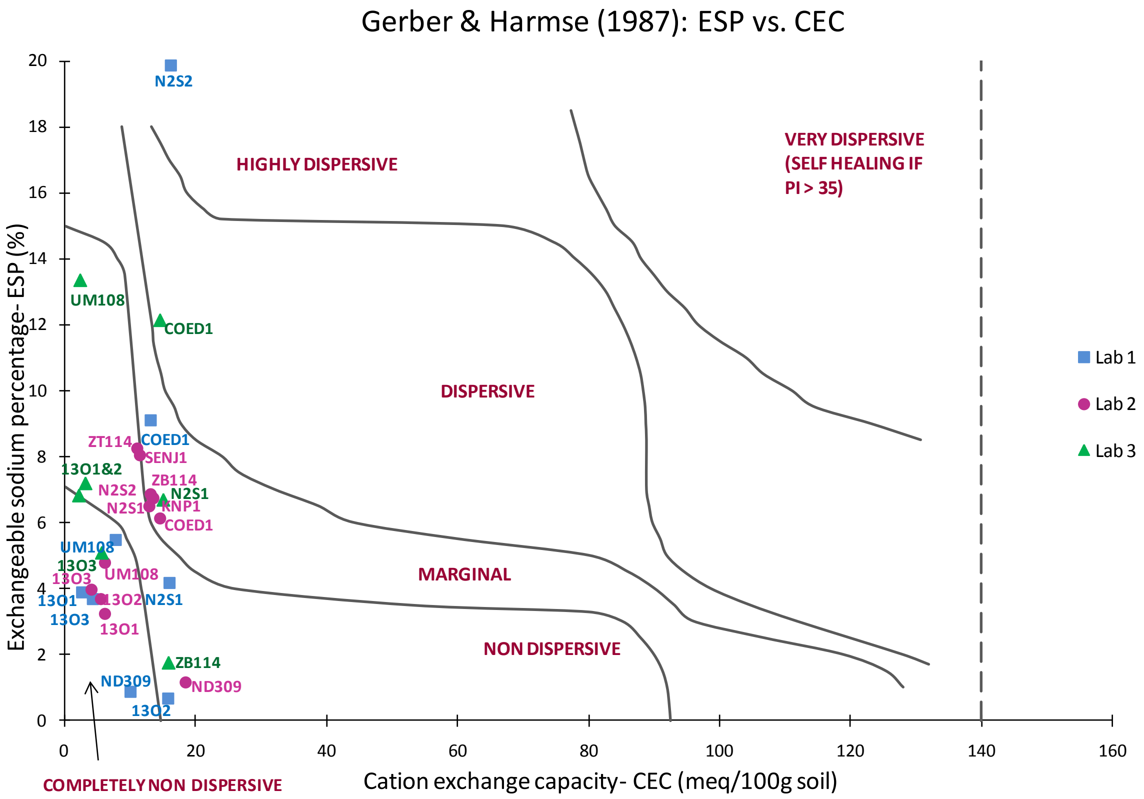


Figure 6-11: Results of chemical analysis from 3 laboratories plotted as ESP (%) vs. CEC (meq/100g soil).

The chemical analysis results obtained from commercial laboratories should always be verified and questioned. Results for CEC are usually given as meq/100 g dry soil and would need to be converted by taking the clay fraction into account. Most clients using the service of the laboratories do not know this, and would generally use the results as presented. Figure 6-11 shows how the misinterpretation of the chemical results can lead to incorrect analysis in the rating systems and hence inaccurate classification of the soil.

Results obtained from the 3 laboratories were also used for analysis in the chart by Sherard et al (1976b). The chart plots the percentage of sodium against the total dissolved salts (TDS) (Figure 6-12). The figure shows that, of the 3 laboratories, only the results from Lab 1 plot the known dispersive and non-dispersive samples in the correct sections. The rest of the results are randomly scattered with no pattern or correct classification.

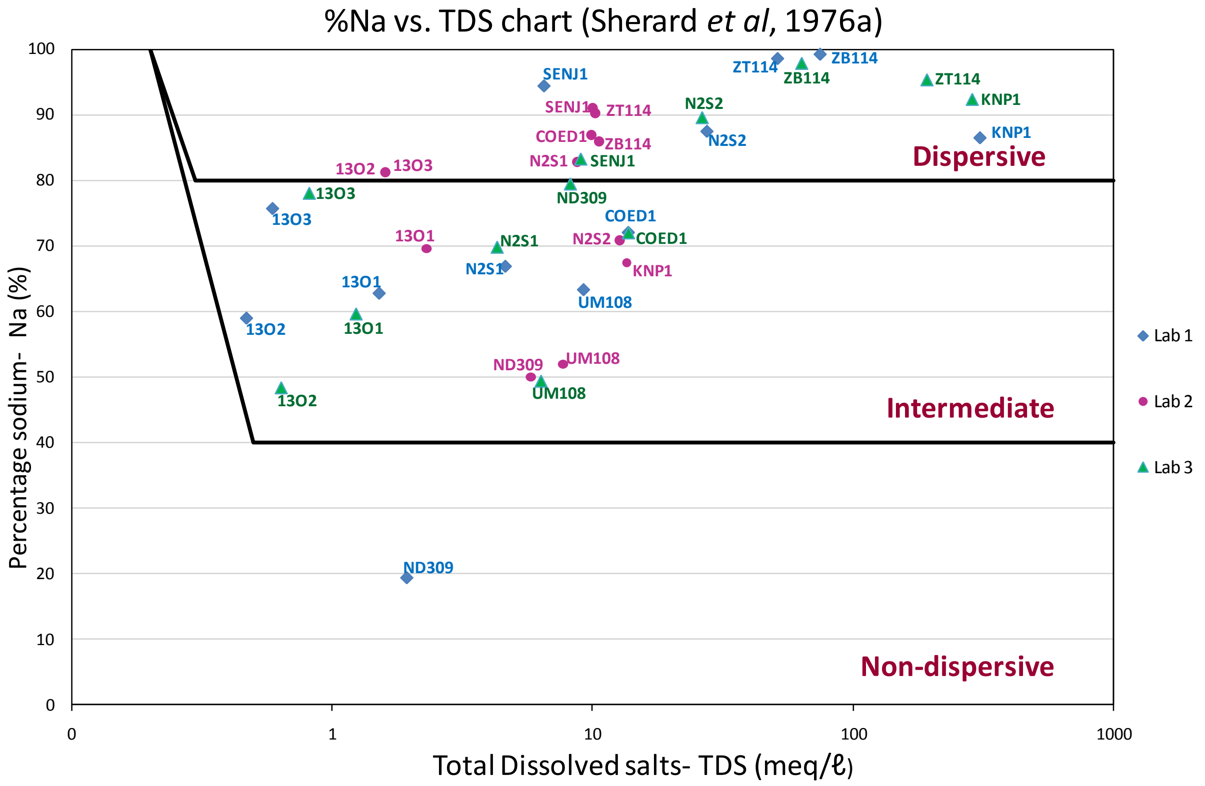


Figure 6-12: Chemical properties from 3 laboratories plotted as % Na vs. TDS (meq/ℓ).

A rating system was developed by Walker (1997) and Bell and Walker (2000) (Table 6-4). The table uses selected values obtained from testing to rate the soil dispersiveness. Factors that are taken into account for the rating system include the pinhole test; Gerber and Harmse' (1987) ESP vs., CEC chart; the crumb test; SAR and Sherard et al' (1976b) TDS vs. %Na chart. Each test/property is given a weighted rating based on the dispersive classification obtained for that particular test. The total rating is the sum of these individual test ratings.

Table 6-4: Rating system for the identification of dispersive soils (Walker, 1997; Bell and Walker, 2000)

Test	Class & weighting	Description of dispersivity			
Pinhole test	Class Rating	Dispersive 5	Moderate 3	Slightly 1	Non-dispersive 0
CEC vs. ESP	Class Rating	Highly 4	Dispersive 3	Marginal 1	Non-dispersive 0
Crumb test	Class Rating	Strong reaction 3	Moderate 2	Slight 1	No reaction 0
SAR	Class Rating	> 2 2	1.5 - 2.0 1		< 1.5 0
TDS vs. %Na	Class Rating	Dispersive 2	Intermediate 1		Non-dispersive 0
Total Dispersivity Rating		**Highly > 12**	**Moderately 8 – 11**	**Slightly 5 - 7**	**Non-dispersive < 4**

The results obtained for the 12 samples tested were assessed using the rating system. Results that were used were those best recommended by the author based on modified test methods and correct interpretation of results. The results for the pinhole test were those obtained using the modified test method (Appendix B). The results for the ESP versus CEC chart were those results converted to meq/ 100g clay using the clay fraction. The crumb test results were those carried out on remoulded soil samples in distilled water (as recommended in Appendix B). SAR was calculated by the laboratory but recalculated by the author to ensure accuracy. All chemical analysis results used in the rating system were those obtained from Lab 1, which appears to be the most consistent of the 3 laboratories. The results used in the rating system and the final classification of the samples are shown in Table 6-5.

Table 6-5: Samples rated according to the rating system by Walker (1997) and Bell and Walker (2000).

Sample #	**Rating Criteria**					**Total Rating**	**Class**
	Pinhole test	**CEC vs. ESP**	**Crumb test**	**SAR**	**TDS vs. %Na**		
13O1	n/a	0	0	1	1	2	ND
13O2	0	0	0	1	1	2	ND
13O3	0	0	0	1	1	2	ND
N2S1	2	0	1	2	1	6	SD
N2S2	2	3	1	2	2	10	MD
SENJ1	4	3	3	2	2	14	HD
KNP1	3	n/a	1	2	2	8	MD
UM108	n/a	0	1	2	1	4	ND
COED1	2	0	1	2	1	6	SD
ZT114	4	4	3	2	2	15	HD
ZB114	4	n/a	3	2	2	11	MD
ND309	0	0	0	0	0	0	ND

Pinhole test results for two samples were inconclusive since the tests were not successful. There are also no results for the CEC versus ESP chart for two samples since the values obtained from the laboratory fell outside the plot area. Assuming a classification for the CEC versus ESP chart would make the final classification unrepeatable although there are good grounds for classifying these materials as dispersive, assuming the trends can be extrapolated linearly. Table 6-5 shows that for the known non-dispersive sample (ND309), the tests and the rating system classify the soil accurately. The problem, it seems, is the identification of the dispersive soils. This is where the testing and the weighted ratings appear to be deficient. The final classification based on Walker's (1997) rating system is graphically presented in a chart where it is compared with the expected dispersivity (Figure 6-13).

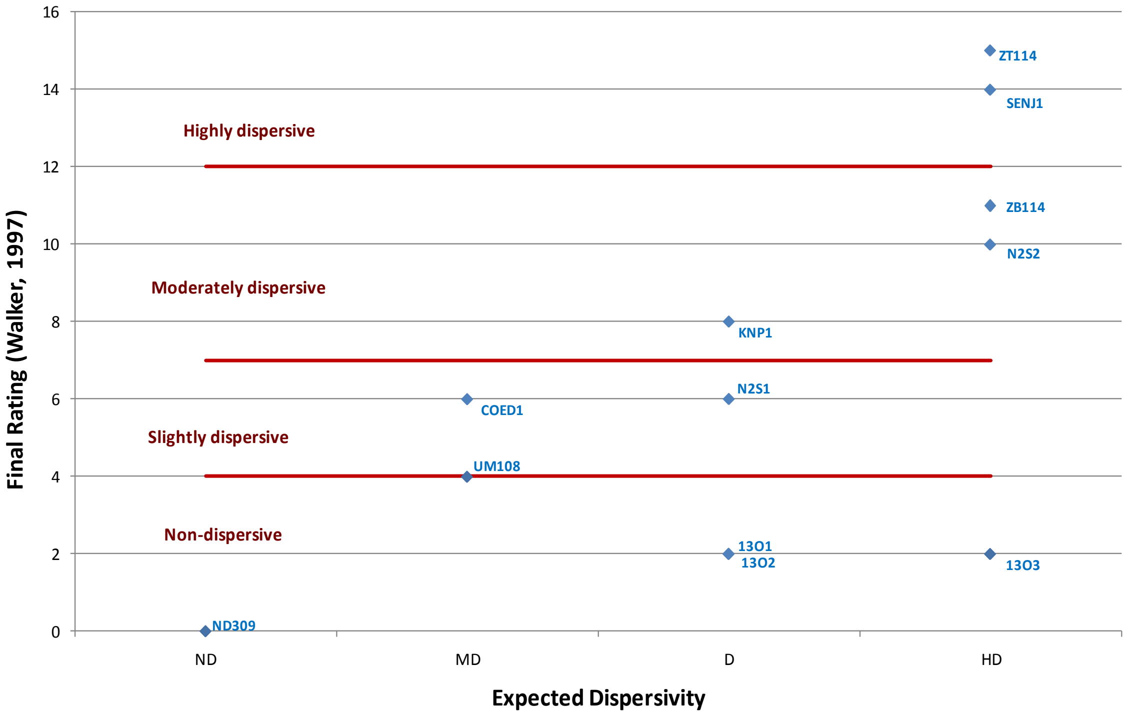


Figure 6-13: Figure showing the final rating versus the expected dispersivity.

The figure confirms some evidence of a trend between the expected dispersivity and the actual classification based on the rating system. However, there are certain outliers. Some samples, which indicated dispersive behaviour in the field by means of erosional features and piping, are classified as non- dispersive in the rating system. These samples include 13O1, 13O2 and 13O3. Samples that were visually categorised as being dispersive are rated as slightly less dispersive based on the tests and rating system. This proves that visual investigations based on erosional behaviour are not a definitive indication of the presence of dispersive soils.

According to Bell and Maud (1994), dispersive soils are typically associated with transported flood plain deposits, slope wash colluvium and lake bed deposits as well as residual soils and are usually found in regions which experience annual rainfall of less than 850 mm. Elges (1985) states that most dispersive soils are located in regions lying between Weinert's climatic N-values of 2 and 10. The climatic N-values for the 12 samples used in this study are shown in Table 6-6. The annual average rainfall is also illustrated based on data obtained from the climatic statistics of the Weather Bureau (1986). The table also lists the expected (estimated) dispersivity and the dispersivity obtained from the rating system (actual).

Table 6-6: Rating based on climatic conditions (i.e. rainfall)

Sample #	Expected dispersivity (Table 3-1)	Actual dispersivity (Table 6-5)	Weinert's N-value (Elges, 1985)	Rainfall (± 850 mm) (Bell & Maud, 1994)
13O1	D	ND	< 2	> 850 mm
13O2	D	ND	< 2	> 850 mm
13O3	HD	ND	< 2	> 850 mm
N2S1	D	SD	2 - 10	< 850 mm
N2S2	HD	MD	2 - 10	< 850 mm
SENJ1	HD	HD	2 - 10	< 850 mm
KNP1	D	MD	2 - 10	< 850 mm
UM108	MD	ND	2 - 10	< 850 mm
COED1	MD	SD	< 2	> 850 mm
ZT114	HD	HD	2 - 10	< 850 mm
ZB114	HD	MD	2 - 10	< 850 mm
ND309	ND	ND	2 - 10	< 850 mm

The climate analysis shows that out of the 12 samples investigated, 8 are located in areas prone to dispersive behaviour, according to Elges (1985) and Bell and Maud (1994). Of the 8 samples located in the 'ideal' climatic conditions, 3 are the known highly dispersive samples. One of the 8 samples is the known non-dispersive sample. Of the 4 samples that are outside the suggested climatic zones, 3 are rated as non-dispersive and 1 slightly dispersive.

Table 6-6 clearly illustrates that climatic N-values and rainfall patterns are thus not reliable indicators of dispersive soil behaviour and should therefore not be the primary investigative method of identification. It does, however, point to the possibility of the problematic sodium ions being leached out of potentially dispersive soils in higher rainfall (N<2) areas.

Investigations into the use of a rating system for the identification of dispersive soils have shown that results can be ambiguous and obscure. The study into the physical test methods used in the rating system has shown, firstly, that the main classification test (pinhole test) is very unreliable. The pinhole test counts for approximately 50 % of the total rating in the rating system and deficiencies in the test method can lead to inaccurate classifications. The second problem noted is the use of SAR in the rating system. The limits for SAR appear to be unreasonable based on results obtained from laboratories (or are evaluated by a different method of calculation). The maximum SAR used for the classification of dispersive soils, according to the rating system is 2 or more. Of the 12 samples tested, 8 had SAR significantly greater than 2 with some results in the range of 100. This poses two questions: firstly, where did the SAR limits originate? And secondly, what is the implication of SAR values in the range of 100 and above? This would make for an interesting topic for a final year university project.

Classifications based on Gerber and Harmse (1987) ESP versus CEC chart show that 2 out of the 12 samples fall outside the range of the chart. As discussed above, the chart was developed based on results from 67 samples, of which 46 were classified as dispersive and 21 non-dispersive. The samples were classified using four properties; however, there is no indication of limits or weightings of each property. The envelopes for the ESP versus CEC chart were established from the results of the 67 samples. Once again, the subdivisions of the highly dispersive, marginal and completely non-dispersive envelopes are questionable.

Another significant point of note is the use of the terms slightly and moderately dispersive in the classification of dispersive soils. The question posed here is: what is the point of having these classes? A soil is either problematic (dispersive) or not. It is nonsensical for a dispersive soil to be a slight or moderate problem. No evidence in the literature suggests that the degree of dispersiveness warrants different remedial measures and it is therefore not necessary to classify it thus. It is recommended that the classification be either dispersive or non-dispersive. There is no point in following a complicated process to determine the level of dispersivity when the soil will still pose a problem and no intermediate treatment options are presented.

6.7 Clay Mineralogy

An examination of previous literature has found that many authors describe dispersive soils as soils in which the clay fraction is composed largely of smectitic and other 2:1 clays (Elges, 1985; Brink, 1985; Bell and Maud, 1994). The results obtained from X-Ray diffraction analyses of the samples used in this investigation show kaolinite as the only common mineral for all samples used in this study. Smectite was present in one sample (ND309), which is the known non-dispersive sample. It is clear that the current thinking regarding the relationship between clay mineralogy and dispersiveness is thus incorrect and this is thus a possible area for further study in the future.

7 Conclusions and recommendations

7.1 Conclusions

The dispersion of clay soils in water and its influence on the stability of various engineered structures has been a topic of concern in various engineering projects for many years. One of the main problems is the seeming inability (particularly in the road construction industry) to positively identify such soils and thereby to reduce the potential for failure of many engineering structures.

Although the causes and consequences of soil dispersion are well understood, the accurate identification of dispersive soils still remains a problem. Many identification methods have been proposed but none has been completely successful. The current identification methods include the pinhole, double hydrometer, crumb and chemical tests, which are commonly used in combination to obtain the most reliable outcome. These laboratory tests, however, have not always been entirely consistent, either when used in combination or individually, and it is possible that the reason lies in the actual testing procedures.

Experience in the literature study shows deficiencies in the identification of dispersive soils and in many cases the identification and classification problems appear to be related to inconsistencies in the test methods and testing protocols.

A pilot study was carried out, which confirmed the deficiencies in the identification process, indicating problems with the test methods. The pilot study allowed for the identification of shortcomings in the test methods and some modifications were made. The modified methods were then used in the main study of 12 materials to assess the test methods fully and ensure that the proposed methods produce more consistent and reliable results.

The specific problems with the test methods were thus identified, the methods modified and implemented and the following conclusions were drawn:

- The pinhole test was found to be a highly unreliable test. The test method is ambiguous and the test procedure is time consuming with very little of the fundamental problems in dispersive soils being addressed. The test might be acceptable for erodible soils but can be problematic for use in dispersive soil identification. Investigations into the testing in South Africa have also found that the majority of commercial soils laboratories do not perform the pinhole test.

- The double hydrometer test is a good indicator of dispersivity if done accurately and repeatably.
- The crumb test is also a good indicator if carried out accurately; however, there is no need for the four classification grades.
- The chemical analysis of the soils should be carried out using the standards employed by the Soil Science Society of South Africa.
- Gerber and Harmse's (1987) ESP versus CEC chart was found to give inconsistent evaluations of dispersivity.
- The current rating system suggested for use in South Africa was also found to be unreliable because it puts a great deal of weight on the poorly reproducible pinhole test.
- Tests utilized for dispersive soil identification should not be based on methods that require opinions but instead, hard evidence. For example, crumb test results should state the presence of colloidal suspension or no suspension. There is no benefit in complicating the test by describing 'slightly', 'moderately' or 'heavy' suspension.
- Most laboratory technicians generally follow a mechanistic process without understanding the theoretical background and test requirements. They mainly execute a specific process or procedure, so the procedure needs to be as simple as possible in order to be repeatable and reproducible.

This investigation was aimed solely at the evaluation of test protocols and not the actual identification of the soil samples, although it was necessary in the investigation to assess the samples tested in terms of their expected dispersivity. The identification of dispersive soils such that a revised classification method can be developed would require the testing of a wide range of materials and the adoption/adaption/modification or replacement of the current rating system and should be carried out as a separate follow-up investigation or research project.

7.2 Recommendations

The conclusions drawn from this study indicated that the tests currently used for the identification of dispersive soils have significant shortcomings with regard to the procedures and in some cases, interpretation of results. Investigations have found that there is no effective standard protocol used for the identification process, which could also be a likely cause of the identification problems. Based on work carried out in this study, the following recommendations are thus proposed:

- The repeatability and reproducibility of the proposed test methods need to be evaluated.
- Further investigations of the Sodium Adsorption Ratio (SAR) limits, origin and variation in results should be assessed.
- The role of the clay mineral type, such as smectites and kaolinites should be evaluated.
- It is also recommended that the proposed test methods are implemented for any dispersive soil investigation.
- Based on this investigation, the following process for the identification of dispersive soils is proposed:
    - An in situ crumb test (at natural moisture content) should be carried out on site using bottled water as a preliminary screening test. If the results should show any evidence of dispersion as discussed in Appendix C, then the soil is likely to be dispersive and should be tested according to the next step. If the results do not show any evidence of dispersion, then the material need not be tested further and is probably only highly erodible or subject to slaking. If there is any doubt or ambiguity regarding the results from the first step, then the next should be followed for more accurate results.
    - If the field crumb test shows evidence of dispersion, a laboratory crumb test should be carried out as specified in Appendix C. Samples are to be remoulded and tested in distilled water. Readings/ observations of colloidal suspension should be recorded after 1 hour. If the results for the laboratory crumb test indicate dispersive behaviour, the testing can proceed to the next step of the process. If there is no sign of dispersivity, then it is probable that the material is not dispersive.
    - The next step in the identification process is the double hydrometer test. The test is to be carried out as accurately as possible following the test method proposed in Appendix C. The double hydrometer test is the main indicator test for the dispersivity and carries significant weight if done correctly. If there is doubt regarding the results for the double hydrometer test, then the next step should be followed for clarification/confirmation of the hydrometer results.

- The final step in the process is the chemical analysis of the soil. This should be done by a competent laboratory using the methods prescribed by the Soil Science Society of South Africa. The test methods are provided in Appendix C. Results obtained from laboratories should always be checked and questioned if the client has doubts.

It is recommended that the above mentioned process is applied to approximately 50 samples of material with a range of different dispersive characteristics in a separate investigation. The aim of an investigation such as this would be to confirm the repeatability and reproducibility of the test methods as well as provide a basis for modifying and improving current rating systems for classifying dispersive soils.

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Appendix A- Test Results

Standard classification tests

Grading

SAMPLE DESCRIPTION						
Sample no	**13O1**	**13O2**	**13O3**	**N2S1**	**N2S2**	**SENJ1**
SIEVE ANALYSIS (%Passing)						
75.0 mm						
53.0mm						
37.5 mm						
26.5 mm						
19.0 mm						
13.2 mm		99.07			97.96	99.15
9.5 mm		98.36			97.11	98.79
6.7 mm		96.94	99.12	99.67	95.81	97.87
4.75 mm	99.68	95.56	98.80	98.87	95.33	96.73
2.00 mm	98.02	91.44	88.46	96.18	92.41	91.81
0.850 mm	95.78	84.81	72.23	94.64	85.34	88.91
0.425 mm	86.03	75.73	61.18	93.74	82.38	85.13
0.250 mm	71.82	69.62	52.18	92.15	80.84	74.42
0.150 mm	56.72	63.27	42.86	80.61	77.78	55.08
0.075 mm	40.67	54.02	32.69	63.33	69.36	40.70

SAMPLE DESCRIPTION						
Sample no	**KNP1**	**UM108**	**COED1**	**ZT114**	**ZB114**	**ND309**
SIEVE ANALYSIS (%Pass)						
75.0 mm						
53.0mm						
37.5 mm						
26.5 mm						
19.0 mm						
13.2 mm						
9.5 mm						99.05
6.7 mm	99.01			99.78		98.21
4.75 mm	98.83	99.34	99.66	98.89	98.76	97.28
2.00 mm	97.34	98.05	99.05	95.79	94.83	90.83
0.850 mm	90.03	96.72	98.05	90.74	89.89	73.50
0.425 mm	78.08	96.01	95.47	88.13	87.23	58.97
0.250 mm	63.92	88.02	88.72	79.33	78.90	40.89
0.150 mm	50.48	73.38	76.11	71.65	72.24	30.73
0.075 mm	40.14	45.75	57.89	60.32	63.51	20.01

Atterberg & ARD

Sample #	LL	PL	PI	ARD
13OCT(1)	39.74	34.15	5.59	2.77
13OCT(2)	44.24	30.54	13.70	2.67
13OCT(3)	23.49	17.02	6.47	2.64
N2 SECT1	31.71	20.84	10.87	2.79
N2 SECT2	33.57	21.64	11.93	2.69
ZB114	26.03	17.95	8.08	2.84
ZT114	20.65	14.03	6.62	2.76
KNP	27.10	18.24	8.86	2.65
ND	27.77	18.78	8.99	2.80
DBN	25.50	16.57	8.93	2.63
Umtata	15.38	10.73	4.65	2.61
SEN-JAC	20.04	14.15	5.89	2.66

XRD

Minerals	Sample Number											
	13O1	**13O2**	**13O3**	**N2S1**	**N2S2**	**SENJ1**	**KNP1**	**UM108**	**COED1**	**ZT114**	**ZB114**	**ND309**
Andalusite										7.6	7.6	
Goethite								2.3		5.2	5.6	
Calcite				0.2	4.0							
Diopside	2.0	1.7	0.1			1.5	2.5		2.5			0.3
Enstatite						1.6	1.5					0.6
Hematite	0.4	0.3	0.1		0.1	0.1	0.2			0.2	0.3	3.8
Kaolinite	**51.9**	**47.2**	**24.6**	**28.9**	**36.8**	**9.0**	**12.9**	**1.7**	**31.1**	**41.8**	**42.7**	**23.8**
Microcline	3.3	9.7	1.6	4.4	3.4	6.4	15.4	1.2	13.5			8.0
Muscovite	7.7	7.3	3.7	6.8	8.0	6.3	5.9	3.0	4.9	7.3	8.0	1.6
Plagioclase	1.2	1.1	3.2	4.9	8.2	5.6	22.8	1.7	18.0			19.1
Quartz	33.5	32.7	66.8	54.7	39.5	69.4	38.9	90.1	30.1	37.9	35.8	23.5
Smectite												**19.3**
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Pinhole

95 % Standard Proctor compaction effort

Sample	Final Head (mm)	Time (min)	Final Flow rate (ml/s)	Colour	Settlement of particles	Pinhole size	Effluent after 1 hour	Classification
13O1	----	----	----	----	----	----	----	----
13O2	180	10	0.8	Clear	None	x 1	----	**Non-dispersive**
13O3	180	10	0.02	Clear	None	----	----	**Non-dispersive**
N2S1	50	10	0.6	Medium	Few	x 4	Slight	***Intermediate (<0.8ml/s) & dispersive (hole>x 2)***
N2S2	50	10	0.6	Dark	Few	x 3	Medium	***Intermediate (<0.8ml/s) & dispersive (hole>x 2)***
SENJ1	50	10	0.5	Dark	Few	x 3	Cloudy	**Dispersive**
KNP1	50	10	0.4	Slight	None	x 1	Slight	**Intermediate**
	180	12	0.9	Slight	None	x 1	Slight	***??***
UM108	----	----	----	----	----	----	----	----
COED1	50	10	0.7	Dark	Few	x 5	Medium	***Intermediate (<0.8ml/s) & dispersive (hole>x 2)***
ZT114	50	10	0.3	Dark	Few	x 2	Dark/Cloudy	**Dispersive**
ZB114	50	10	0.2	Dark	None	x 2	Dark/Cloudy	**Dispersive**
ND309	180	10	0.8	Clear	None	x 1	----	**Non-dispersive**

Modified AASHTO compaction effort

Sample	Final Head (mm)	Time (min)	Final Flow rate (ml/s)	Colour	Settlement of particles	Pinhole size	Effluent after 1 hour	Classification
13O1	50	7	0.1	Clear	----	----	----	**Non-dispersive**
13O2	180	5	1.04	Clear	None	x 1	----	**Non-dispersive**
KNP1	50	5	0.03	Slight	----	x 1	----	***Intermediate??***
	180	5	0.9	Slight	Few	x 1	Slight	***??***
KNP1	50	5	0.3	Slight	Few	x 1	----	***Intermediate??***
	180	5	0.7	Slight	Few	x 1	Slight	***??***
COED1	50	10	0.3	Medium	Few	----	Slight	***Dispersive?? (Flow < 0.8ml/s)***
ZB114	50	10	0.5	Dark	Few	x 2	Dark/Cloudy	***Intermediate (<0.8ml/s) & dispersive (hole>x 2)***

Hydrometer

Hydrometer Calibration- (152H62) #347.060 ASSG

R_h	Di	$R_h + N$	H_R
60	0	10.56	73.146
55	7.49	18.05	80.636
50	15.71	26.27	88.856
45	23.52	34.08	96.666
40	31.72	42.28	104.866
35	39.66	50.22	112.806
30	48.01	58.57	121.156
25	56.17	66.73	129.316
20	68.25	78.81	141.396
15	72.51	83.07	145.656
10	80.89	91.45	154.036
5	89.42	99.98	162.566
0	97.98	108.54	171.126
-5	106.3	116.86	179.446

$H = N + R_h$

$HR = H + 0.5 (h - Vh/900 * L)$

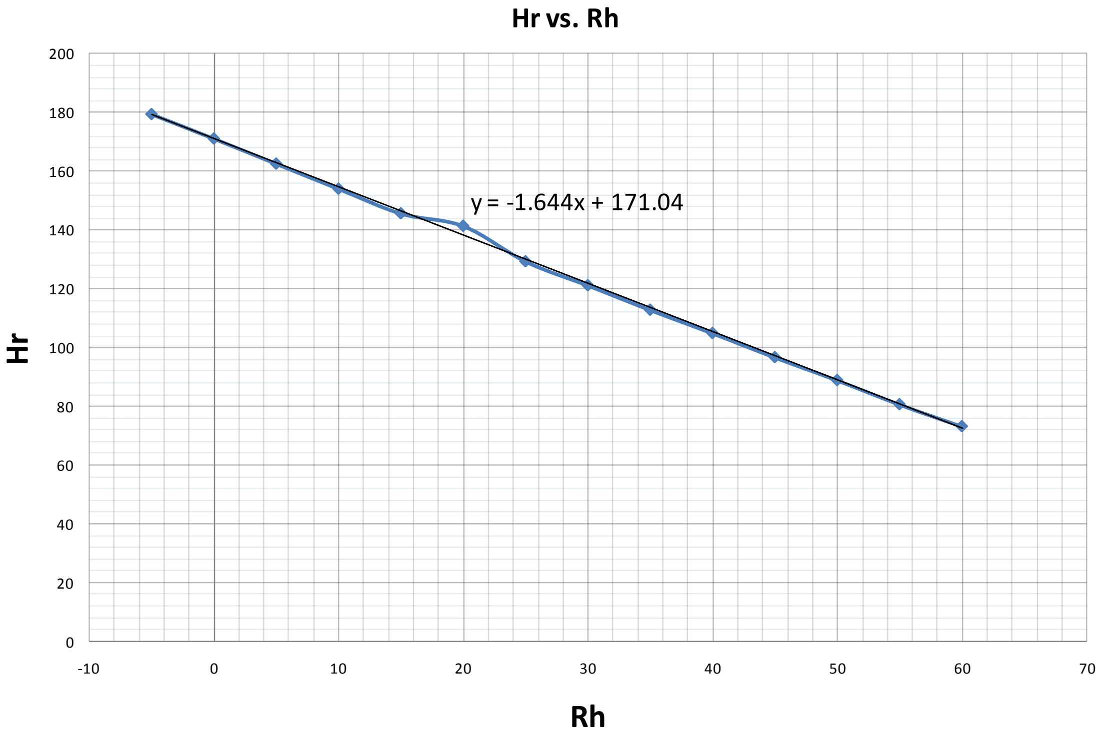
$V_h =$ 44.2 g

L = 306 mm

h = 140.2 mm

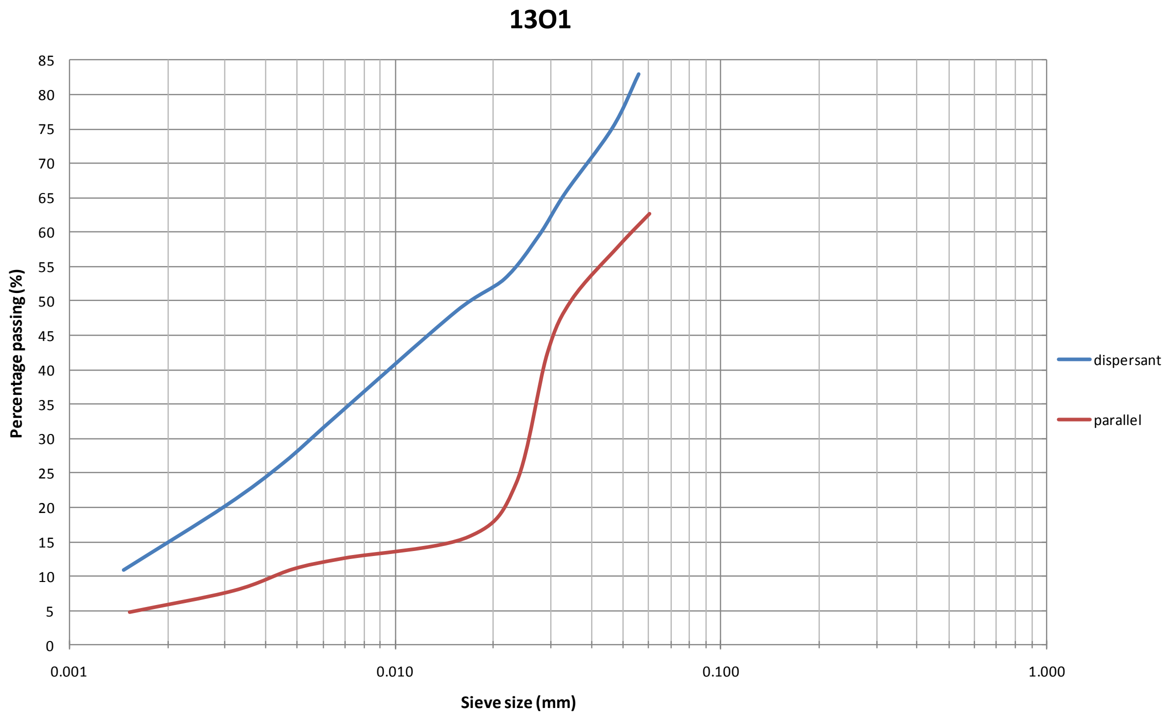
Cm = 1

N = 10.56 mm



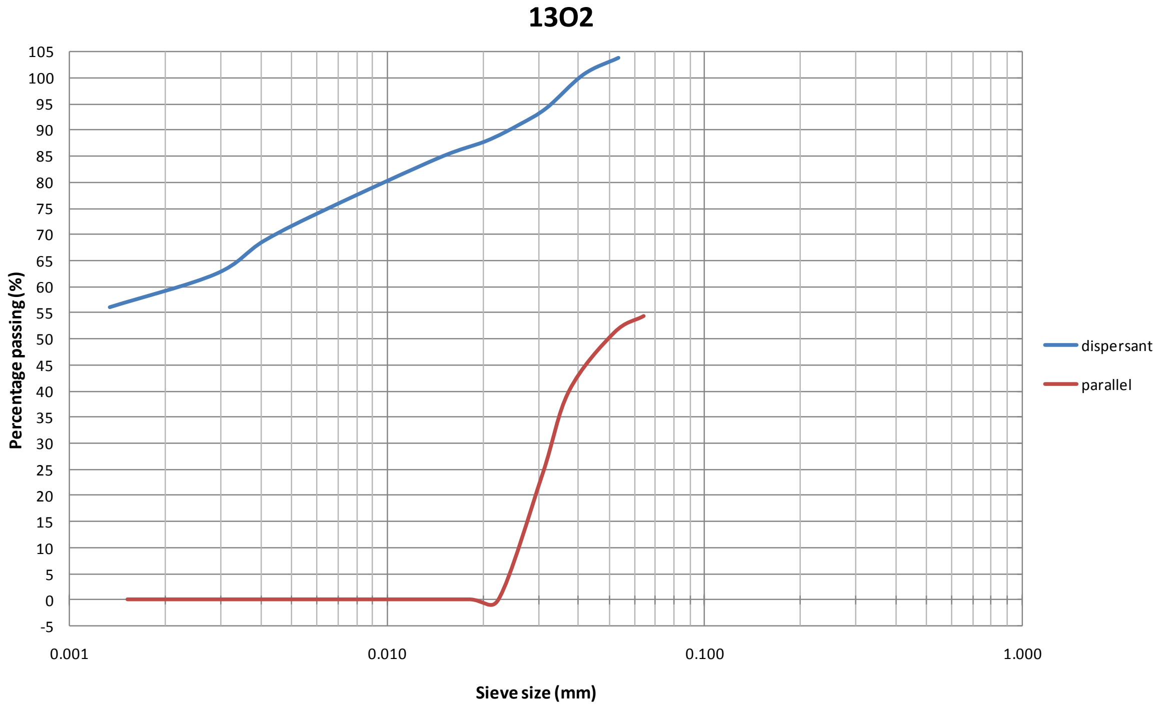
13O1

13O1- Hexametaphosphate							
Elapsed time *t* (min)	**Temperature** ***T*** **(°C)**	**Reading *Rh'***	***Rh' + Cm = Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh' - Ro' = Rd***	**Percentage finer than *D*** ***K*** **(%)**
0.67	20	30	31	120.1	0.0559	26.5	82.9
1.00	20	27.5	28.5	124.2	0.0464	24	75.1
2	20	24.5	25.5	129.1	0.0333	21	65.7
3	20	22.5	23.5	132.4	0.0276	19	59.5
5	20	20.5	21.5	135.7	0.0216	17	53.2
10	20	19	20	138.2	0.0154	15.5	48.5
61	20	14	15	146.4	0.0064	10.5	32.9
124	20	12	13	149.7	0.0046	8.5	26.6
288.00	20	10	11	153.0	0.0030	6.5	20.3
1266.00	20	7	8	157.9	0.0015	3.5	11.0
13O1- Parallel							
Elapsed time ***t*** **(min)**	**Temperature** ***T*** **(°C)**	**Reading *Rh'***	***Rh' + Cm = Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh' - Ro' = Rd***	**Percentage finer than *D*** ***K*** **(%)**
0.67	20	18.5	19.5	139.0	0.0601	20	62.6
1.05	20	17	18	141.4	0.0483	18.5	57.9
2.10	20	14.5	15.5	145.6	0.0346	16	50.1
3	20	12	13	149.7	0.0292	13.5	42.3
5	20	6	7	159.5	0.0234	7.5	23.5
10	20	3.5	4.5	163.6	0.0167	5	15.6
60	20	2.5	3.5	165.3	0.0069	4	12.5
123	20	2	3	166.1	0.0048	3.5	11.0
287	20	1	2	167.8	0.0032	2.5	7.8
1265	20	0	1	169.4	0.0015	1.5	4.7



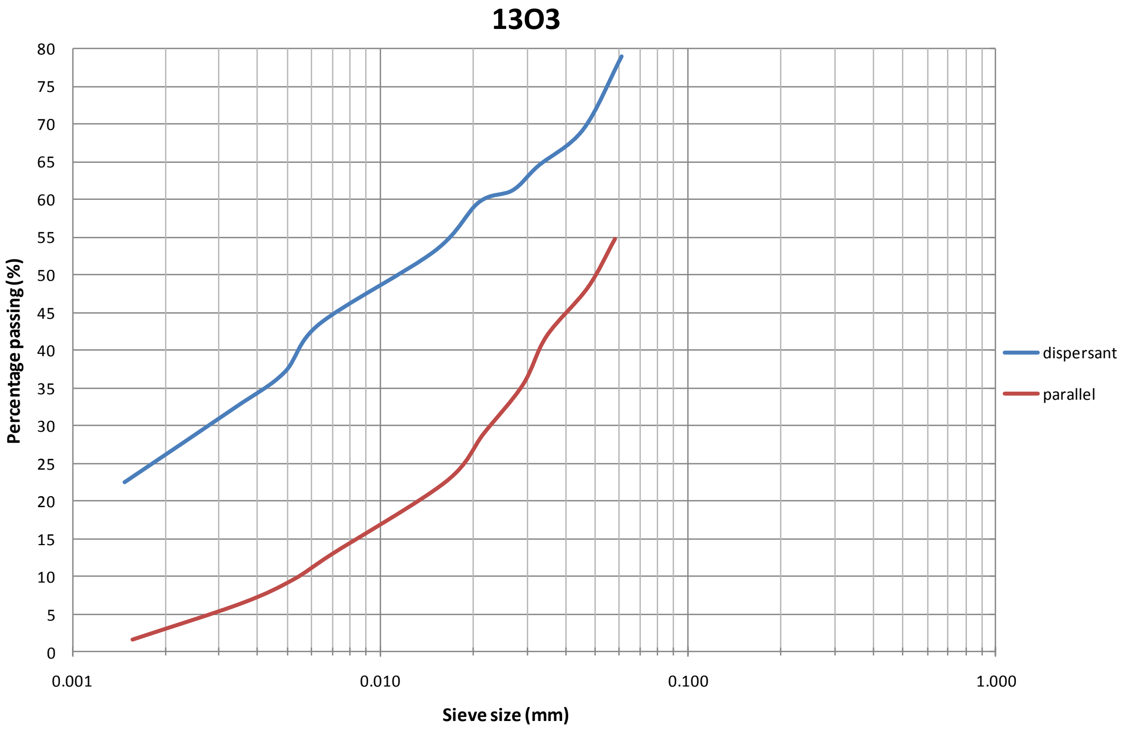
13O2

13O2- Hexametaphosphate							
Elapsed time *t* (min)	**Temperature** ***T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.68	20	38	39	106.9	0.0536	32.5	103.9
1.15	20	37	38	108.6	0.0416	31.5	100.7
2.02	20	35	36	111.9	0.0319	29.5	94.3
3.03	20	34	35	113.5	0.0262	28.5	91.1
5	20	33	34	115.1	0.0206	27.5	87.9
10	20	32	33	116.8	0.0146	26.5	84.7
51	20	29	30	121.7	0.0066	23.5	75.1
136	20	27	28	125.0	0.0041	21.5	68.7
282	20	25	26	128.3	0.0029	19.5	62.4
1346	20	23	24	131.6	0.0013	17.5	56.0
13O2- Parallel							
Elapsed time *t* (min)	**Temperature *T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.63	20	17	18	141.4	0.0640	17	54.4
0.98	20	16	17	143.1	0.0517	16	51.2
1.97	20	12.5	13.5	148.8	0.0373	12.5	40.0
3.05	20	7.5	8.5	157.1	0.0307	7.5	24.0
6.22	20	0	1	169.4	0.0224	0	0.0
9.52	20	0	1	169.4	0.0181	0	0.0
50	20	0	1	169.4	0.0079	0	0.0
137	20	0	1	169.4	0.0048	0	0.0
283	20	0	1	169.4	0.0033	0	0.0
1347	20	0	1	169.4	0.0015	0	0.0



13O3

13O3- Hexametaphosphate							
Elapsed time *t* (min)	**Temperature** ***T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D*** ***K* (%)**
0.55	20	30	31	120.1	0.0610	24.5	78.9
1.02	20	27	28	125.0	0.0458	21.5	69.2
2	20	25.5	26.5	127.5	0.0327	20	64.4
3	20	24.5	25.5	129.1	0.0270	19	61.2
5	20	24	25	129.9	0.0209	18.5	59.6
10	20	22	23	133.2	0.0151	16.5	53.1
64	20	19	20	138.2	0.0064	13.5	43.5
111	20	17	18	141.4	0.0049	11.5	37.0
244	20	15.5	16.5	143.9	0.0033	10	32.2
1271	20	12.5	13.5	148.8	0.0015	7	22.5
13O3- Parallel							
Elapsed time ***t* (min)**	**Temperature** ***T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D*** ***K* (%)**
0.72	20	17	18	141.4	0.0580	17	54.7
1.10	20	15	16	144.7	0.0473	15	48.3
2.08	20	13	14	148.0	0.0348	13	41.9
3	20	11	12	151.3	0.0292	11	35.4
6	20	9	10	154.6	0.0218	9	29.0
10	20	7	8	157.9	0.0164	7	22.5
63	20	4	5	162.8	0.0070	4	12.9
110	20	3	4	164.5	0.0053	3	9.7
244	20	2	3	166.1	0.0036	2	6.4
1270	20	0.5	1.5	168.6	0.0016	0.5	1.6



N2S1

N2S1- Hexametaphosphate

Elapsed time *t* (min)	**Temperature** ***T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.67	20	37	38	108.6	0.0528	31.5	98.2
1	20	35	36	111.9	0.0431	29.5	92.0
2	20	31	32	118.4	0.0321	25.5	79.5
3	20	29	30	121.7	0.0264	23.5	73.3
5	20	28	29	123.4	0.0206	22.5	70.1
10	20	26.5	27.5	125.8	0.0147	21	65.5
59	20	25	26	128.3	0.0061	19.5	60.8
128	20	24.5	25.5	129.1	0.0042	19	59.2
298	20	24	25	129.9	0.0027	18.5	57.7
1271	20	23	24	131.6	0.0013	17.5	54.6

N2S1- Parallel

Elapsed time *t* (min)	**Temperature** ***T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.67	20	28	29	123.4	0.0563	28	87.3
1.23	20	23	24	131.6	0.0427	23	71.7
2	20	18	19	139.8	0.0327	18	56.1
3	20	16	17	143.1	0.0286	16	49.9
5	20	12	13	149.7	0.0223	12	37.4
10	20	8	9	156.2	0.0161	8	24.9
58	20	5	6	161.2	0.0069	5	15.6
126	20	3	4	164.5	0.0047	3	9.4
296	20	2	3	166.1	0.0031	2	6.2
1264	20	0.5	1.5	168.6	0.0015	0.5	1.6

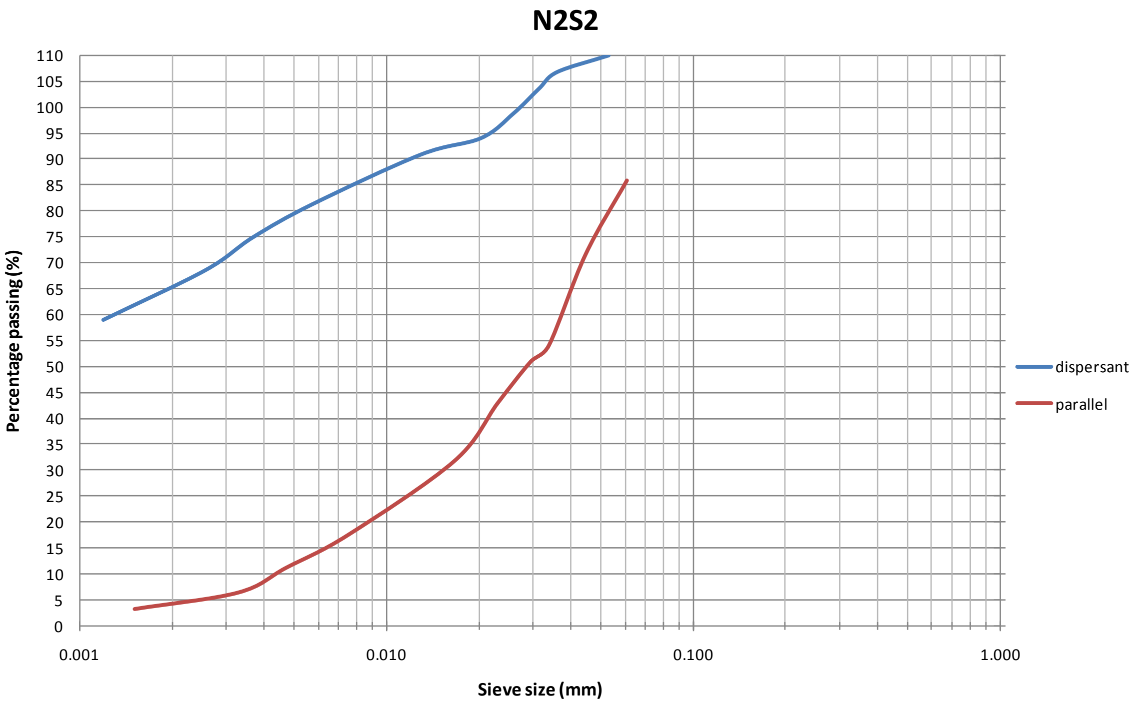
N2S2

N2S2- Hexametaphosphate

Elapsed time *t* (min)	**Temperature *T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.68	20	39	40	105.3	0.0529	34.5	109.8
1.50	20	38	39	106.9	0.0360	33.5	106.6
2	20	37	38	108.6	0.0314	32.5	103.5
3	20	35.5	36.5	111.0	0.0259	31	98.7
5	20	34	35	113.5	0.0203	29.5	93.9
10	20	33	34	115.1	0.0129	28.5	90.7
53	20	30	31	120.1	0.0057	25.5	81.2
133	20	28	29	123.4	0.0037	23.5	74.8
280	20	26	27	126.7	0.0026	21.5	68.4
1344	20	23	24	131.6	0.0012	18.5	58.9

N2S2- Parallel

Elapsed time *t* (min)	**Temperature *T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.62	20	27	28	125.0	0.0606	27	86.0
1.22	20	22.5	23.5	132.4	0.0444	22.5	71.6
2.25	20	17	18	141.4	0.0338	17	54.1
3	20	16	17	143.1	0.0294	16	50.9
5	20	13.5	14.5	147.2	0.0230	13.5	43.0
10	20	10	11	153.0	0.0166	10	31.8
52	20	5.5	6.5	160.4	0.0075	5.5	17.5
135	20	3.5	4.5	163.6	0.0047	3.5	11.1
281	20	2	3	166.1	0.0033	2	6.4
1345	20	1	2	167.8	0.0015	1	3.2



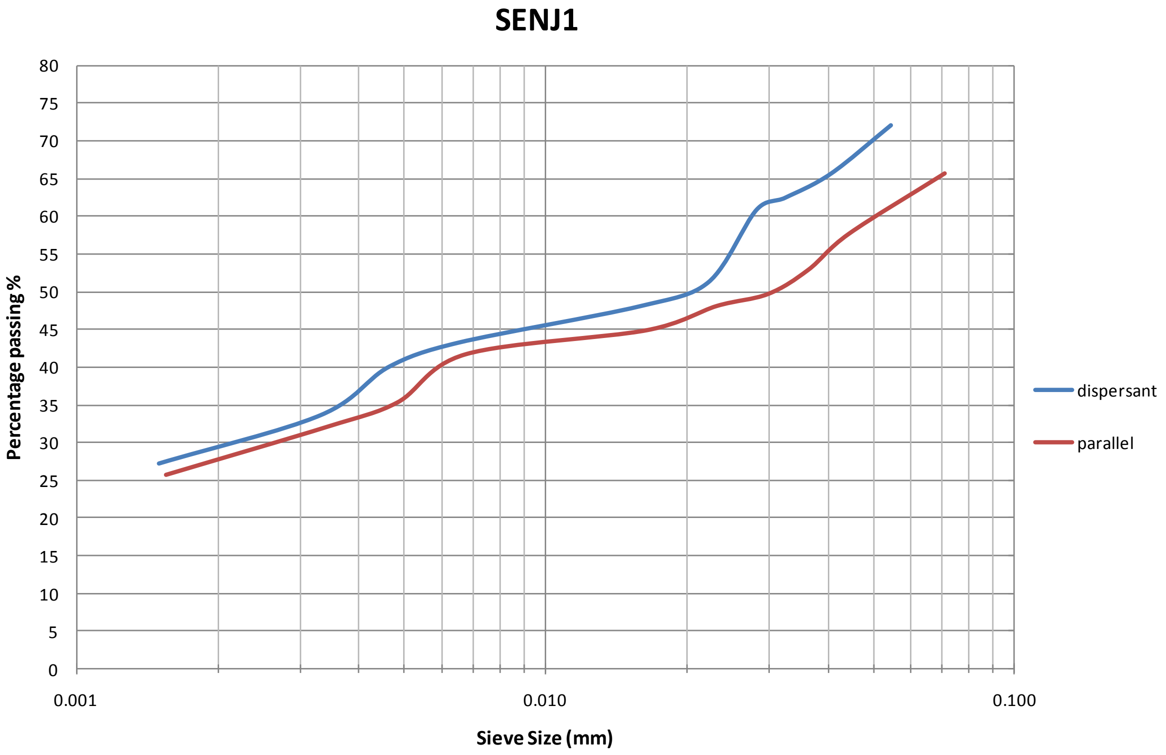
SENJ1

SENJ1- Hexametaphosphate

Elapsed time *t* (min)	Temperature *T* (°C)	Reading *Rh'*	*Rh'* + *Cm* = *Rh*	Effective depth *Hr* (mm)	Particle Diameter *D* (mm)	*Rh'* - *Ro'* = *Rd*	Percentage finer than *D* *K* (%)
0.77	20	28	29	123.36	0.0545	22.5	72.11
1.42	20	26	27	126.65	0.0406	20.5	65.70
2.25	20	25	26	128.30	0.0324	19.5	62.49
3	20	24.5	25.5	129.12	0.0282	19	60.89
5	20	21.5	22.5	134.05	0.0223	16	51.28
10	20	20.5	21.5	135.69	0.0158	15	48.07
60	20	19	20	138.16	0.0065	13.5	43.27
120	20	18	19	139.80	0.0046	12.5	40.06
240	20	16	17	143.09	0.0033	10.5	33.65
1200	20	14	15	146.38	0.0015	8.5	27.24

SENJ1- Parallel

Elapsed time *t* (min)	Temperature *T* (°C)	Reading *Rh'*	*Rh'* + *Cm* = *Rh*	Effective depth *Hr* (mm)	Particle Diameter *D* (mm)	*Rh'* - *Ro'* = *Rd*	Percentage finer than *D* *K* (%)
0.50	20	20.5	21.5	135.69	0.0708	20.5	65.70
1.32	20	18	19	139.80	0.0443	18	57.69
2	20	16.5	17.5	142.27	0.0362	16.5	52.88
3	20	15.5	16.5	143.91	0.0298	15.5	49.67
5	20	15	16	144.74	0.0231	15	48.07
10	20	14	15	146.38	0.0164	14	44.87
60	20	13	14	148.02	0.0067	13	41.66
120	20	11	12	151.31	0.0048	11	35.25
240	20	10	11	152.96	0.0034	10	32.05
1200	20	8	9	156.24	0.0016	8	25.64



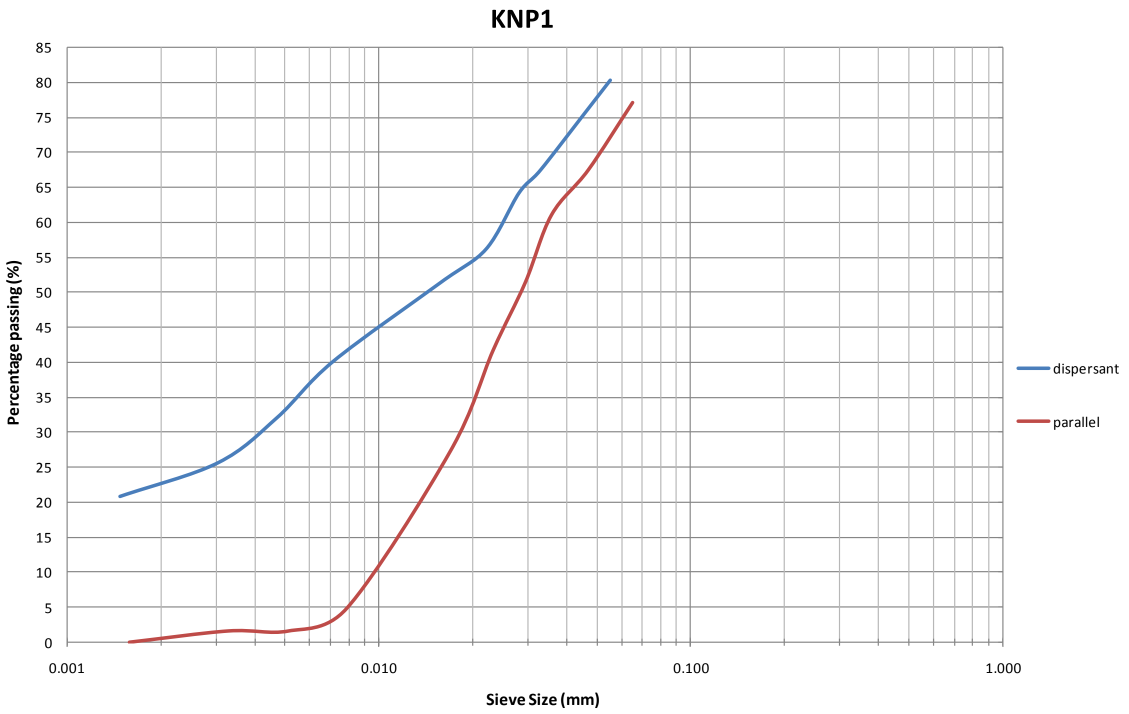
KNP1

KNP1- Hexametaphosphate

Elapsed time *t* (min)	**Temperature *T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.73	20	30.5	31.5	119.3	0.0550	25	80.3
1.10	20	29	30	121.7	0.0453	23.5	75.5
2.17	20	26.5	27.5	125.8	0.0328	21	67.5
3	20	25.5	26.5	127.5	0.0281	20	64.2
5	20	23	24	131.6	0.0220	17.5	56.2
10	20	21.5	22.5	134.1	0.0157	16	51.4
51	20	18	19	139.8	0.0071	12.5	40.2
120	20	15.5	16.5	143.9	0.0047	10	32.1
292	20	13.5	14.5	147.2	0.0031	8	25.7
1261	20	12	13	149.7	0.0015	6.5	20.9

KNP1- Parallel

Elapsed time *t* (min)	**Temperature *T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.57	20	24	25	129.9	0.0653	24	77.1
1.13	20	21	22	134.9	0.0470	21	67.5
2	20	19	20	138.2	0.0358	19	61.0
3	20	16	17	143.1	0.0295	16	51.4
5	20	13	14	148.0	0.0233	13	41.8
10	20	8.5	9.5	155.4	0.0170	8.5	27.3
50	20	1.5	2.5	166.9	0.0079	1.5	4.8
119	20	0.5	1.5	168.6	0.0051	0.5	1.6
291	20	0.5	1.5	168.6	0.0033	0.5	1.6
1260	20	0	1	169.4	0.0016	0	0.0



UM108

UM108- Hexametaphosphate							
Elapsed time *t* (min)	**Temperature *T* (°C)**	**Reading *Rh'***	***Rh' + Cm = Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh' - Ro' = Rd***	**Percentage finer than *D* *K* (%)**
0.53	20	32	33	116.8	0.0646	26.5	85.9
1.02	20	30	31	120.1	0.0474	24.5	79.4
2	20	25.5	26.5	127.5	0.0348	20	64.8
3	20	24	25	129.9	0.0286	18.5	60.0
5	20	22	23	133.2	0.0225	16.5	53.5
10	20	20.5	21.5	135.7	0.0161	15	48.6
54	20	18	19	139.8	0.0070	12.5	40.5
123	20	15.5	16.5	143.9	0.0047	10	32.4
295	20	14	15	146.4	0.0031	8.5	27.6
1264	20	12.5	13.5	148.8	0.0015	7	22.7
UM108- Parallel							
Elapsed time *t* (min)	**Temperature *T* (°C)**	**Reading *Rh'***	***Rh' + Cm = Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh' - Ro' = Rd***	**Percentage finer than *D* *K* (%)**
0.55	20	22	23	133.2	0.0679	22	71.3
1.12	20	18	19	139.8	0.0488	18	58.4
2.15	20	14	15	146.4	0.0360	14	45.4
3	20	12	13	149.7	0.0308	12	38.9
5	20	10.5	11.5	152.1	0.0238	10.5	34.0
10	20	8	9	156.2	0.0172	8	25.9
52	20	3	4	164.5	0.0078	3	9.7
121	20	1.5	2.5	166.9	0.0051	1.5	4.9
293	20	1	2	167.8	0.0033	1	3.2
1262	20	0	1	169.4	0.0016	0	0.0

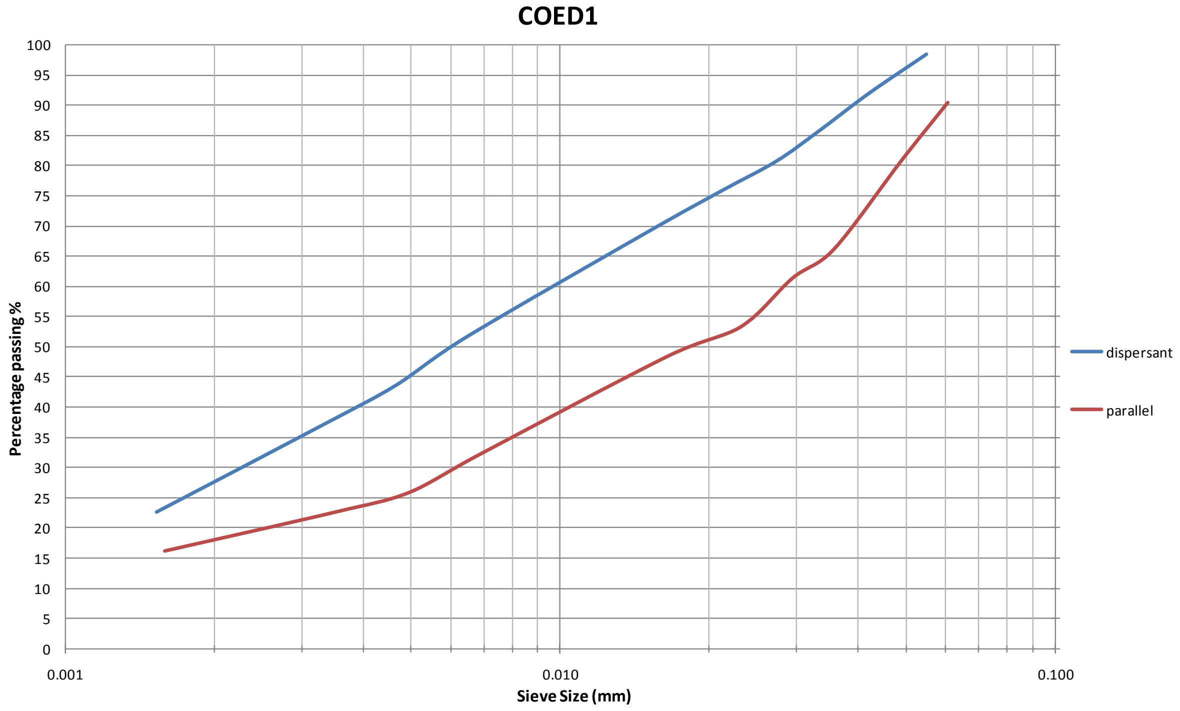
COED1

COED1- Hexametaphosphate

Elapsed time *t* (min)	**Temperature *T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.68	20	36	37	110.2	0.0551	30.5	98.4
1.20	20	34	35	113.5	0.0422	28.5	92.0
2	20	32	33	116.8	0.0331	26.5	85.5
3	20	30.5	31.5	119.3	0.0273	25	80.7
5	20	29	30	121.7	0.0213	23.5	75.8
10	20	27	28	125.0	0.0153	21.5	69.4
60	20	21.5	22.5	134.1	0.0065	16	51.6
120	20	19	20	138.2	0.0047	13.5	43.6
240	20	17	18	141.4	0.0033	11.5	37.1
1200	20	12.5	13.5	148.8	0.0015	7	22.6

COED1- Parallel

Elapsed time *t* (min)	**Temperature *T* (°C)**	**Reading *Rh'***	***Rh'* + *Cm* = *Rh***	**Effective depth *Hr* (mm)**	**Particle Diameter *D* (mm)**	***Rh'* - *Ro'* = *Rd***	**Percentage finer than *D* *K* (%)**
0.63	20	28	29	123.4	0.0605	28	90.4
1.02	20	25	26	128.3	0.0487	25	80.7
2	20	20.5	21.5	135.7	0.0357	20.5	66.2
3	20	19	20	138.2	0.0294	19	61.3
5	20	16.5	17.5	142.3	0.0231	16.5	53.2
10	20	15	16	144.7	0.0165	15	48.4
60	20	10	11	153.0	0.0069	10	32.3
120	20	8	9	156.2	0.0049	8	25.8
240	20	7	8	157.9	0.0035	7	22.6
1200	20	5	6	161.2	0.0016	5	16.1



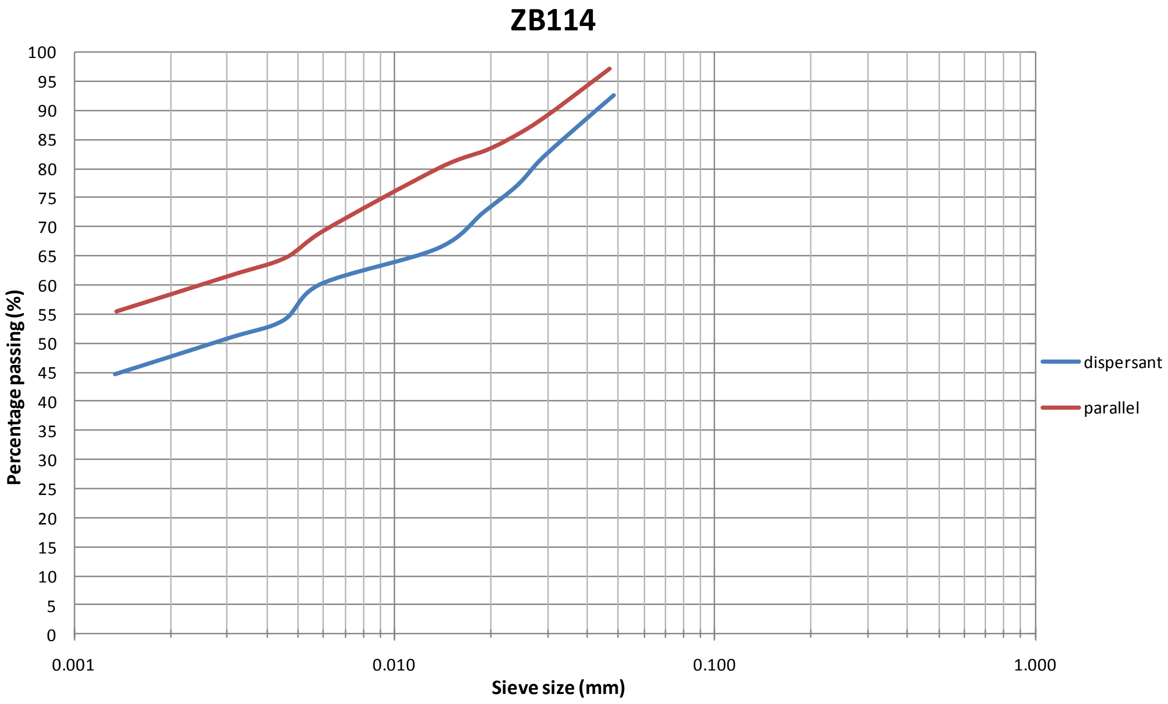
ZT114

ZT114- Hexametaphosphate							
Elapsed time *t* (min)	**Temperature** ***T*** **(°C)**	**Reading** ***Rh'***	***Rh'*** **+** ***Cm*** **=** ***Rh***	**Effective depth** ***Hr*** **(mm)**	**Particle Diameter** ***D*** **(mm)**	***Rh'*** **-** ***Ro'*** **=** ***Rd***	**Percentage finer than** ***D*** ***K*** **(%)**
0.65	20	35	36	111.9	0.0547	29.5	92.5
1.07	20	32.5	33.5	116.0	0.0435	27	84.7
2.13	20	28	29	123.4	0.0317	22.5	70.6
3	20	26.5	27.5	125.8	0.0270	21	65.9
5	20	24	25	129.9	0.0213	18.5	58.0
10	20	21.5	22.5	134.1	0.0153	16	50.2
63	20	20	21	136.5	0.0061	14.5	45.5
126	20	19	20	138.2	0.0044	13.5	42.3
290	20	16.5	17.5	142.3	0.0029	11	34.5
1266	20	15	16	144.7	0.0014	9.5	29.8

ZT114- Parallel							
Elapsed time ***t*** **(min)**	**Temperature** ***T*** **(°C)**	**Reading** ***Rh'***	***Rh'*** **+** ***Cm*** **=** ***Rh***	**Effective depth** ***Hr*** **(mm)**	**Particle Diameter** ***D*** **(mm)**	***Rh'*** **-** ***Ro'*** **=** ***Rd***	**Percentage finer than** ***D*** ***K*** **(%)**
0.73	20	26.5	27.5	125.8	0.0547	26.5	83.1
1.00	20	25	26	128.3	0.0473	25	78.4
2.05	20	22	23	133.2	0.0336	22	69.0
3	20	21	22	134.9	0.0280	21	65.9
5	20	19.5	20.5	137.3	0.0216	19.5	61.2
10	20	18	19	139.8	0.0156	18	56.5
62	20	17	18	141.4	0.0063	17	53.3
125	20	16	17	143.1	0.0045	16	50.2
289	20	15	16	144.7	0.0030	15	47.0
1267	20	13	14	148.0	0.0014	13	40.8

ZT114

ZB114- Hexametaphosphate							
Elapsed time *t* (min)	**Temperature** ***T*** **(°C)**	**Reading** ***Rh'***	***Rh'*** **+** ***Cm*** **=** ***Rh***	**Effective depth** ***Hr*** **(mm)**	**Particle Diameter** ***D*** **(mm)**	***Rh'*** **-** ***Ro'*** **=** ***Rd***	**Percentage finer than** ***D*** ***K*** **(%)**
0.72	20	35.5	36.5	111.0	0.0485	30.0	92.6
1.15	20	34	35	113.5	0.0387	28.5	88.0
2.12	20	32	33	116.8	0.0289	26.5	81.8
3	20	30.5	31.5	119.3	0.0242	25.0	77.2
5	20	29	30	121.7	0.0190	23.5	72.5
10	20	27	28	125.0	0.0137	21.5	66.4
62	20	25	26	128.3	0.0059	19.5	60.2
108	20	23	24	131.6	0.0045	17.5	54.0
242	20	22	23	133.2	0.0030	16.5	50.9
1268	20	20	21	136.5	0.0013	14.5	44.8
ZB114- Parallel							
Elapsed time ***t*** **(min)**	**Temperature** ***T*** **(°C)**	**Reading** ***Rh'***	***Rh'*** **+** ***Cm*** **=** ***Rh***	**Effective depth** ***Hr*** **(mm)**	**Particle Diameter** ***D*** **(mm)**	***Rh'*** **-** ***Ro'*** **=** ***Rd***	**Percentage finer than** ***D*** ***K*** **(%)**
0.82	20	31.5	32.5	117.6	0.0468	31.5	97.2
1.17	20	30.5	31.5	119.3	0.0394	30.5	94.2
2	20	29	30	121.7	0.0304	29	89.5
3	20	28	29	123.4	0.0250	28	86.4
5	20	27	28	125.0	0.0195	27	83.3
10	20	26	27	126.7	0.0138	26	80.3
61	20	22.5	23.5	132.4	0.0060	22.5	69.5
107	20	21	22	134.9	0.0046	21	64.8
241	20	20	21	136.5	0.0031	20	61.7
1267	20	18	19	139.8	0.0014	18	55.6



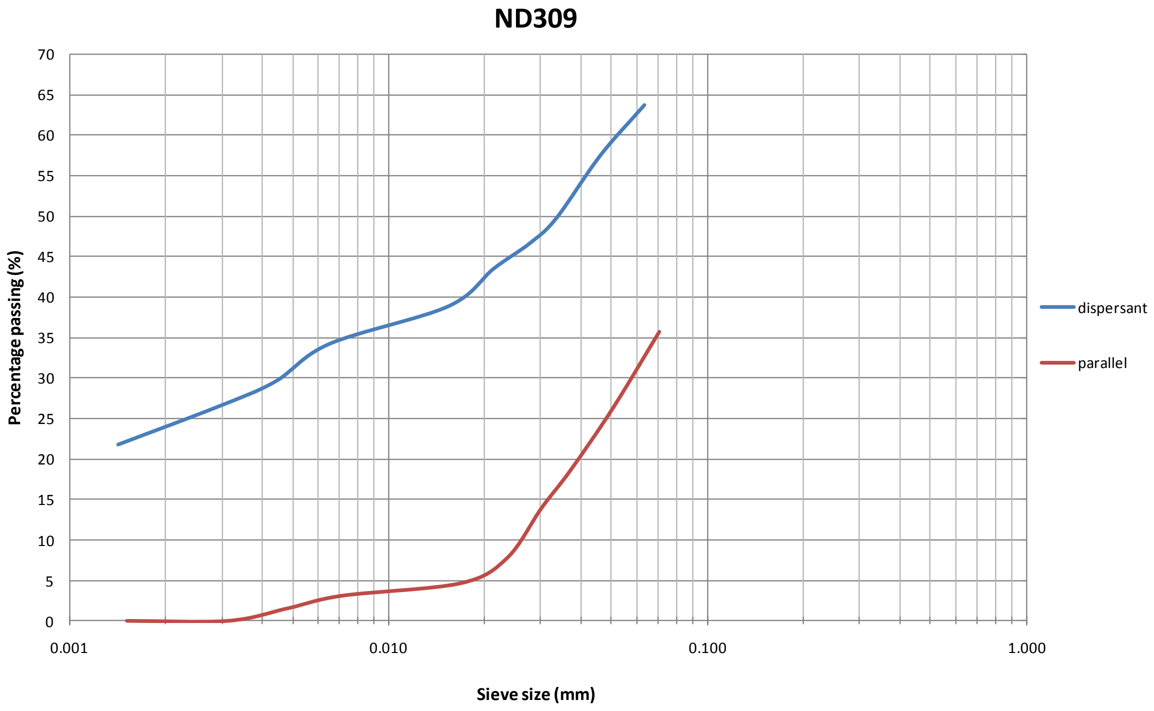
ND309

ND309- Hexametaphosphate

Elapsed time *t* (min)	Temperature *T* (°C)	Reading *Rh'*	*Rh' + Cm = Rh*	Effective depth *Hr* (mm)	Particle Diameter *D* (mm)	*Rh' - Ro' = Rd*	Percentage finer than *D* *K* (%)
0.53	20	26	27	126.7	0.0636	20.5	63.8
1	20	24	25	129.9	0.0463	18.5	57.6
2	20	21.5	22.5	134.1	0.0336	16.0	49.8
3	20	20.5	21.5	135.7	0.0278	15.0	46.7
5	20	19.5	20.5	137.3	0.0214	14.0	43.6
10	20	18	19	139.8	0.0154	12.5	38.9
57	20	16.5	17.5	142.3	0.0065	11.0	34.2
127	20	15	16	144.7	0.0044	9.5	29.6
295	20	14	15	146.4	0.0029	8.5	26.4
1263	20	12.5	13.5	148.8	0.0014	7.0	21.8

ND309- Parallel

Elapsed time *t* (min)	Temperature *T* (°C)	Reading *Rh'*	*Rh' + Cm = Rh*	Effective depth *Hr* (mm)	Particle Diameter *D* (mm)	*Rh' - Ro' = Rd*	Percentage finer than *D* *K* (%)
0.52	20	11.5	12.5	150.5	0.0704	11.5	35.8
1.03	20	8.5	9.5	155.4	0.0506	8.5	26.4
1.97	20	6	7	159.5	0.0372	6	18.7
3	20	4.5	5.5	162.0	0.0302	4.5	14.0
5	20	2.5	3.5	165.3	0.0235	2.5	7.8
10	20	1.5	2.5	166.9	0.0169	1.5	4.7
56	20	1	2	167.8	0.0071	1	3.1
123	20	0.5	1.5	168.6	0.0048	0.5	1.6
294	20	0	1	169.4	0.0031	0	0.0
1262	20	0	1	169.4	0.0015	0	0.0



Crumb Test

Medium	Crumb of condition	Time	Sample #											
			ZT114	ZB114	COED1	KNP1	ND309	13O1	13O2	13O3	N2S1	N2S2	SENJ1	UM108
Distilled Water	**Air dried**	**10 min**	4	3	2	1	2	1	1	3	1	1	4	1
		2 hrs	4	4	2	1	1	1	1	1	1	1	4	1
		16 hrs	4	4	1	1	1	1	1	1	1	1	4	1
	Oven dried	**10 min**	4	2	3	1	1	1	1	2	3	3	4	2
		2 hrs	4	4	1	1	1	1	1	1	2	2	4	1
		16 hrs	4	4	1	1	1	1	1	1	1	2	4	1
	Remoulded	**10 min**	4	4	3	3	2	1	1	1	1	3	4	4
		2 hrs	**4**	**4**	**2**	**3**	**1**	**1**	**1**	**1**	**2**	**2**	**4**	**4**
		16 hrs	4	4	2	2	1	1	1	1	2	1	4	2
0.001N NaOH	**Air dried**	**10 min**	3	2	3	2	1	2	1	2	1	2	4	1
		2 hrs	4	4	2	1	1	1	1	1	1	1	4	1
		16 hrs	4	4	1	1	1	1	1	1	1	1	4	1
	Oven dried	**10 min**	1	3	2	2	1	3	1	3	2	1	2	2
		2 hrs	3	3	2	1	1	2	1	3	1	1	3	2
		16 hrs	3	3	1	1	1	1	1	1	1	1	3	1
	Remoulded	**10 min**	4	4	3	2	2	3	1	4	3	3	4	4
		2 hrs	4	4	2	1	1	2	1	3	4	3	4	4
		16 hrs	4	4	2	1	1	1	1	2	3	2	4	3
Overall Best-fit classification			**4**	**4**	**2**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**4**	**2**

Chemical Analysis

Lab 1

EXCHANGEABLE CATIONS							
Sample #	**pH**	**Clay %**	**CEC (meq/100g soil)**	**CEC* (meq/100g clay)**	**Exch. Na$^+$ (meq/100g clay)**	**ESP 1 (meq/100g soil)**	**ESP 2 (meq/100g clay)**
13O1	5.37	0.15	4.39	29.27	0.16	3.67	0.55
13O2	5.40	0.59	9.98	16.91	0.09	0.87	0.51
13O3	6.21	0.26	2.75	10.56	0.11	3.90	1.01
N2S1	8.06	0.66	16.12	24.61	0.67	4.16	2.72
N2S2	8.67	0.56	16.23	28.99	3.22	19.86	11.12
SENJ1	8.96	0.30	11.71	39.71	2.62	22.33	6.59
KNP1	8.24	0.23	14.94	66.38	25.71	172.14	38.73
UM108	4.88	0.25	7.81	31.88	0.43	5.48	1.34
COED1	6.12	0.28	13.05	47.45	1.19	9.09	2.50
ZT114	9.44	0.32	14.80	46.24	8.54	57.72	18.47
ZB114	9.65	0.48	15.96	33.24	10.56	66.20	31.78
ND309	6.51	0.24	15.78	65.73	0.11	0.67	0.16

SATURATION EXTRACT CATIONS							
Sample #	**Ca^{2+} (meg/ℓ)**	**Mg^{2+} (meg/ℓ)**	**K$^+$ (meg/ℓ)**	**Na$^+$ (meg/ℓ)**	**TDS (meg/ℓ)**	**% Na**	**SAR**
13O1	0.13	0.31	0.13	0.95	1.52	62.74	2.03
13O2	0.03	0.10	0.06	0.28	0.47	58.94	1.09
13O3	0.03	0.07	0.04	0.45	0.59	75.68	2.00
N2S1	0.64	0.84	0.06	3.10	4.63	66.85	3.60
N2S2	1.40	1.98	0.07	24.09	27.55	87.47	18.53
SENJ1	0.16	0.13	0.08	6.16	6.52	94.41	16.17
KNP1	14.38	26.50	0.75	266.33	307.96	86.48	58.91
UM108	1.63	1.67	0.10	5.86	9.25	63.28	4.56
COED1	0.56	3.22	0.07	9.90	13.75	72.03	7.20
ZT114	0.39	0.23	0.11	50.72	51.45	98.58	91.09
ZB114	0.33	0.18	0.06	74.38	74.95	99.24	147.29
ND309	0.61	0.89	0.07	0.37	1.94	19.29	0.43

Lab 2

EXCHANGEABLE CATIONS							
Sample #	**pH**	**Clay %**	**CEC (meq/100g soil)**	**CEC* (meq/100g clay)**	**Exch. Na$^+$ (meq/100g clay)**	**ESP 1 (meq/100g soil)**	**ESP 2 (meq/100g clay)**
13O1	4.94	0.15	6.21	41.40	0.20	3.22	0.48
13O2	5.13	0.59	5.45	9.24	0.20	3.67	2.17
13O3	5.83	0.26	4.02	15.46	0.16	3.98	1.03
N2S1	6.99	0.66	12.94	19.76	0.84	6.49	4.25
N2S2	7.92	0.56	13.40	23.93	0.91	6.79	3.80
SENJ1	8.08	0.30	11.05	37.46	0.91	8.24	2.43
KNP1	8.02	0.23	13.10	58.22	0.90	6.87	1.55
UM108	4.16	0.25	6.07	24.78	0.29	4.78	1.17
COED1	5.50	0.28	14.66	53.31	0.90	6.14	1.69
ZT114	9.05	0.32	11.47	35.84	0.92	8.02	2.57
ZB114	9.42	0.48	13.48	28.08	0.91	6.75	3.24
ND309	6.07	0.24	18.50	77.08	0.21	1.14	0.27

SATURATION EXTRACT CATIONS							
Sample #	**Ca^{2+} (meg/ℓ)**	**Mg^{2+} (meg/ℓ)**	**K$^+$ (meg/ℓ)**	**Na$^+$ (meg/ℓ)**	**TDS (meg/ℓ)**	**% Na**	**SAR**
13O1	0.30	0.20	0.20	1.60	2.30	69.57	3.20
13O2	0.10	0.10	0.10	1.30	1.60	81.25	4.11
13O3	0.10	0.10	0.10	1.30	1.60	81.25	4.11
N2S1	0.80	0.50	0.20	7.20	8.70	82.76	8.93
N2S2	2.20	1.10	0.40	9.00	12.70	70.87	7.01
SENJ1	0.30	0.20	0.40	9.10	10.00	91.00	18.20
KNP1	1.90	1.50	1.00	9.10	13.50	67.41	6.98
UM108	2.40	1.00	0.30	4.00	7.70	51.95	3.07
COED1	0.20	0.80	0.30	8.60	9.90	86.87	12.16
ZT114	0.40	0.20	0.40	9.20	10.20	90.20	16.80
ZB114	0.80	0.10	0.60	9.10	10.60	85.85	13.57
ND309	1.50	1.10	0.30	2.90	5.80	50.00	2.54

Lab 3

EXCHANGEABLE CATIONS							
Sample #	**pH**	**Clay %**	**CEC (meq/100g soil)**	**CEC* (meq/100g clay)**	**Exch. Na^{+} (meq/100g clay)**	**ESP 1 (meq/100g soil)**	**ESP 2 (meq/100g clay)**
13O1	4.99	0.15	3.20	21.33	0.23	7.19	1.08
13O2	5.17	0.59	2.20	3.73	0.15	6.82	4.02
13O3	5.97	0.26	5.70	21.92	0.29	5.09	1.32
N2S1	7.44	0.66	15.10	23.05	1.01	6.69	4.38
N2S2	8.58	0.56	22.40	40.00	5.48	24.46	13.70
SENJ1	8.53	0.30	12.60	42.71	3.87	30.71	9.06
KNP1	8.47	0.23	18.10	80.44	22.70	125.41	28.22
UM108	4.65	0.25	2.40	9.80	0.32	13.33	3.27
COED1	6.16	0.28	14.60	53.09	1.77	12.12	3.33
ZT114	9.21	0.32	8.50	26.56	11.57	136.12	43.56
ZB114	9.45	0.48	15.90	33.13	14.70	92.45	44.38
ND309	6.47	0.24	15.90	66.25	0.28	1.76	0.42

SATURATION EXTRACT CATIONS							
Sample #	**Ca^{2+} (meg/ℓ)**	**Mg^{2+} (meg/ℓ)**	**K^{+} (meg/ℓ)**	**Na^{+} (meg/ℓ)**	**TDS (meg/ℓ)**	**% Na**	**SAR**
13O1	0.23	0.27	0.00	0.74	1.24	59.68	1.48
13O2	0.20	0.13	0.00	0.31	0.64	48.44	0.76
13O3	0.11	0.07	0.00	0.64	0.82	78.05	2.13
N2S1	0.63	0.67	0.00	3.01	4.31	69.84	3.73
N2S2	1.06	1.69	0.00	23.60	26.35	89.56	20.13
SENJ1	0.39	1.12	0.00	7.51	9.02	83.26	8.64
KNP1	8.11	13.81	0.00	264.30	286.22	92.34	79.83
UM108	1.36	1.85	0.00	3.14	6.35	49.45	2.48
COED1	0.56	3.22	0.07	9.90	13.75	72.03	7.20
ZT114	3.25	5.73	0.00	182.90	191.88	95.32	86.32
ZB114	0.83	0.55	0.00	62.10	63.48	97.83	74.76
ND309	0.36	1.33	0.00	6.54	8.23	79.47	7.11

Appendix B- Modified test methods used in the final study

a) Pinhole Test

General: In this test distilled water is caused to flow through a 1 mm diameter hole in a compacted specimen that is approximately 38 mm long under a controlled hydraulic head. The principle of the test is to simulate the action of water flowing through a crack/fissure and observe the reaction.

Apparatus:

- Pinhole test apparatus as shown in Figure 2-5 (Chapter 2) consisting of the following:
  - A cylindrical body (corrosion-resistant metal) of 100 mm in length and approximately 32 mm in diameter.
  - Corrosion-resistant end plates, one fitted with water inlet and standpipe connections, the other with an outlet connection.
  - O-ring seals to ensure watertight fit between the body and end plates
  - Four discs, of suitable diameter, of wire mesh having apertures of 1 mm (x 2) and 2 mm (x 2).
  - A nipple of plastic or corrosion-resistant metal, in the form of a truncated cone 13 mm long with a hole of 1.5 mm diameter.
- Corrosion resistant metal moulds to fit into cylinder at lengths of 12 mm and 50 mm for compaction process.
- A standpipe tube of glass or transparent plastic of approximately 3 mm internal diameter and 400 mm long.
- A scale for the standpipe tube marked in millimetres (mm).
- A hypodermic needle or similar, about 100 mm long, with an external diameter of 1 mm ± 0.1 mm.
- A burette stand to support the pinhole apparatus, standpipe and scale.
- A 1ℓ graduated glass measuring cylinder (measuring in 10 mℓ intervals).
- A stopwatch or timer, readable to 1 s.
- Pea gravel, consisting of single sized particles of about 5 mm diameter.
- A constant-head supply tank, adjustable between 50 mm and 400 mm above the centreline of the pinhole apparatus.
- A supply of distilled water for the constant-head tank.
- A test sieve, with 2 mm aperture.
- A balance readable to 0.1 g.
- A flat ended tamping rod.
- Apparatus for static compaction: Hydraulic press.
- Apparatus for the dry preparation of sample (Method: SANS 3001- GR2)
- Apparatus for the determination of Atterberg limits (Method: SANS 3001- GR12)
- Apparatus for the determination of apparent relative density (ARD) (Method: SANS 3001- AG20)

Sample preparation and assembly:

- Determine Atterberg limits of sample according to method SANS 3001- GR12.
- Determine ARD of sample according to method SANS 3001- AG20.
- Determine grading curve according to method SANS 3001- GR2.
- Calculate the predicted moisture-density relationship by using the following equations:

$$MDD\ (mod.AASHTO)(\%SD) = k_6.(GF)^{0.85} + k_7.C + k_8.(LS) + k_9.C^3 + k_{10} \quad (1)$$

$$OMC\ (mod.AASHTO)(\%) = k_{16}.(GF)^{0.85} + k_{17}.C + k_{18}.(LS) + k_{19}.C^3 + k_{20} \quad (2)$$

Where GF = Grading factor as defined in Equation (3)
C = (% passing the 0.425 mm sieve/100). $(LL/100)^{0.1}$
LL = Liquid limit
LS = Linear shrinkage
K_n = Regression coefficient (Table 1)

GF = Σ (percentage passing sieve size/normal sieve size (mm))/100 (for the 75 mm, 63 mm, 53 mm, 37.5 mm, 26.5 mm, 19 mm, 13.2 mm,, 4.75 mm, 2.00 mm sieve sizes) (3)

Table 1: Regression Coefficients by Semmelink (1991)

k_6	k_7	k_8	k_9	k_{10}	k_{16}	k_{17}	k_{18}	k_{19}	k_{20}
-33.7346	19.27655	-1.20764	-12.3063	99.93611	7.175719	0.346294	0.555493	2.861833	0.800098

$$MDD\ (kg/m3) = (\%SD / 100) \times ARD \quad (4)$$

$$MDD_P = 1.2\ (MDD_M) - 533 \quad (7)$$

$$OMC_P = 1.25\ (OMC_M) – 0.5 \quad (8)$$

where MDD_P = Proctor maximum dry density
MDD_M = modified AASHTO maximum dry density
OMC_P = Proctor optimum moisture content
OMC_M = modified AASHTO optimum moisture content

- Determine proportions of solid (air dried soil) and distilled water (OMC + 3.5%) at 95% of proctor density using predicted density and volume of compacted sample in cylinder (i.e.: Volume(V)=$\pi.r^2.h$, where r is the radius of the cylinder and h is the height/length o the compacted specimen: 0.038 m)
- Accurately weigh out air dried soil and distilled water and mix thoroughly- store in an airtight plastic bag and leave to cure overnight.
- To compact sample: Place 12 mm mould into cylinder. Lightly compact sample (with tamping rod) in 3 layers on top of 12 mm mould. Place 50 mm mould on top of lightly compacted sample and compact in a hydraulic press until mould is flush with the top of the cylinder. Remove moulds.
- To assemble cylinder: push nipple into the middle of the top end of sample (end with the 12 mm spacing) using finger pressure until the upper face is flush with the sample surface. Insert needle through the nipple and compacted sample. Place 1 mm wire mesh on sample surface followed by the pea gravel. Place 2 mm wires mesh over pea gravel and fit the end plate onto the cylinder (with water inlet and standpipe connections). Repeat this at the bottom end of cylinder fitting the end plate with the outlet connection to the cylinder.
- Support the apparatus in the burette stand with its cylindrical axis horizontal.
- Set constant-head reservoir of the distilled water supply so that water level can be maintained at a height of 50 ± 5 mm above centreline of the apparatus. Close inlet valve.

- Connect the inlet on the pinhole apparatus to the water supply from the reservoir and the standpipe connection to the standpipe, supported by the burette stand. Place the measuring cylinder under the outlet pipe.

Test Procedure:

- Open the inlet valve to allow water from the reservoir to enter the apparatus and flow through the sample. Start the stopwatch and observe and record the time taken to fill the cylinder in 10 mℓ intervals.
- If no flow occurs after 2 minutes, close the valve, dismantle the apparatus and re-punch the hole. Assemble the apparatus and start the test again.
- Observe and record the appearance of the effluent exiting the apparatus (i.e.: colour).
- At 50 mm head, run test for 5 minutes. If the effluent is visibly cloudy and does not become clearer with time, continue running the test for a total of 10 minutes. Unless the colour of the flow clears substantially, the test is complete. The hole should be increased to approximately 2 needle diameters and colloidal suspension should still be present after 1 hour. Classify the sample as highly dispersive (D1).
- If flow, at 50 mm of head, has slight but visible colour at the end of 5 minutes, continue for 10 minutes. If flow does not clear, stop test, set sample aside and observe effluent colour after 1 hour. If effluent is cloudy (colloidal suspension) after an hour, classify sample as dispersive (D2). Pinhole diameter after test should be slightly increased but this is not always the case.
- If flow at 50 mm of head is clear at the end of 5 minutes, raise head to 180 mm and continue test for another 5 minutes.
- If flow at 180 mm of head has colour and rate of flow increases, stop the test. Set effluent in cylinder aside for an hour and observe colour/ colloidal suspension after the hour. If effluent is cloudy (Presence of colloidal suspension), classify sample as moderately dispersive (MD1). If all particles settle after an hour with no colloidal suspension visible, classify sample as non-dispersive (ND1).
- If flow at 180 mm of head is clear after 5 minutes, continue test for 10 minutes. If flow is till clear after 10 minutes, stop test and classify sample at non-dispersive (ND2).
- NOTE: The principal differentiation between dispersive and non-dispersive soils is given by the test results under 50 mm of head. If the flow under 50 mm of head is visibly cloudy and does not clear with time, then the specimen is failing in the fashion typical of dispersive soils. The main indicator is the colloidal suspension of the effluent. All effluents should be kept aside for a period of 1 hour to determine the characteristics of the suspension. If the suspension settles at the end of an hour and no cloudiness is visible, then the sample is not dispersive but instead erodible. The recommended pinhole test for dispersiveness only classifies the soils based on the 50 mm and 180 mm constant head of flow. Any other increase in the constant head would results in the determination of erodible soils, which is not the primary objective of this test procedure.

b) Double Hydrometer

General: In this test the extent of natural dispersion of clay particles is compared with that obtained with the use of standard chemical and mechanical dispersion. A hydrometer sedimentation test is carried out on two identical soil samples, one with and one without the use of a chemical dispersant and mechanical agitation. The ratio between the clay fractions gives the measure of dispersivity of the clay. The requirements of SANS 3001-GR3, where appropriate, shall apply to this method.

Apparatus:

- The apparatus required for this method shall be the same as specified in SANS 3001-GR3:2012, except as follows:
    - Samples shall be air dried as described in SANS 3001-GR5.
    - Four 1000 mℓ glass cylinders are required.
    - Only one sieve is required: Aperture size 0.425 mm.
- Reagent: Sodium hexametaphosphate solution as specified in SANS 3001-GR3.
- Hydrometer apparatus shall be calibrated as specified in SANS 3001-GR3.

Sample preparation:

- Prepare two test specimens of equal mass from the fraction of air dried soil passing the 0.425 mm sieve, as described in SANS 3001-GR3.
- Designate specimens as follows:
    - Specimen A: To be tested with chemical dispersant and mechanical agitation as described in SANS 3001-GR3.
    - Specimen B: To be tested without chemical dispersant and mechanical agitation.

Test Procedure:

- Specimen A: Carry out the test as described in SANS 3001-GR3, with the exception of the “sieve analysis of the hydrometer material”.
- Specimen B: Add 200 mℓ of distilled water to the soil in the glass jar and agitate sufficiently to bring the soil into suspension. Do not shake vigorously or se mechanical shaking. Stirring with a glass rod should be sufficient. Allow to soak for at least 16 hours. After soaking period, gently stir material with a glass rod again to bring soil into suspension.
    - Transfer the suspension (slurry) to the cylinder and add distilled water until the total volume is 1000 mℓ.
    - Prepare a 1000 mℓ blank solution comprising only distilled water in a second cylinder.
    - Proceed with hydrometer sedimentation test as described in SANS 3001-GR3 except that the cylinder containing distilled water replaces the cylinder containing the dispersant solution.

NOTE: Although the readings allow for temperature corrections, it is best that the cylinders are placed in the temperature bath (20°C) for approximately 2 hours to gain equilibrium. Once the temperature of the material in the cylinder reaches 20°C, then the cylinder can be shaken as described in SANS 3001-GR3 and the hydrometer readings taken at the specified time intervals. The temperature of the material in the cylinder should still be recorded and corrections then applied if it does not remain at 20°C.

Calculations and plotting:

- Calculate the particle sizes and percentages passing as described in SANS 3001-GR3. (NB: The value of RB relates to the hydrometer reading in the dispersant solution for specimen A and in distilled water for specimen B).

- Draw the resulting particle size distribution (PSD) curves on a semi-logarithmic chart
- Determine the percentage of clay-size particles from the intercept of each curve with the 0.002 mm ordinate, denoted by P_A (with dispersant) and P_B (parallel)
- Calculate the Dispersion ratio/percentage as follows:

$$\% \, Dispersion = \frac{P_{\mathrm{B}}}{P_{\mathrm{A}}} \times 100$$

Where:

P_B is the percentage of clay without the dispersant (read off the PSD chart)
P_A is the percentage of clay with the dispersant (read off the PSD chart)

c) Crumb Test

General: In this test, dispersive soils are identified by observing the behaviour of a "crumb" (*in situ* or remoulded) of soil when placed in a beaker of distilled water without any disturbances.

Apparatus:

- A 100 mℓ glass beaker
- Distilled water
- Mortar and pestle for minor crushing
- A palette knife or spatula
- A flat glass plate, on which soil is mixed for remoulded samples

Sample preparation:

- If *in situ* samples are available, then intact crumbs with diameters of approximately 40 mm should be used for the test procedure.
- If soil is air dried, then remoulded crumbs should be prepared as follows:
    - Slightly crush the soil using the mortar and pestle to make it workable (without breaking down solid particles).
    - Transfer sample onto the glass plate and add sufficient distilled water till the soil sample is close to plastic limit. (Use the thread rolling procedure as described in SANS 3001- GR12 as an indication of the required consistency)
    - Prepare specimen to be tested by rolling the moist soil into spherical shaped crumbs, approximately 40 mm in diameter.

Test Procedure

- Fill beakers with distilled water to the half way point.
- Gently drop the prepared crumbs into the beaker making sure there is minimal disturbance in the water.
- Observed the reaction as the crumb starts to hydrate at time intervals of 10 minutes, 1 hour and 2 hours.
- The behaviour of the crumb at specified time intervals should be recorded in accordance with the following guidelines:

Grade	**Reaction**	**Description**
1	No reaction	Crumbs may slake, but no sign of cloudiness caused by colloids in suspension
2	Slight reaction	Bare hint of cloudiness in water at surface of crumb.
3	Moderate reaction	Easily recognisable cloud of colloids in suspension, usually spreading out in thin streaks on bottom of beaker.
4	Strong reaction	Colloid cloud covers nearly the whole bottom of the beaker, usually as a thick skin.

- Grades 1 and 2 represent a non-dispersive reaction and grades 3 an4 a dispersive reaction.

Appendix C- Proposed test methods for dispersive soil identification

a) Crumb Test

General: In this test, dispersive soils are identified by observing the behaviour of a “crumb” (*in situ* or remoulded) of soil when placed in a beaker of distilled water without any disturbances.

Apparatus:

- A 100 mℓ glass beaker
- Distilled water
- Mortar and pestle for minor crushing
- A palette knife or spatula
- A flat glass plate, on which soil is mixed for remoulded samples

Sample preparation:

- If *in situ* samples are available, then intact crumbs with diameters of approximately 40 mm should be used for the test procedure.
- If soil is air dried, then remoulded crumbs should be prepared as follows:
    - Slightly crush the soil using the mortar and pestle to make it workable (without breaking down solid particles).
    - Transfer sample onto the glass plate and add sufficient distilled water till the soil sample is close to plastic limit. (Use the thread rolling procedure as described in SANS 3001- GR12 as an indication of the required consistency)
    - Prepare specimen to be tested by rolling the moist soil into spherical shaped crumbs, approximately 40 mm in diameter.

Test Procedure

- Fill beakers with distilled water to the half way point.
- Gently drop the prepared crumbs into the beaker making sure there is minimal disturbance in the water.
- Observed the reaction as the crumb starts to hydrate at time intervals of 10 minutes, 1 hour and 2 hours.
- The behaviour of the crumb at specified time intervals should be recorded in accordance with the following guidelines:

Grade	**Reaction**	**Description**
1	No reaction	Crumbs may slake, but no sign of cloudiness caused by colloids in suspension
2	Strong reaction	Colloidal suspension evident in distilled water after 1 hour and still visible after 2 hours..

b) Double Hydrometer

General: In this test the extent of natural dispersion of clay particles is compared with that obtained with the use of standard chemical and mechanical dispersion. A hydrometer sedimentation test is carried out on two identical soil samples, one with and one without the use of a chemical dispersant and mechanical agitation. The ratio between the clay fractions gives the measure of dispersivity of the clay. The requirements of SANS 3001-GR3, where appropriate, shall apply to this method.

Apparatus:

- The apparatus required for this method shall be the same as specified in SANS 3001-GR3:2012, except as follows:
    - Samples shall be air dried as described in SANS 3001-GR5.
    - Four 1000 mℓ glass cylinders are required.
    - Only one sieve is required: Aperture size 0.425 mm.
- Reagent: Sodium hexametaphosphate solution as specified in SANS 3001-GR3.
- Hydrometer apparatus shall be calibrated as specified in SANS 3001-GR3.

Sample preparation:

- Prepare two test specimens of equal mass from the fraction of air dried soil passing the 0.425 mm sieve, as described in SANS 3001-GR3.
- Designate specimens as follows:
    - Specimen A: To be tested with chemical dispersant and mechanical agitation as described in SANS 3001-GR3.
    - Specimen B: To be tested without chemical dispersant and mechanical agitation.

Test Procedure:

- Specimen A: Carry out the test as described in SANS 3001-GR3, with the exception of the “sieve analysis of the hydrometer material”.
- Specimen B: Add 200 mℓ of distilled water to the soil in the glass jar and agitate sufficiently to bring the soil into suspension. Do not shake vigorously or se mechanical shaking. Stirring with a glass rod should be sufficient. Allow to soak for at least 16 hours. After soaking period, gently stir material with a glass rod again to bring soil into suspension.
    - Transfer the suspension (slurry) to the cylinder and add distilled water until the total volume is 1000 mℓ.
    - Prepare a 1000 mℓ blank solution comprising only distilled water in a second cylinder.
    - Proceed with hydrometer sedimentation test as described in SANS 3001-GR3 except that the cylinder containing distilled water replaces the cylinder containing the dispersant solution.

NOTE: Although the readings allow for temperature corrections, it is best that the cylinders are placed in the temperature bath (20°C) for approximately 2 hours to gain equilibrium. Once the temperature of the material in the cylinder reaches 20°C, then the cylinder can be shaken as described in SANS 3001-GR3 and the hydrometer readings taken at the specified time intervals. The temperature of the material in the cylinder should still be recorded and corrections then applied if it does not remain at 20°C.

Calculations and plotting:

- Calculate the particle sizes and percentages passing as described in SANS 3001-GR3. (NB: The value of RB relates to the hydrometer reading in the dispersant solution for specimen A and in distilled water for specimen B).

- Draw the resulting particle size distribution (PSD) curves on a semi-logarithmic chart
- Determine the percentage of clay-size particles from the intercept of each curve with the 0.002 mm ordinate, denoted by P_A (with dispersant) and P_B (parallel)
- Calculate the Dispersion ratio/percentage as follows:

$$\% \, Dispersion = \frac{P_{\mathrm{B}}}{P_{\mathrm{A}}} \times 100$$

Where:

P_B is the percentage of clay without the dispersant (read off the PSD chart)
P_A is the percentage of clay with the dispersant (read off the PSD chart)

c) Chemical analysis

I. pH (H_2O)

General: This procedure determines the pH of a soil in a 1:2.5 soil/water ratio suspension on a mass basis. By definition pH is the negative logarithm to base 10 of the H^+ ion activity. Due to the possible presence of soluble cations with a greater affinity for adsorption on exchange sites on the soil, adsorbed H^+ ions will be displaced from such sites, leading to a lowering of pH. Carbon dioxide will also lower the pH of calcareous soils and care must be taken to exclude CO_2.

Apparatus:

- A balance accurate to 0.1 g
- Beakers, 50 mℓ capacity
- Measuring cylinders or automatic dispenser, 25 mℓ
- Glass rods
- pH meter, readings reproducible to 0.05 pH units
- A combined glass-calomel electrode system or separate glass or calomel electrodes.
- Reagent: Buffer solutions- Use commercially available buffer solutions, pH = 4.0; 7.0 and 8.0

Test Procedure

- The pH meter is calibrated at a given constant temperature with commercially available standard buffer solutions.
- Re-calibrate hourly to compensate for drift.
- Place 10 g dried soil (≤ 2 mm) in a glass beaker
- Add 25 mℓ de-ionised water
- Stir the contents rapidly for 5 seconds with a glass rod
- Stir again after 50 minutes and allow to stand for 10 minutes.
- Determine pH after 30 seconds with the electrodes positioned in the supernatant.
- Results are reported as pH (H_2O).

II. Electrical conductivity and water soluble cations of the saturation extract

General: Electrical conductivity (EC) of the saturation extract is indicative of the total dissolved salts in the extract and therefore of soluble salts in the soil. The EC values are used to classify the salt hazard of brackish soils and to estimate the leaching requirements of brackish soils for reclamation purposes. EC values can be used to predict crop reduction as a result of high salt concentrations.

Sodium adsorption ratio (SAR) values are used to characterise brackish soils with regard to the reaction between sodium and calcium plus magnesium in the saturation extract. The sodium adsorption ratio value is used to determine whether high sodium content is likely to be physically detrimental to a soil.

Apparatus:

- A conductivity cell with a known cell constant of ± 1 cm^{-1}
- A conductivity bridge
- Buchner funnels, 100 mm in diameter or Richard's funnels
- Whatman no. 50 filter paper for Buchner or Richard's funnels
- Suitable test tubes for receiving filtrate
- Spatulas
- Suction flasks, 300 mℓ capacity
- Vacuum system
- Flame spectrophotometer
- Burette
- Plastic or porcelain dishes
- Reagents:
    - **Ammonia buffer, pH 10**: Dissolve 67.5 g ammonium chloride in 200 mℓ of de-ionised water. Add 570 mℓ concentrated ammonia solution and dilute to 1 ℓ with de-ionised water.
    - **Sodium hydroxide, pH 12**: Dissolve 200 g sodium hydroxide in 400 mℓ de-ionised water and dilute to 1 ℓ.
    - **EDTA solution, 0.01 mol/ℓ**: Prepare from commercially available standard solution. Standardise against standard solutions of calcium and magnesium respectively.
    - **Potassium cyanide, 1 % solution**: Dissolve 1 g KCN in 100 mℓ de-ionised water.
    - **Hydroxylamine solution, 5 %**: Dissolve 5 g hydroxylamine hydrochloride in 100 mℓ de-ionised water.
    - **Tri-ethanolamine (TEA)**: Dilute 1:1 with de-ionised water.
    - **Indicator, Ca**: Mix together in a mortar 0.2 g calcein, 0.12 g thymolphthalein and 20 g potassium chloride (AR).
    - **Indicator, Ca and Mg**: Dissolve 0.5 g methyl red in 300 mℓ ethyl alcohol and make up to 500 mℓ with de-ionised water.
      Dissolve 0.2 g Eriochrome Black T in 50 mℓ ethyl alcohol. The solution is stable for 3 weeks.

Sample preparation

Preparation of the saturated soil paste and saturation extract

- ***By Hand***:
  A 250 g air dried soil sample is placed in a suitable container and moistened with de-ionised water while mixing with a spatula. Consolidate the mixture from time to time by tapping the container on the work bench. Test for the properties of a saturated paste and add more de-ionised water if necessary. Allow to stand for atleast an hour and test whether it still has saturation properties. If left overnight, cover the container. Special care should be taken to ensure that the water does not collect

and that the paste does not dry out too much. Add more de-ionised water if required. If too much water is added, repeat the procedure. Note the total volume of water added.

- ***Properties of a saturated paste***
  In a saturated soil paste, all the pores are filled with water.
  It has the following characteristics: The surface is shiny; the paste flows slightly when the container is tilted; free water does not collect when a small trench is drawn on the surface and it does not cling to the spatula (with the exception of a clayey soil).
- ***By capillary saturation***
  Based on the method of Longenecker and Lyerly (1964), sample holders are prepared from Whatman no. 50 filter paper, 180 mm diameter. A 250 g air dried soil sample is transferred to each filter paper holder, which is then placed on sand (about 40 mm thick) in a plastic container with de-ionised water. The level of water is controlled to saturate the bottom 10 mm of sand. The sample is allowed to absorb water for 24 hours. The sample is then emptied into a plastic dish and carefully mixed to ensure even distribution of soluble salts. Before extraction of moisture, determine mass of soil and absorbed moisture. Soils high in sodium or clay do not saturate satisfactorily with this method and the hand method should be used.
- ***Preparation of saturation extract***
  Filter the soil paste by suction through Whatman no. 50 paper on a Buchner or Richard's funnel.
  Collect filtrate in a test tube placed under the funnel in the suction flask
  Repeat filtration if the solution is not clear
  Store filtrate in a plastic bottle with a drop of toluene added as a bacteriostat.

Determination

Determination of EC of the saturation extract

- Calibrate the conductivity cell with 0.01 mol/ℓ KCL solution. This solution has an electrical conductivity of 141.18 mS/m at 25°C.
  Rinse the conductivity cell with the saturation extract.
  Determine the conductivity of the saturation extract and calculate the electrical resistance from this value.
  Temperature control is necessary because conductance increases with temperature. Conductivity of the saturation extract is expressed in mS/m.

Determination of water soluble cations in the saturation extract

- ***Calcium***
  Take 5 mℓ of saturation extract and dilute to 100 mℓ
  Pipette a 20 mℓ aliquot of the diluted saturation extract in a 500 mℓ Erlenmeyer flask, add 2 mℓ sodium hydroxide solution, 1 mℓ TEA and calcium indicator. Titrate with 0.01 mol/ℓ of EDTA. The end point is indicated by a change of colour from pink-green to pink. Record the volume of EDTA titrated (**a** mℓ).
- ***Magnesium plus calcium***
  The procedure is the same as for calcium but use ammonia buffer solution (10 mℓ) instead of NaOH. Use 1.5 mℓ methyl red and 0.5 mℓ Eriochrome Black T as indicator. Titrate with 0.01 mol/ℓ of EDTA from purple to green. Record the volume of EDTA titrated (**b** mℓ).
- ***Sodium and potassium***
  Sodium and potassium are determined by flame emission spectroscopy against standard solutions prepared with de-ionised water.

Calculations

- ***Standardisation of EDTA***:
  Standardise the EDTA solution against standard solutions of calcium and magnesium respectively.

$$\text{Concentration of EDTA (mol/}\ell\text{)} = \frac{\text{Volume of Ca/Mg Standard (m}\ell\text{) x Concentration of Ca/Mg Standard (mol/}\ell\text{)}}{\text{Volume EDTA (m}\ell\text{)}}$$

- **Calcium**

$$\text{mg/kg of Ca in soil} = \frac{\mathbf{b} \times \mathbf{a} \times 40.08 \times w \times 1000}{20 \times 250} \times 20$$

$$\text{c mol (+)/kg Ca in soil} = \frac{\text{mg/kg of Ca in soil}}{20.04 \times 10}$$

$$\text{mg/}\ell\text{ Ca in Saturation extract} = \frac{\mathbf{b} \times \mathbf{a} \times 40.08 \times 1000}{w} \times 20$$

$$\text{m mol (+)/}\ell\text{ Ca in Saturation extract} = \frac{\text{mg/}\ell\text{ Ca in Saturation extract}}{20.04}$$

- **Magnesium**

$$\text{mg/kg of Mg in soil} = \frac{(\mathbf{c} - \mathbf{b}) \times \mathbf{a} \times 24.31 \times w \times 1000}{20 \times 250} \times 20$$

$$\text{c mol (+)/kg Mg in soil} = \frac{\text{mg/kg of Mg in soil}}{12.15 \times 10}$$

$$\text{mg/}\ell\text{ Mg in Saturation extract} = \frac{(\mathbf{c} - \mathbf{b}) \times \mathbf{a} \times 24.31 \times 1000}{w} \times 20$$

$$\text{m mol (+)/}\ell\text{ Mg in Saturation extract} = \frac{\text{mg/}\ell\text{ Mg in Saturation extract}}{12.15}$$

- **Potassium and Sodium**
  Let the concentration of K/Na be **k** mg/ℓ as read from the calibration curve:

$$\text{mg/kg of Na/K in soil} = \frac{\mathbf{k} \times \mathbf{w}}{250} \times 20$$

$$\text{m mol (+)/ℓ Na in Saturation extract} = \frac{\mathbf{k} \times 20}{22.99}$$

$$\text{c mol (+)/kg Na in soil} = \frac{\text{mg/kg of Na in soil}}{22.99 \times 10}$$

$$\text{c mol (+)/kg K in soil} = \frac{\text{mg/kg of K in soil}}{39.1 \times 10}$$

Where: a = Volume (mℓ) of EDTA used in Ca Titration
b = Volume (mℓ) of EDTA used in Mg + Ca titration
c = Concentration of EDTA (mol/ℓ)
w = Volume (mℓ) of water absorbed by 250 g soil.

- **Calculation of saturation percentage**

$$\text{\% Saturation} = \frac{\mathbf{w} \times 100}{250}$$

- **Calculation of Sodium Adsorption Ratio**

$$SAR = \frac{Na}{\sqrt{0.5\,(Ca + Mg)}}$$

Where: Ca, Mg and Na are expressed as m mol (+)/ℓ.

III. Cation Exchange Capacity (CEC) and Exchangeable plus water soluble cations: Ammonium Acetate (1 mol/ℓ, pH 7)

General: An ammonium acetate solution (1 mol/ℓ) serves as extractant for exchangeable plus water soluble cations (Schollenberger & Simon, 1945). The maximum exchange occurs in a few minutes.

In the presence of free lime and gypsum, the most questionable cations extracted with this method are Ca2+ and Mg2+. In the case of soils containing free lime or gypsum, this method should not be used if accurate results for exchangeable Ca2+ and Mg2+ or CEC are required. The level of extractable potassium may increase on drying of some soils. However, soil samples can be extracted in a moist state.

The water soluble cations are determined separately in soils containing significant quantities (resistance < 460 ohms) of soluble salts. These are subtracted from extractable cations to obtain the exchangeable cations.

After the exchange complex has been saturated with the index cation, the adsorbed cation and the small amount of solution entrained by the soil after centrifuge can be directly displaced by another salt solution, such as potassium chloride. Ammonia is separated by steam distillation (Bremner & Keeney, 1965) and is taken as equal to the CEC of the soil.

Apparatus:

- Centrifuge
- Reciprocating shaker- 180 oscillations per minute
- Balance accurate to 0.05 g
- pH meter
- Plastic containers, various volumetric flasks, beakers, pipettes, centrifuge tubes and Erlenmeyer flasks
- Flame photometer
- Atomic absorption spectrophotometer
- Steam distillation unit
- Vortex mixer
- Reagents:
    - **Ammonium acetate, 1 mol/ℓ, pH 7:** Dilute 114 mℓ glacial acetic acid (AR) with de-ionised water to about 1 ℓ. Add 138 mℓ concentrated ammonia solution and de-ionised water to a volume of 1980 mℓ. Adjust pH to 7 by adding more ammonia solution if necessary. Make final solution up to 2 ℓ with de-ionised water.
    - **Ammonium acetate, 0.1 mol/ℓ:** Dilute the 1 mol/ ℓ solution ten times with de-ionised water.
    - **Potassium chloride, 1 mol/ℓ**: Dilute 74.4 g KCl (AR) in 1 ℓ de-ionised water.
    - **Potassium standard and working standards**: From commercially available sources make up a standard in de-ionised water containing 1000 mg/ℓ K. Prepare working standards in 1 mol/ℓ ammonium acetate (pH 7) to cover a range of 0 to 10 mg/ℓ K.
    - **Sodium standard and working standards**: From commercially available sources make up a standard in de-ionised water containing 1000 mg/ℓ Na. Prepare working standards ranging from 1 to 10 mg/ℓ Na in 1 mol/ℓ ammonium acetate.
    - **Lanthanum chloride solution**: Add 500 mℓ de-ionised water to 9.4 g La_2O_3 in a 1 ℓ flask. While swirling, slowly add 40 mℓ concentrated hydrochloric acid. Mix well to dissolve oxide before making up to volume with de-ionised water. Filter if necessary.
    - **Calcium and magnesium standards**: Prepare working standards from commercially available stock, ranging from 1 to 5 mg/ℓ Ca and Mg. Use 1 mol/ℓ ammonium acetate solution (pH 7) in the same proportion as the samples to prepare working standards.

    - **Boric acid indicator solution**: Dissolve 20 g boric acid (AR) in about 700 mℓ hot water and transfer the cooled solution to a 1 ℓ volumetric flask containing 200 mℓ ethanol (95%) and 20 mℓ mixed indicator solution, prepared by dissolving 0.330 g bromocresol green and 0.165 g methyl red in 500 mℓ ethanol (95%). After mixing contents of the flask, add about 0.05 mℓ 1 mol/ℓ NaOH carefully until indicator colour changes from pink to pale green when 1 mℓ solution is treated with 1 mℓ water. Make up to 1 ℓ with de-ionised water.
    - **Sulphuric acid**: 0.05 mol/ℓ, standardised
    - **Magnesium oxide**: Heavy (AR).

Test Procedure

Extraction

- Place 10 g air-dry, ≤ 2 mm soil in a 100 mℓ centrifuge tube, stopper and determine the mass of the tube and soil (**X_1** g)
- Add 50 mℓ 1 mol/ℓ ammonium acetate solution and shake horizontally for 60 minutes.
- Remove samples from shaker and leave overnight.
- Centrifuge at 2000 to 5000 rpm to obtain a clear supernatant solution (about 10 minutes).
- Decant supernatant liquid as completely as possible into a 100 mℓ volumetric flask, without losing any soil.
- Again add 50 mℓ 1 mol/ℓ ammonium acetate solution to the soil and shake tubes well by hand to ensure that the soil is dispersed properly (use a vortex mixer if necessary)
- Place tubes on shaker for 30 minutes, centrifuge and decant clear solution in the same 100 mℓ volumetric flask. Make up to volume with ammonium acetate solution, filter and keep this solution for the determination of Ca, Mg, Na and K (solution **A**)
- Add 50 mℓ 0.1 mol/ℓ ammonium acetate solution to the soil in the centrifuge tube. Shake for 30 minutes ensuring that the soil has dispersed properly. Centrifuge as before. Decant clear supernatant solution into a plastic storing bottle for the determination of NH_4^+ in the occluded solution (solution **B**). Stopper centrifuge tube and determine mass of centrifuge tube plus soil and occluded solution (**X_2** g).
- Finally add 50 mℓ KCl solution (1 mol/ℓ) to the soil in the centrifuge tube, shake for 30 minutes as described, centrifuge and decant supernatant solution into a 200 mℓ volumetric flask. Repeat operation with a second aliquot of 50 mℓ of KCl solution, again ensuring that the soil is dispersed properly. Fill the volumetric flask to volume with 1 mol/ℓ KCl solution (solution **C**).

Determination

- **CEC**
    - Add 10 mℓ boric acid indicator solution to a 100 mℓ Erlenmeyer flask marked to indicate a volume of 50 mℓ.
    - Place the flask under the exit of the condenser of the steam distillation apparatus
    - In separate distillations, pipette 5 mℓ of the ammonium acetate solution (solution **B**) or 10 mℓ of the KCl extract (solution **C**) into the distillation flasks. Increase the volume to about 20 mℓ with de-ionised water. Ass 1 teaspoon (2.5 mℓ) heavy MgO through a dry funnel into the bulb of the flask.
    - Connect the distillation flask without delay to the steam generator and distil to a volume of ±50 mℓ in the flask containing the boric acid indicator.
    - Stop distillation by opening the stopcock on the steam by-pass tube and then remove the distillation flask.
    - Rinse the exit tube of the condenser
    - Determine NH_4^+ by titrating with 0.05 mol/ℓ sulphuric acid

  - The colour change at the end point is from green to a permanent faint pink.
- **Calcium and magnesium**
  - Pipette 5 mℓ ammonium acetate extract of the soil into a 200 mℓ volumetric flask. Add 10 mℓ La-solution and 10 mℓ 6 mol/ℓ HCl to dissolve any precipitate. Make up to volume with de-ionised water. Mix well and filter if necessary.
  - Determine Ca and Mg on an atomic absorption spectrophotometer.
- **Potassium and sodium**
  - The wavelength of the spectral line used for determining potassium is 766.5 nm on the atomic absorption spectrophotometer.
  - The most usable emission spectra for sodium analysis are the 589.0 and 589.6 nm lines. All alkali metals are easily excited by a flame. To reduce interference, a low (cold) flame is recommended.
  - Alternatively, a flame photometer can be used if the matrix of the sample and the standards are matched.

Calculations

Cation exchange capacity

$$\text{CEC} \quad = \quad (T_1 \times 20) - (X_2 - X_1) \times 0.2 \times T_2 \, \text{cmol(+)/kg}$$

Where: T_1 = Titration value for KCl solution

T_2 = Titration value for ammonium acetate solution

X_1 = Mass of tube plus soil (g)

X_2 = Mass of tube plus occluded solution (g)

Calcium and magnesium

10 g soil is extracted with 100 mℓ ammonium acetate and 5 mℓ of this solution is subsequently diluted to 200 mℓ.

Let Ca/Mg concentration in this solution be **s** mg/ℓ, then

$$\text{Ca/Mg in soil (mg/kg)} \quad = \quad \frac{\mathbf{s} \times 100 \times 40}{10\ \text{(g)}}$$

Potassium and sodium

10 g soil is extracted with 100 mℓ extractant

Let Na/K concentration of the extract be **n** mg/ℓ, then

$$\text{Na/K in soil (mg/kg)} \quad = \quad \frac{\mathbf{n} \times 100}{10\ \text{(g)}}$$

Cations

Let concentration in original (solution **A**) be a mg/ℓ, then

$$\text{Cmol (+)/kg Ca} = \frac{\mathbf{a}}{20.04}$$

$$\text{Cmol (+)/kg Mg} = \frac{\mathbf{a}}{12.16}$$

$$\text{Cmol (+)/kg K} = \frac{\mathbf{a}}{39.10}$$

$$\text{Cmol (+)/kg Na} = \frac{\mathbf{a}}{22.99}$$