An analysis of the factors influencing the relationship between soil properties and optimum moisture content and the formulation of an abbreviated test method of determining maximum dry density.

by

ANTHONY JAMES ALLINSON

Dissertation submitted in compliance with the requirements

for the

Masters Degree in Technology:

Civil Engineering:Road & Transport

in the

Department of Civil Engineering and Surveying

at the

Technikon Natal

Date of Submission 27 March 1997

DECLARATION:
I declare that this dissertation represents my own work.

A J ALLINSON

APPROVED FOR FINAL SUBMISSION.

..................................DATE. 1997-03-27
Dr D J Coertze DSc(PUCHO), MBL(UNISA), Pr.Sci.N.
SUPERVISOR

..................................DATE. 1997-03-27
Dr D L WEBB, Pr Eng, BSc(Eng)(Rand), PhD(Eng)(London)
SUPERVISOR

SUPERVISORS

Dr D L Webb, Pr.Eng, BSc(Eng)(Rand), PhD(Eng)(London)

D L Webb & Associates, Durban, South Africa.

Dr D Coertze, DSc(PUCHO), MBL(UNISA), Pr.Sci.N.

Centre for Enterprise Development, Technikon Natal, Durban, South Africa.

SUMMARY

The strength and durability of any soil structure is dependent on the quality of the compaction of the soil. This quality is measured by employing a standard compaction test, which provides a standard with which density may be compared, called the maximum dry density, and the moisture content of the soil at which this is achieved, called the optimum moisture content. As a matter of routine during quality control, the particle size distribution, plasticity index and liquid limit of the soil are determined at the same time as its maximum dry density and optimum moisture content.

The determination of maximum dry density and optimum moisture content requires considerable time and effort. The objective of this study is to use the particle size distribution, plasticity index and liquid limit, and other values derived from these to estimate the optimum moisture content of the soil sufficiently accurately and consistently to enable the standard test method to be abbreviated to the compaction of a single specimen.

An analysis was made of about 5000 soil test results of maximum dry density, optimum moisture content, particle size distribution, plasticity index and liquid limit. These results were obtained from the Kwazulu Natal Provincial Administration Roads Branch, and were representative of the geographical area of Kwazulu Natal and all the major soil types and geological formations present in the province. The analysis included a variety of different models for

estimating optimum moisture content. The models used showed correlations that were statistically significant in almost all cases, and it was concluded that the optimum moisture content showed a real correlation with the particle size distribution and plasticity parameters.

The analysis also showed that the models used explained only a small proportion of the variance present in the results. Consequently the confidence intervals for the prediction of optimum moisture were large relative to the interval within which a predicted optimum moisture content would have to lie in order for it to be sufficiently precise to obtain an accurate measurement of maximum dry density by compacting a single specimen at that moisture content. It was concluded that particle size distribution and plasticity characteristics provided insufficient information to permit the accurate estimation of an optimum moisture content on their own, and thus it was not possible to design an abbreviated test based solely on these characteristics. This conclusion may be extended to other soil properties that depend on the state of compaction of the soil.

Although this result appears to be negative, it is nonetheless valid, and may be regarded as valuable because the use of particle size and plasticity parameters to estimate soil compaction characteristics has been proposed previously. This study allows a quantitive measure of the precision of the estimates to be stated.

The confidence limits for the prediction of average optimum moisture content of various groups of soils were relatively small, and a number of equations are presented that can be used to estimate average optimum moisture content to a known degree of accuracy.

ACKNOWLEDGEMENTS

I wish to express my sincere thanks to the following for their generous assistance.

The Executive Director of Roads, Kwazulu Natal Provincial Administration Roads Branch, and in particular Mr R F Ashworth, for permission to use materials test data, and Messrs T W McKune, B C Honey and S Pienaar for kindly assisting me and making me welcome whilst I was collecting data.

My Supervisors, Dr D L Webb and Dr D Coertze, for their energetic, enthusiastic, knowledgable and competent assistance, without which I would not have been able to complete this undertaking.

The Head of Department of Civil Engineering and Surveying, Mr T W McKune, and the former Head of Department of Civil Engineering and Surveying, Mr K E Tarbett, for their encouragement, assistance, and above all patience.

My family, for their unfailing support, abundant encouragement and patience.

To my daughter

Maria

whose encouragement was constant

Contents

Figures

Tables

Chapter 1

THE PROBLEM AND ITS SETTING

1.1 Introduction

Roads, fills, earth dams and other structures are constructed from soil which is compacted using various types of compaction equipment such as rollers, vibrators and tampers. The strength and durability of the structure will depend on the quality of the compaction. In order to assess the quality, the engineer measures the density of the soil and compares it with the density obtained from a laboratory compaction test. The comparison is measured by the ratio of the density of the compacted material to the density obtained from the laboratory test, expressed as a percentage.

The method of carrying out the test has been standardized by a number of bodies, notably the American Association of State Highway and Transport Officials (AASHTO). Many countries have established their own standard method to suit local conditions, but most are derivatives of either the AASHTO standard or the Proctor method. In South Africa, National Institute for Transport and Road Research Method A7 (TMH1 1986) is widely used. Method A7 permits both Mod AASHTO and standard Proctor compactive efforts to be used, some others. Two parameters are obtained from the test, namely the optimum moisture content and the maximum dry density. The maximum dry density is the maximum density to which the soil can be compacted under the conditions of the test, and the optimum moisture content is the moisture content of the soil, expressed as a percentage of soil solids by mass, at which this density is achieved. The parameters are established by compacting at least five specimens of soil, each at a different moisture content, using a standard compactive effort in a mould of standard dimensions. The density of each specimen is plotted against its moisture content, thus defining a continuous curve from which the maximum dry density and the optimum moisture content can be obtained.

The degree to which the soil constituting an earth structure must be compacted is almost always specified as a percentage of the maximum dry density obtained from the laboratory test, and generally forms a part of the contract. For this reason, the control of compaction requires many laboratory tests to be carried out, both by the contractor to determine whether he has compacted the soil sufficiently, and by the engineer in charge of the work in order to accept or to reject the quality of the compaction and to document compliance with the specifications. Each compaction test entails a substantial expenditure of labour and time, so a reduction in the time and effort required to carry out the test could result in more economical compaction control.

In principle, it has been found possible to relate optimum moisture content and certain other basic soil properties, such as plasticity and clay content, some of which are carried out as a routine check of the quality of the material. If relationships could be found that would enable the optimum moisture content to be predicted within sufficiently narrow limits, it would be possible to reduce the number of soil specimens required to obtain the maximum dry density. If it were possible to predict the optimum moisture content so that the predicted value fell within the range of repeatability of the standard test, then it would be necessary to compact only a single specimen of soil to measure the maximum dry density. Taken further, if more were known about the moisture density curves themselves it might be possible to predict the entire moisture density curve. At the very least, the predicted optimum moisture content would provide a starting point for the test that could be expected, in most cases, to be closer to the real optimum moisture content than the present method provides, and thus require fewer points to determine the true optimum moisture content.

Previous related studies (Hammond 1980, Hammond and Gyimah 1984) have given inconclusive and inconsistent results, have relied partly on parameters, such as clay content, that will not be considered in this study, and have not attempted to evaluate critically the "one-point method" that is the subject of these investigations. The maximum dry densities obtained using the "one-point method" quoted by Hammond (1980) are not consistent with those obtained from the standard test to a degree that would permit the "one-point method" to be used as a substitute for the standard method under South African conditions. The studies consider a limited range of soil types, and the samples were processed specifically for the purposes of the research. The following points indicate the importance of the proposed study in contrast to previous studies.

1. It will attempt to demonstrate the feasibility of using information based on basic soil properties to shorten the standard compaction test method.

2. The study will be based on a comprehensive range of soil types representative of those used in Kwazulu Natal. The results should therefore be valid within Kwazulu Natal, and also in other areas of South Africa which have soil types and conditions similar to those of Kwazulu Natal. The methods used in the study should be applicable even in those areas that do not have soils and conditions similar to those of Kwazulu Natal.

3. The relationships to be used in predicting optimum moisture content will be derived from those soil properties that are determined as a matter of routine in the control of compaction materials quality, and therefore no information other than that which is normally available will be required in order to be able to employ any methods of testing that result from this study.

4. The relationships to be used in predicting optimum moisture content will be based on tests carried out during routine compaction control in a variety of field laboratories, by a variety of technicians, operating under normal field conditions. The relationships thus obtained will therefore take account of the variation inherent in the normal operating environment, and the methods obtained from the study should be directly applicable to construction projects without having to transfer them from "laboratory environment" to "field environment".

5. The proposed study will attempt to evolve techniques to achieve an accuracy comparable with that of the standard test, and to indicate the conditions which are appropriate to its use, and those that are not.

1.2 Statement of the Problem

The purpose of this study is to analyse the factors influencing the relationship between soil properties used for classification and identification and optimum moisture content as defined by Method A7 of TMH1(1986), the Standard Methods of Testing Road Construction Materials, of specified soils used in construction for the purpose of formulating and evaluating an abbreviated method of determining maximum dry density.

1.3 Statement of the Sub-problems

1.3.1 First sub-problem

The first sub-problem is to analyse the factors influencing the relationship between soil properties used for classification and identification, and optimum moisture content in order to identify and quantify those that are most effective in predicting optimum moisture content.

1.3.2 Second sub-problem

The second sub-problem is to employ the most effective of the factors influencing the relationship between soil properties used for classification and identification, and optimum moisture content in order to formulate a test method of determining maximum dry density for comparison with the standard test in terms of accuracy and consistency.

1.3.3 Third sub-problem

The third sub-problem is to evaluate the test method in order to validate the use of the test method as an alternative to the standard test method of determining maximum dry density.

1.4 Hypotheses

1.4.1 First hypothesis

It is hypothesized that relationships exist between soil index properties and optimum moisture content that can be quantified so that optimum moisture content can be predicted from them, and that some will be more effective than others.

1.4.2 Second hypothesis

It is hypothesized that a test method for the determination of maximum dry density can be formulated that will be shorter than the standard method of test while producing results of comparable accuracy and consistency.

1.4.3 Third hypothesis

The third hypothesis is that the test method will determine maximum dry density with an accuracy and consistency that will make it an acceptable alternative to the standard method.

1.5 Assumptions

It is assumed that

1. The materials described by the data used in the study are representative of the road building materials used in Kwazulu Natal.

2. The testing of the materials from which the data was derived was consistent, controlled, and carried out according to TMH1 (1986).

1.6 Delimitations

The study will be limited to naturally occurring materials used in Kwazulu Natal by the Kwazulu Natal Provincial Administration Roads Branch for the construction of roads. Manufactured materials, such as ash, will not be considered. It is intended that all relevant information available from the Kwazulu Natal Provincial Administration Roads Branch should be used, except for data that does not meet the admissibility criteria. The objective of these limits is to obtain as representative and as comprehensive a set of data as possible, in order to make the results of the study generally valid. It is felt that by excluding other sources of data, such as local authorities, bias towards certain areas and particular materials will be avoided.

Only unstabilized materials, that is soils which do not contain any additives such as lime or cement, will be used in the investigation.

The only soil properties to be used in the statistical analysis will be those that are determined on a routine basis by the Kwazulu Natal Provincial Administration Roads Branch Laboratories during materials control, or parameters that can be calculated from these properties.

Properties of soils derived from soil tests will only be used if those test methods are standard test methods published in TMH1 (1986).

Chapter 2

REVIEW OF THE RELATED LITERATURE

Soil is used extensively in engineering both as a material on which other structures are founded, and as a construction material in its own right in structures such as roads, earth dams and embankments. Practically every structure is built on or in soil or rock, and soil or rock form at least a part of most structures (Brink 1979, p 23).

2.1 Review of literature related to the statement of the problem

2.1.1 Definition of soil

The three constituents of soil are solid particles, air and water. The soil particles may be arranged in different ways, but there will always be spaces, or voids, between the particles. The air, other gases such as water vapour, and water fill the voids. The soil particles are generally not of a uniform size, and they may consist of a variety of substances, with a diversity of physical and chemical properties. The various sizes of particles are usually not distributed uniformly throughout the soil. The smallest particles, consisting of clays and silts, and having dimensions in the range less than one micron to sixty microns, often form coatings around the larger particles and agglomerations of particles. The physical properties that are of importance in engineering are strength, compressibility, permeability, volume change, compactibility and frost susceptibility (Yong and Warkentin 1975, p2).

2.1.2 Classification of soil

Various systems exist for the the classification of soils for engineering purposes. The object of classification is to divide soils into groups having similar characteristics from which their engineering properties may be inferred. Amongst the systems for classification cited by D.O.E. Transport and Road Research Laboratory (U.K.) (1952, pp 66-88) are the Casagrande Classification System (p 66) which is based on soil type, index properties and particle size, the Revised U.S. Public Roads Administration (P.R) System of Classification (p 74), which is based on the same properties, and textural classifications, which are based exclusively on particle size distribution. The classification selected for use in this study is the AASHTO classification (AASHTO 1982), because it is directed towards the assessment of the suitability of soils for pavement subgrades (Carter and Bentley 1991, p21). Weinert (1980,p 150 ff) has developed a classification of Southern African road building materials, which places them into ten groups according to their potential durability and their technical properties, based on the quartz content of the material. The classification combines the materials into two major classes, Decomposing Rocks and Disintegrating Rocks, and a third, minor class, Special Groups of Rocks. There is a further group "soils" which may be regarded as a class of its own, and comprises pedogenic materials and soils. The quartz content may be derived from the lithological classification of the material or by observation, either in hand specimen or with the aid of a microscope. Brink (1979, p 33) states that the stratigraphic origin of the parent material of a residual soil may be used to predict, even if only at a broad level of generalisation, the distinctive engineering properties of that soil.

2.1.3 Compaction of Soil

It is unusual for soils in their natural state to exhibit sufficient strength and stability to make them capable of sustaining the loads generated by a structure of any significant size. To overcome this, either the structures have to be designed to apply a load that is within the bearing capacity of the soil, or the engineering properties of the soil must be improved. Since the earliest times, various methods including soil compaction have been employed to improve the engineering properties of soils. Weinert (1980, p 2) for example, mentions that the Babylonians used compacted soil, sun dried bricks and road surfacing consisting of dressed limestone and breccia bonded with asphalt in the construction of their roads over 2500 years ago.

Development of infrastructure, such as roads, railways, dams, embankments, airports, harbours, factories and housing, especially since 1920, has required the development, refinement and exploitation of technologies for the improvement of soil properties in an effective and economical way. One of the most widely used of these technologies is compaction. Compaction as defined in D.O.E. Transport and Road Research Laboratory (U.K.) (1952, p 154) is "the process whereby particles are constrained to pack more closely together through a reduction in the air voids, generally by mechanical means". It further states that the object of compacting a soil is to improve its properties, and in particular to increase its strength and bearing capacity, reduce its compressibility, and decrease its ability to absorb water.

Compaction was described extensively by R.R.Proctor in a series of four articles published in Engineering News Record in 1933, and in particular the effect of water on the process of compaction was first discussed in this series of articles. Akroyd (1957, p 157) has summarised this discussion. In order to make a soil compact, the compacting forces must overcome the friction existing between the particles of soil comprising the soil skeleton. The addition of water to a partly saturated, fine grained soil displaces some of the air in the voids and decreases the molecular attraction between adsorbed layers of water surrounding particles, having the effect of lubricating the particles. Thus, for any particular constant compactive effort, the addition of water to a partly saturated soil will result in a greater degree of compaction. This effect remains with the addition of more water until sufficient water has been added to fill the voids with the exception of a small amount of air that cannot be removed by the compaction process. The effect of adding more water after the voids have been filled is to cause the particles to move apart, thus reducing the density of the soil. The effect of adding moisture to a soil which is compacted using a constant compactive effort is to increase the density of the soil to a maximum and then to decrease the density. The density of the soil is expressed in terms of the unit mass of soil particles, and the maximum density that can be achieved using a given compactive effort is termed the maximum dry density, and the corresponding moisture content of the soil is called the optimum moisture content.

This series of articles also introduced the first laboratory compaction test, which is used to give a standard by which compaction of earthworks in the field may be judged. This test, with some minor modifications, is still in general use in one form or another, and is the basis on which most standard compaction tests have been specified, including those of the American Association of State Highway and Transportation Officials, the American Society for Testing Materials, the British Standards Association and the South African National Institute of Transport and Road Research Standard methods of testing road materials, described in TMH1 (1986, Method A7). The test method requires that a number of specimens be compacted using a standard compactive effort at varying moisture contents. The moisture content and density of the compacted specimens are measured and plotted in order to define the relationship between moisture content and dry density, from which the optimum moisture content and maximum dry density may be obtained.

It has been recognized that some highly permeable soils, such as clean gravels, uniformly graded and coarse clean sands do not exhibit a clear optimum moisture content (BS 1377:Part4:1990). Alternative methods employing vibration are available for testing this type of soil (BS 1377:Part4:1990) and TMH1 (1986, Method A11T). Method A11T is a tentative method, and Method A7 has been, and still is used extensively for cohesionless and free draining soils. The compaction test results acquired from the Kwazulu Natal Provincial Administration Roads Branch for use in this study were all obtained from tests carried out using TMH1 A7, including those from cohesionless soils.

The method can be tedious and time consuming (Hammond 1980) and this has led to various shortened methods having been proposed for determining maximum dry density both in the laboratory and in the field. Hammond draws attention to the disadvantages of elaborate testing procedures or complicated data processing associated with these methods, and goes on to propose a method which uses index properties to predict the optimum moisture content. A single specimen of soil is compacted at that moisture content to obtain the maximum dry density.

2.2 The first sub-problem

2.2.1 Introduction

The optimum moisture content and maximum dry density of a soil depend upon soil structure. Soil structure is the property of a soil that is responsible for the response of the soil to external forces, and includes the gradation and arrangement of soil particles, and the specific interaction developed between particles through associated electrical forces (Yong and Warkentin 1975,p 71). Two major types of soils may be distinguished, granular soils, in which inter-particle electrical forces are negligible, and clay soils, in which the inter-particle forces are significant. Natural soils very often are a mixture of granular and clay particles.

In granular soils, the maximum density and optimum moisture content are dependent on the packing of the particles, which in turn depends upon the particle size, the particle size distribution and the shape of the particles. It has been found that fine grained, uniformly graded granular soils tend to have a higher optimum moisture content than coarse grained, well graded soils (D.O.E. Transport and Road Research Laboratory (U.K.) 1985, p 159). Statistical studies of the relationship between particle size and optimum moisture content indicate that generally optimum moisture content is proportional to the amount of fine material present in the soil (Hammond 1980, Hammond and Gyimah 1984).

Hammond (1984) carried out a series of 10 tests on each of black cotton soil, laterite and micaceous soil, measuring percentage fines, plasticity index, plastic limit, liquid limit and linear shrinkage as independent variables, and optimum moisture content as the dependent variable. The correlation between optimum moisture content and percentage fines was positive, but unfortunately in a subsequent paper (Hammond and Gyimah 1984) some of the regression coefficients quoted for this study conflict with those published in the earlier paper, and since no explanation was offered confidence cannot be placed on their reliability. A second set of tests conducted to appraise statistically the methods proposed in the first study gave results that differed considerably from both sets of figures given for the first set of data, although in all cases the correlation was positive. Considerable scatter was exhibited by the results.

Yong & Warkentin (1975, p 72) show that it is possible to construct an ideal distribution of grain sizes to achieve optimum density, based on the interstices between larger particles being filled by smaller particles. One of the soil tests routinely carried out for the classification and identification of soils is the particle size distribution test, and part of the study to be carried out will be to investigate the effect of particle size, and the goodness of fit between actual and theoretical particle size distributions on optimum moisture content.

Clay particles in soils commonly do not occur singly but in groups known as fabric units (Yong and Warkentin 1975, p 82). The fabric units combine with each other, granular particles, voids and water to form the fabric of a clay soil. It has been found that clays compacted at moisture contents appreciably lower than the optimum moisture content exhibit a randomly oriented fabric, while increasing the water content reduces the randomness of the particle arrangement. The particle arrangement in a clay fabric is dominated by the nature and magnitude of forces originating from the soil and fabric units, and between soil and water. The inter-particle forces may be forces of repulsion or of attraction, and depend on the types of clay present, the amount of water in the soil, the size of the clay particles, the distance they are apart and the presence of granular particles. Compaction of a clay, and the optimum moisture content for compaction, is affected both by the rearrangement of the fabric units and the rearrangement of the individual clay particles composing the fabric units. However, none of these properties is measured directly during the routine testing of soil.

Soil index properties, namely liquid limit, plastic limit and plasticity index are measured as a matter of course for the identification and classification of soils. Rowlands (Rowlands 1984) has shown that the index properties, by plotting plasticity index versus liquid limit, can be used to assess the type of clay present, its activity (which is a function of the inter-particle forces) and to estimate the proportion of granular material composing the soil.

Hammond (1980) and Hammond and Gyimah (1984) show that there is a general increase of optimum moisture content associated with an increase in the values of the index properties, which is consistent with the way in which clay fabric affects the optimum moisture content, but the values given show considerable variation and some inconsistencies. A similar study, (Al-Khafaji 1979) conducted on clayey soils to assess their suitability for use in embankments in irrigation projects, shows the same trend of the optimum moisture content increasing with increase in the values of the index properties. Larger coefficients of correlation were obtained in this study than in those of Hammond and Hammond and Gyimah.

TMH1 (1986, p30) recommends approximating optimum moisture content by subtracting 2 from the Plastic Limit, corrected for the percentage passing the 0,425 mm sieve, to guard against obtaining a "false optimum" when compacting sandy and silty materials.

Semmelink (1991) evaluated the compactability of a variety of road building materials using a vibratory compaction table, and found that it was most significantly influenced by total grading, liquid limit, linear shrinkage, shaken bulk density and the physical shape of the individual particles expressed by a shape factor. He also presents a single model, based on multiple linear regression, that can be used to predict maximum dry density from the vibratory compaction test, the critical moisture content, the maximum dry density using mod AASHTO compactive effort, and optimum moisture content using mod AASHTO compactive effort. The parameters used in the model are based on the grading, Liquid Limit and Linear Shrinkage of the soils investigated.

Carter and Bentley (1991, pp 46 - 47) present ranges of values of optimum moisture content for various soil types using both the Unified and the AASHTO classification systems, and some relationships between optimum moisture content and plastic limit obtained by Morin and Todor (1977) for African and South American red tropical soils.

Brink (1979, p 19) has pointed out that the engineering properties of rock and soil are predictable, at least to some extent, from a knowledge of their geological origin and their stratigraphical classification. Weinert (1980, p 151) by contrast regards a relatively simple lithological classification based on quartz content, used in conjunction with a climatological classification of the area of origin as a practical method of predicting the engineering properties of rock and soil. This classification, for example, is able to predict the type of clay likely to be present in a soil (p 149). The two methods are in fact complementary. The work of these authors is quite sufficient justification for classifying and separating soils by both methods before applying any other methods for investigating the factors influencing the relationships between optimum moisture content and other soil properties.

2.2.2 Hammond (1980)

Hammond (1980) investigates a "one-point method" of carrying out the compaction test. The principle of the test is that the optimum moisture content of a soil is predicted using one or more of its index properties. The soil is then compacted at the predicted optimum moisture content to obtain the maximum dry density. Using the models shown in Table 2.1, he predicted the optimum moisture content, and obtained the corresponding compacted dry density. Each dry density was subtracted from the maximum dry density of the soil being tested, in order to evaluate the accuracy of the test. The procedure was applied to three types of soil. Four models were used for each soil type, and ten individual soil samples were used for each model.

Table 2.1: Models used by Hammond (1980) to predict optimum moisture content

$$OMC = a_0 + a_1 LL \tag{2.1}$$
$$OMC = a_0 + a_1 PI \tag{2.2}$$
$$OMC = a_0 + a_1 PL \tag{2.3}$$
$$OMC = a_0 + a_1 (\%\ Fines) \tag{2.4}$$
$$OMC = a_0 + a_1 (PI + LS) \tag{2.5}$$
$$OMC = a_0 + a_1 LS \tag{2.6}$$

OMC = the optimum moisture content
LL = liquid limit
PI = the plasticity index
PL = the plastic limit
LS = the linear shrinkage
% Fines was not defined by the author
a_0 and a_1 are coefficients, which vary with soil type.

Table 2.2 shows the average deviations between standard maximum dry density and dry density obtained from the "one-point" method.

Table 2.2: 95% confidence limits for the average deviation actual density - observed density as a percentage of actual density

Model No	Lateritic Soils	Micaceous Soils	Black Cotton Clays
1	-2,11 to +11,78	+2,26 to +5,35	
2	+4,23 to +9,47		
3	+4,31 to +10,51	+0,26 to +3,74	-1,49 to +3,83
4	+8,56 to +15,78	+0,78 to +2,86	+0,60 to +4,54
5		+1,24 to +4,47	+0,34 to +1,88
6			+0,07 to +2,55

The values in the table show the range within which the average deviation of a number of "one-point" tests would fall with a 95% probability. The deviations are expressed as a percentage of the maximum dry density obtained from the standard test method. A positive deviation indicates that the "one-point" method has underestimated the standard maximum dry density. For example, if a number of "one-point" tests were carried out on a micaceous soil using Model 3, it would be expected that the average "one-point" density would be between 99,74% and 96,26% of the standard maximum dry density, with a most likely density of 98% of standard maximum dry density.

Differences between the standard and "one-point" densities can be ascribed to two causes. Firstly, there is the normal error inherent in the standard test. D.O.E. Transport and Road Research Laboratory (U.K.) (1952, p 165) indicates that repetitions of the BS test do not differ by more than 1 lb per cubic foot (16 kg per cubic metre), when the results are reported to the nearest whole number, and the test is carefully done. Up to 1% of a difference between the two types of the test may therefore be expected from the reproducibility of the standard test, and result in either overestimate or underestimate.

Secondly, differences must arise due to the estimate of optimum moisture content differing from true optimum moisture content. This will result in the "one-point" method underestimating the maximum density, since compaction on either side of optimum will result in a density less than maximum. Some idea of the magnitude of error involved can be gained from Figure 2.1, which was constructed from one of the typical moisture-density curves exhibited in Figure 2 of the paper.

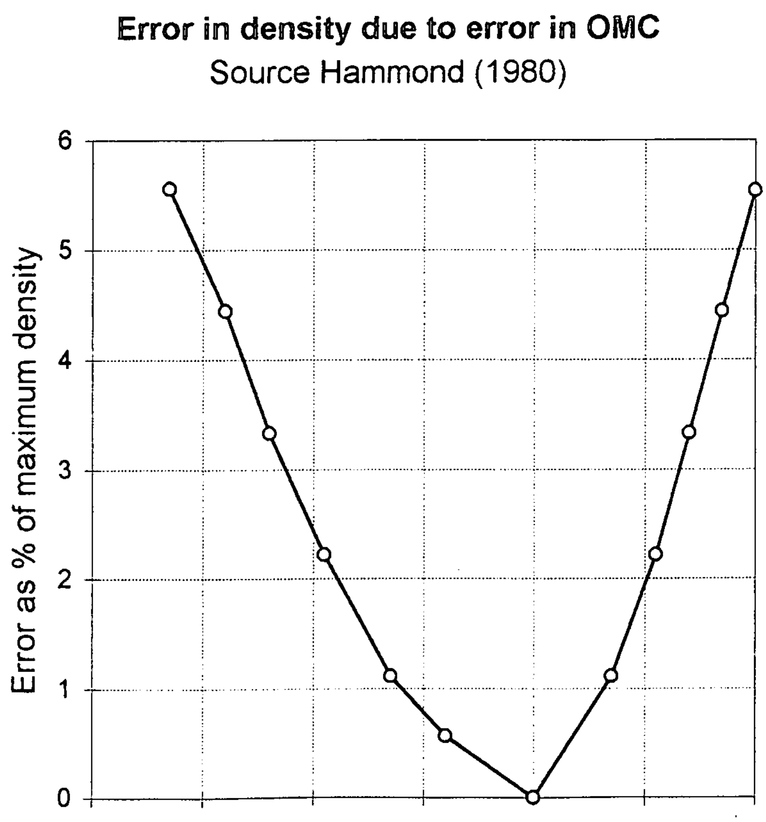


Figure 2.1: Error in Maximum Density resulting from compacting soil at varying moisture contents

The magnitude of error increases rapidly, especially on the wet side of the moisture-density curve. In this particular example, compacting the soil one percent wet of optimum results in an error of nearly two percent in density, while compacting two percent wet of optimum gives an error of nearly six percent in density. In order for the error in density to be one percent or less, the error in estimating optimum moisture content would need to be half a percentage point or less. This agrees more or less with the figure of one percent given as the repeatability of the optimum moisture content in the standard test quoted in D.O.E. Transport and Road Research Laboratory (U.K.)(1952, p 165). In order for the test to be viable as a substitute for the standard test, the optimum moisture content would need to be predicted to within one percent of the true value. In particular, it should be noted that the "one-point" method will tend to give lower densities than the standard test, and where used to approve compaction its use could lead to below standard compaction being approved. The values given in Table 2.2 indicate that it might be possible to achieve sufficient accuracy in predicting optimum moisture content, but that investigation would be required to determine how much variation of the results can be explained by variation in the soil properties. Suitable models also need to be devised and evaluated to minimise variation.

2.2.3 Hammond and Gyimah (1984)

This paper sets out to evaluate the "one-point" method described in Hammond (1980). Using the same three soil types as Hammond regression analyses were carried out on 150 new samples to determine the degree of correlation between optimum moisture content and the parameters used in the models shown in Table 2.1. The coefficients used in the models were recalculated using the new experimental data. The coefficients of correlation quoted in the paper ranged between 0,940 and 0,988. The 99% confidence interval of the population correlation coefficient corresponding to the correlation coefficient of a sample of 50 is 0,88 (lower limit) to 0,97 (upper limit) (Biometrika 1976, Table 15), indicating that the correlation is highly statistically significant. However, in two cases the gradients of the models do not differ significantly from zero, so that the variable concerned, the percentage of fines, would be of no help in predicting the optimum moisture content. The standard error of the mean, which is a measure of the dispersion of the observed values from the mean value obtained from the regression, varies from 1,58 to 5,44. This indicates that at best, 5% of the observed values would fall more than 3 percentage points from the mean value. Predicted values could be expected to show a similar, but possibly smaller spread. However the spread is rather larger than is desirable. Unfortunately, the authors do not investigate the implications of this spread on the accuracy of the "one-point" method, but do go on to say that on the whole the "one-point" method was found to be "statistically acceptable".

No results of multiple linear regression analyses are given in the paper, but the authors state that very poor multiple coefficients of determination were obtained. (The coefficient of determination is the square of the coefficient of correlation.) The use of multiple correlation may not be valid unless it can be shown that the variables used are linearly independent.

2.2.4 Al-Khafaji (1987)

This paper describes methods used to predict Proctor maximum density and optimum moisture content from liquid limit, or liquid limit and clay content in combination in order to select borrow areas of fill for use in irrigation canal embankments. Selection of borrow material requires that it be capable of being compacted to a minimum field dry density of 1,65 t/m^3. The author presents maximum values of liquid limit and clay content of soils that will compact to the minimum field dry density.

Simple linear regression equations were obtained which relate optimum moisture content to liquid limit and to clay content. These equations were then combined by addition to obtain an equation relating optimum moisture content to both liquid limit and clay content. This equation is not the same as a multiple linear regression equation. The equations are given in Table 2.3.

Table 2.3: Equations used to predict optimum moisture content by Al-Khafaji

		r
OMC = 8,7 + 0,26LL	(2.7)	0,85
OMC = 11,07 + 0,26C	(2.8)	0,7
OMC = 0,5 + 0,26(LL + C)	(2.9)	0,82*

OMC = the optimum moisture content
LL = the liquid limit
C = the clay content (%) of the soil
r = the coefficient of correlation
* calculated from results presented in the paper

It will be noticed that the coefficients of correlation are lower than those quoted by Hammond and Gyimah (1984). Nonetheless, they are all highly significant. The coefficient of correlation of Equation (2.9) is less than that of Equation (2.7). This shows that incorporating the clay content is not useful in predicting optimum moisture content, or that Equation (2.9) can be improved. To investigate this, regression analyses were carried out as shown in Table 2.4. A scatter diagram, showing the regression line obtained from Equation 2.10 is given in Figure 2.2.

Table 2.4: Regression analyses of data presented in Al-Khafaji (1987)

		r	se
OMC = 8,94 + 0,25LL	(2.10)	0,85	1,700
OMC = 8,76 + 0,24LL + 0,019C	(2.11)	0,84	1,705
OMC = 8,267 + 0,15(LL + C)	(2.12)	0,82	1,828

OMC = the optimum moisture content
LL = the liquid limit
C = the clay content (%) of the soil
r = the coefficient of correlation
se = the standard error of estimate

Equation (2.10) is essentially the same as Equation (2.7). Equation (2.11) takes into account both liquid limit and the clay content of the soil. The coefficient of correlation is not significantly different from that given for Equation (2.10), showing that incorporating clay content cannot improve the prediction of the optimum moisture content for this particular group of soils. The significance level of the coefficient corresponding to the clay content is 61%, well below 95%, which further confirms this conclusion. It is found that the differences between observed optimum moisture content and optimum moisture content calculated using Equation (2.11) range from 4,09% dry of optimum to 5,16% wet of optimum, about the same range (4,06% wet to 5,19% dry of optimum) as the differences found from using Equation (2.10). The differences between observed optimum moisture content and optimum moisture content obtained by using Equation (2.9) are in the range 6,82% wet of optimum to 6,18% dry of optimum. This is a much larger range than that obtained by using Equation (2.10) or Equation (2.7) and also shows that clay content should not be used in combination with liquid limit to predict optimum moisture content. This contradicts the conclusion made by Al-Khafaji. It is explained by the fact that the liquid limit is a measure of the amount of clay present in the soil (Rowlands 1984) and therefore the clay content is not independent of the liquid limit. This invalidates the use of a multiple linear regression incorporating these two variables, since using the liquid limit on its own takes into account the variability of the optimum moisture content due to the clay content.

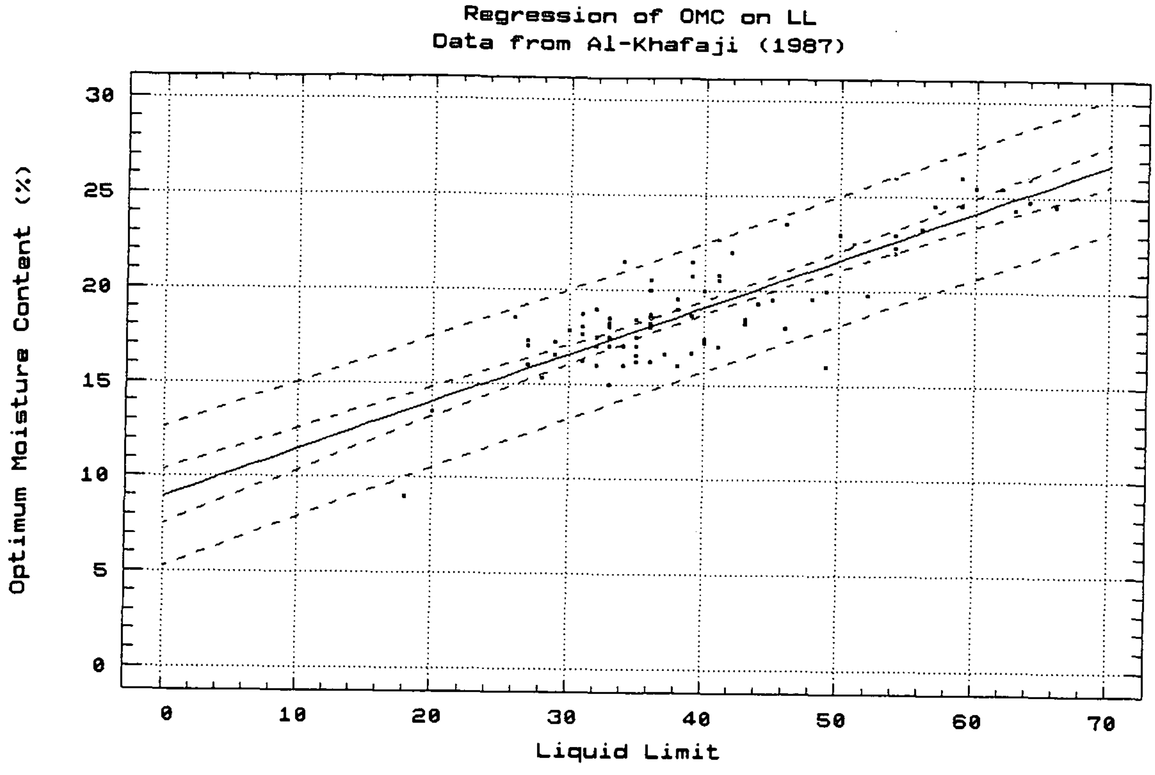


Figure 2.2: Linear regression of optimum moisture content vs liquid limit.

Equation (2.12) is of the same form as Equation (2.9), but the coefficients have been adjusted to minimise the squares. Both equations render the same coefficient of correlation, but the two equations would diverge significantly outside the range of optimum moisture content investigated.

Al-Khafaji also presents a number of moisture density curves, which gives the opportunity of assessing the error that would be encountered if the "one-point" method of Hammond (1980) were used. By predicting the optimum moisture content and reading the corresponding density from the appropriate moisture density curve, the difference between maximum dry density and the density that would be obtained from the "one-point" method if it were carried out perfectly was calculated for each of the twelve curves shown in the paper. The results appear in Figure 2.3.

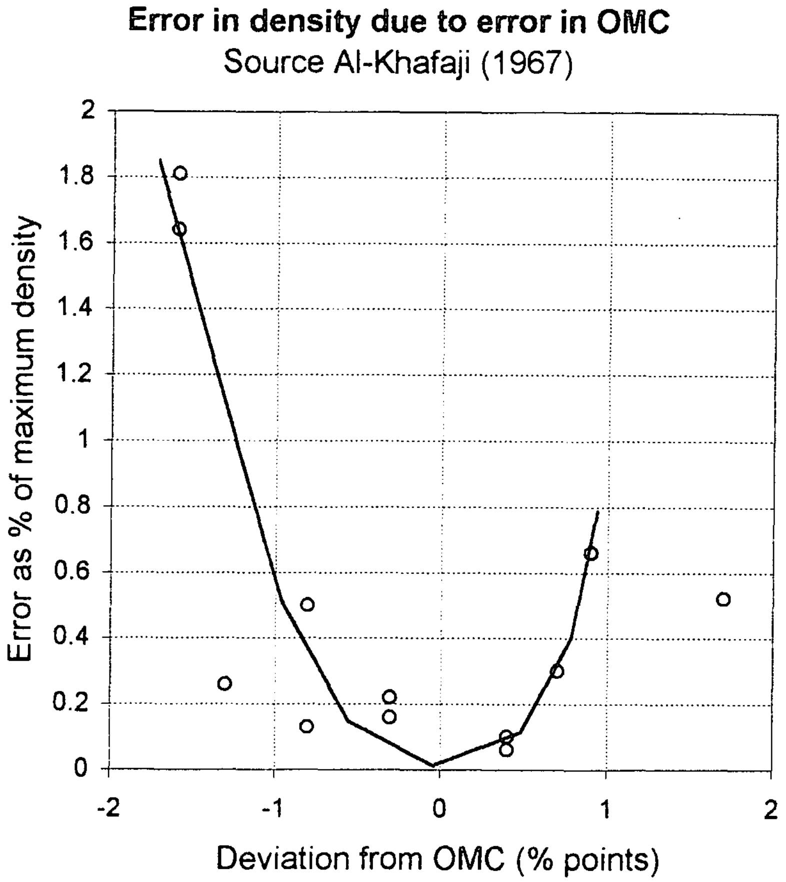


Figure 2.3: Error in density due to error in predicting optimum moisture content

It can be seen that once the predicted moisture content is more than one percentage point from the optimum, the concomitant error in density increases very rapidly. Within this range, however, errors in density are small in this instance. Since the standard errors of estimate are about 1,7 percentage points, the range within which 95% of predicted values would fall would certainly be greater than ±3% points. This is illustrated in Figure 2.2, where the outer dashed lines show the limits within which 95% of predicted values would fall, in this case a range of ±3,4% points.

2.2.5 Semmelink (1991)

Factors influencing the compactability of untreated roadbuilding materials are discussed in this paper. The author presents the following model (Equation 2.13) which, it is stated, is applicable to maximum dry density (vibratory), maximum dry density (Mod AASHTO), critical moisture content and optimum moisture content (Mod AASHTO).

$$X = a_0 + a_1(GF)^{0,85} + a_2A + a_3(LS) + a_4A^3 \qquad (2.13)$$

a_n = regression constant

X = maximum dry density (vibratory)

OR X = maximum dry density (Mod AASHTO)

OR X = critical moisture content

OR X = optimum moisture content (Mod AASHTO)

A = $(\%pass\ 0,425mm/100).(LL/100)^{0,1}$

GF = grading factor

LL = liquid limit

LS = linear shrinkage

The grading factor is expressed as

GF = Σ(% passing sieve size/nominal sieve size (mm))/100 for sieve sizes 75mm, 63mm, 53mm, 37,5mm, 26,5mm, 19mm, 13,2mm, 4,75mm and 2,00mm

When applied to a group of 21 soils to predict optimum moisture content, the coefficient of correlation between predicted and observed values was 0,955, a figure comparable to those achieved by Hammond and Gyimah (1984). No data was collected about linear shrinkage (which has been omitted from the latest (1986) version of TMH1). To test the equation on data collected for the present study, plasticity index was substituted for linear shrinkage, as linear shrinkage is widely regarded as being closely related to plasticity index. (Most local soil laboratories use the linear shrinkage as a check on plasticity index. The linear shrinkage of a soil is usually about half the numerical value of the plasticity index for soils commonly used in road construction). When applied to a random sample of 436 soils selected from the data used in the present investigation, the coefficient of correlation obtained was 0,548, and the 95% confidence limits for prediction were ±4,2% points. These limits are shown as dotted lines in the scatter diagram of predicted vs observed values of optimum moisture content shown in Figure 2.4.

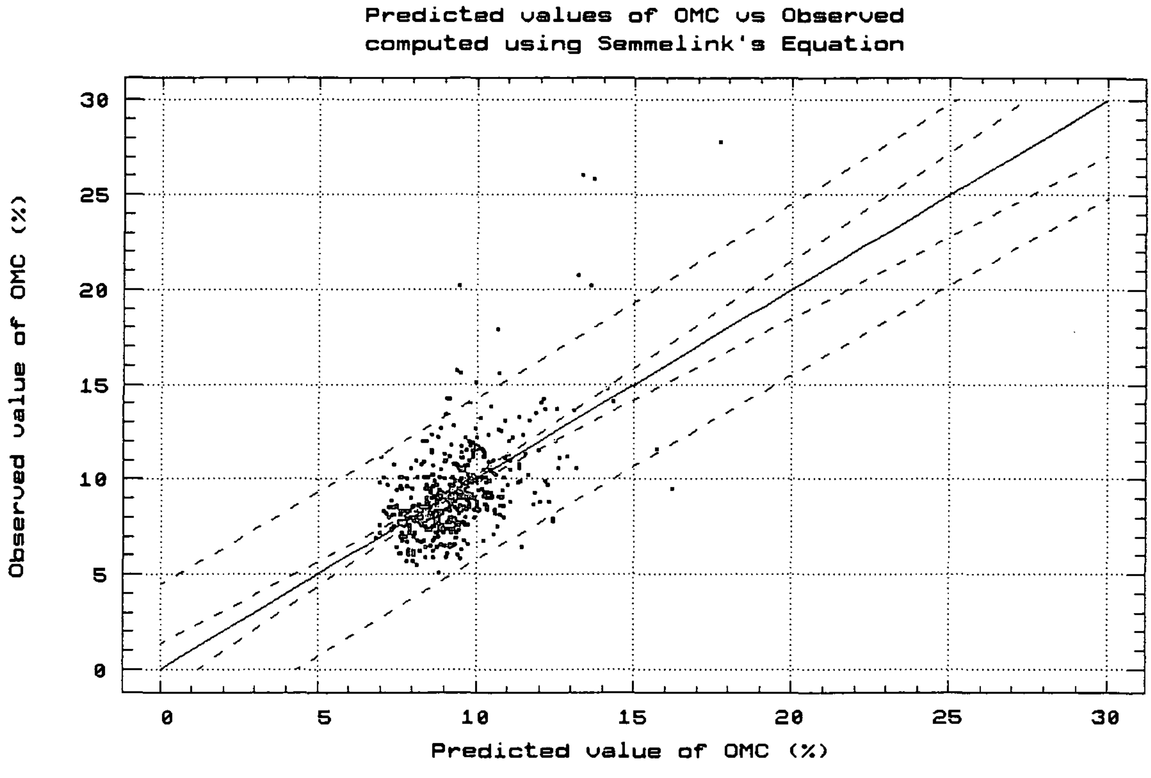


Figure 2.4: Relation between predicted optimum moisture content and observed optimum moisture content

The correlation was considerably less than that achieved by Semmelink. On investigating the individual components of the equation, it was found that only A and plasticity index made a significant contribution to the correlation coefficient. The equation was tested again on a sample of 780 granite soils obtained from data used in the present study, to see if a more homogeneous material would yield a higher coefficient of correlation. In this case the coefficient of correlation was 0,507, about the same magnitude as that of the first sample. However, in this instance the significant components were $GF^{0,85}$ and plasticity index, both A and A^3 being not significant. These inconsistencies can also be explained in that the variables in the multiple linear regression equation cannot be guaranteed to be linearly independent, as the regression procedure assumes. Multiple linear regression should therefore not be employed in the present study, since the set of variables being investigated cannot be guaranteed to be linearly independent.

2.2.6 Summary

Attempts have been made by a number of authors to develop methods of predicting optimum moisture content from a variety of variables. The key to refining the "one-point" method of compaction testing developed by Hammond (1980) is to find a method of predicting optimum moisture content consistently to within ±1% point of the true optimum. The important parameters in this regard are the 95% confidence limits for prediction. The results appearing in the surveyed literature are inconclusive. Some methods may possibly be capable of providing predictions sufficiently accurate to be of use, others obviously will not.

Statistical models should be restricted to simple linear regression models. Multiple linear regression models may give inconsistent results due to the impossibility of guaranteeing linear independence of the variables used. None of the results presented justify a non-linear model.

2.3 The second sub-problem

The second sub-problem requires the use of the most effective parameters which influence the relationship between optimum moisture content and other soil properties. There is little in the literature to indicate what the most effective factors might be. The studies of Hammond (1980) and Hammond and Gyimah (1984) are not conclusive in this regard, for reasons already discussed. Hammond and Gyimah note that the U.S. Corps of Engineers uses a correlation between liquid limit and Proctor maximum dry density and optimum moisture content. The study by Al-Khafaji (1979) indicates that liquid limit and clay content are likely to be among the more effective predictors of optimum moisture content.

It is interesting to note that Al-Khafaji (1979) proposes linear relationships between index properties and optimum moisture content, and between index properties and maximum dry density. This suggests that the development of a test method may not be necessary, given that the maximum dry density can be obtained from the index properties. Two reasons can be advanced for not adopting this approach. Firstly, if both optimum moisture content and maximum dry density were linearly dependent on index properties, then they would be linearly dependent on one another. This is inconsistent with the non linear relationship that exists between maximum dry density and optimum moisture content (D.O.E. Transport and Road Research Laboratory (U.K.) 1985, p 157) and can be illustrated by plotting density and moisture content obtained from Figure 13 on Figure 7 of Al-Khafaji (1979). Secondly, it is necessary to obtain as accurate a value of maximum dry density as possible, and this can only be determined by means of a physical test.

Semmelink (1991) evaluated the compactability of a variety of road building materials using a vibratory compaction table, and found that it was most significantly influenced by total grading, liquid limit, linear shrinkage, shaken bulk density and the physical shape of the individual particles expressed by a shape factor. Of these, only grading and liquid limit are being investigated, since they are the only tests routinely carried out that are standardized in TMH1 (1986).

2.4 The third sub-problem

The third sub-problem is to evaluate the test method. Hammond (1980) compares the results obtained from a proposed method of determining maximum density with the standard method by expressing the deviations of the proposed method from the standard method as a percentage of the standard method, but does not attempt to evaluate them further. Depending on the particular application, the minimum level of compaction of soil is set variously at 93%, 95%, 98% and 100% of Mod AASHTO. Any method that cannot discriminate between these is not likely to gain acceptance for compaction control, which is the main reason for carrying out compaction tests. The abbreviated test method therefore would be required to give results consistently within one percent of Mod AASHTO, and this in turn relies on optimum moisture content being consistently predicted to within at least one percentage point of optimum.

2.5 Summary

Soil compaction testing is an important and necessary part of the construction of many civil engineering projects. The methods currently used for the determination of the maximum dry density of a soil, as embodied in various standards, and in particular Method A7 of TMH1, were first developed over fifty years ago and have not changed in any major way since then. The method used is tedious and time consuming, and a shorter method would be of advantage to civil engineering construction. The thrust of this research is to apply knowledge about the soil which is obtained from routine testing to the standard test method in such a way that the test may be conducted using fewer test specimens, thus shortening the test. Certain fundamental soil properties are known to affect optimum moisture content and maximum dry density, and although these cannot be measured directly as a matter of routine, other properties can be used to estimate them indirectly and apply them to the estimation of optimum moisture content. Among these other properties are the index properties and particle size distribution. Soil can be compacted at the estimated optimum moisture content in order to estimate the maximum dry density, which is the parameter of greatest interest in compaction control. The accuracy with which the maximum dry density is estimated has to be comparable with the value obtained from the standard test for it to be of any use and this is of critical importance in the formulation of an alternative, abbreviated test method. Thus, part of the formulation of the method needs to be a set of criteria that can be used to judge the accuracy of any particular test, and to guide the test process to a more accurate estimate should the previous estimate not be sufficiently accurate. Although efforts have been made to formulate methods based on the estimation of optimum moisture content from other soil parameters, no systematic study has been carried out which describes and evaluates a method that is capable of giving results comparable in accuracy with the standard test.

Chapter 3

THE DATA FOR THE FIRST SUB-PROBLEM

3.1 Sources of Information

Data for this investigation was gathered in its entirety from the archives of the Kwazulu Natal Provincial Administration Roads Branch. The reasons for selecting this source of information, and for restricting the investigation to this information are

1. The information was comprehensive, covering a large portion of the province of Kwazulu Natal.

2. The information was available in a clear and consistent format that was easy to gather. This permitted other information to be inferred. For example, clear records of the sources of road building materials tested allowed the geological formations from which it was derived to be deduced.

3. The information in the archives had been generated by a number of personnel, both from the Kwazulu Natal Provincial Administration Roads Branch and from consultants, so that it would reflect the normal variation due to individual differences between technicians, yet it was consistent in the sense that

such variation is within limits acceptable in every day engineering practice.

4. The testing procedures were carried out according to the standards of TMH1 (TMH1 1986) or its predecessors, either in the laboratories of the Roads Branch or of consultants. Tests carried out by consultants were subject to check testing (Stephens 1988).

This information could thus be regarded as comprehensive and well distributed geographically, and homogeneous and of high standard with regard to quality, yet retaining that amount of variation due to individual differences of laboratory and technician that is regarded as acceptable in practice.

Other sources of data were considered but rejected because

1. The sources of data tended to be local, for example from a particular municipal area, or industrial project, and would therefore tend to give bias to particular areas.

2. There was the possibility of duplication of information.

3. There was the possibility of an unacceptable level of variation due to individual differences between laboratories and technicians.

3.2 Format of Data

The information required for this investigation was extracted from A1 size books of materials completion data. At the time the data was being collected, the books were being recorded on microfiche. The information contained in each book consisted of plans of the section of road constructed, records of fill testing, long sections, details of the materials used in construction by layer, and density and moisture content of each layer. From this the data in Table 3.1 was transcribed by hand on to worksheets, an example of which is shown in Appendix C.

Table 3.1: Data recorded from NPA Roads Branch Materials Completion Drawings.

Item
Road Number and Route
Book Number
Layer
Page
Soil description
Source of construction material
Percent passing:
37,5 mm
26,5 mm
19,0 mm
13,2 mm
4,75 mm
2,00 mm
0,425 mm
0,075 mm
Mortar analysis
Grading Modulus
Plasticity Index
Liquid Limit
Optimum Moisture Content
Maximum Dry Density

The data was then captured from the worksheets to spreadsheets using a personal computer. The spreadsheets were used to generate a DBASE database file, called

NPA.DBF. Using NPA.DBF, the data was checked for errors in transcription by applying checks for reasonableness to the data. Descriptions were checked using the largest scale geological maps available. No other checks were carried out, since to check the transcribed data against the original would have doubled the cost (in time and money) of the data collection, and any errors giving values that passed the reasonableness tests would be minor anyway. The Grading Modulus of the soils was recalculated, although it was available from the completion drawings. Errors were traced back to their origin, and the original worksheets, spreadsheet files and the database file NPA.DBF were corrected.

There were 5704 sets of data collected. Of these, 299 were discarded because the soils were of mixed origin, not identifiable, or belonged to minor geological horizons, leaving 5405 records. The surviving records were gathered into a DBase file called NPA1.DBF for analysis. Three subsets of the data were generated, non-plastic soils (595 sets), plastic soils, having a plasticity index greater than 0 (4362 sets) and plastic and slightly plastic soils, having a plasticity index of 0 or more (4810 sets). Plastic soils are those which have a measured liquid limit and plastic limit. Slightly plastic soils do not have a measurable liquid limit, but exhibit signs of plasticity leading to them being described as "slightly plastic". A value of 0 was assigned to the plasticity index of these soils. The databases were converted to DBase format database files whose names are shown in Table 3.2.

Table 3.2: DBase database files

File Name	Size (Records)	Contents
NPA1.DBF	5405	All soils, except those rejected
NPA1NP.DBF	595	Non-plastic soils from NPA1.DBF
NPA1P.DBF	4362	Plastic soils from NPA1.DBF
NPA1PS.DBF	4810	Plastic and slightly plastic soils from NPA1.DBF

The structure of the databases is shown in Table 3.3. Subsets of these data bases were constructed and used for analysis as needed. All databases were derived from NPA1.DBF.

Table 3.3: Structure of DBase databases

Structure for database: npa1.dbf
Number of data records: 5405

Field	Name	Type	Width	Dec	Contents
1	NO	Numeric	5		Serial number of record, corresponding to serial number of record on original data collection worksheet
2	BOOK	Character	3		Materials completion drawing book number
3	ROAD	Character	13		Road designation or number
4	POSN	Character	3		Position from which soil sample was taken, using Kwazulu Natal Provincial Administration Roads Branch 1:50 000 sheet references (Fig 3.1)
5	HORIZ	Character	5		Geological horizon, using 1:1 000 000 geological map of South Africa (Geological Survey 1984)
6	ROCKTYPE	Character	5		Parent rock from which soil was derived
7	WEIN	Character	3		Classification according to Weinert's scheme (Weinert 1980)
8	DESC	Character	21		Description of soil
9	MAXDENS	Numeric	5		Maximum dry density (kg/m^3) (Mod AASHTO)
10	OMC	Numeric	5	1	Optimum moisture content (%)
11	P50	Numeric	3		% passing 53 mm sieve
12	P37_5	Numeric	3		% passing 37,5 mm sieve
13	P26_5	Numeric	3		% passing 25 mm sieve
14	P19	Numeric	3		% passing 19 mm sieve
15	P13_2	Numeric	3		% passing 13,2 mm sieve
16	P4_75	Numeric	3		% passing 4,75 mm sieve
17	P2	Numeric	3		% passing 2 mm sieve
18	P425	Numeric	3		% passing 0,425 mm sieve
19	P075	Numeric	3		% passing 0,075 mm sieve
20	GM	Numeric	5	2	Grading modulus
21	PI	Numeric	3		Plasticity index
22	LL	Numeric	3		Liquid limit
23	CLASS	Character	5		AASHTO classification (AASHTO 1982)
24	OK	Logical	1		Field used for checking validity of original data
** Total **			113		

Field 21 (PI) is omitted from NPA1NP.DBF

Field 22 (LL) is omitted from NPA1NP.DBF and NPA1PS.DBF

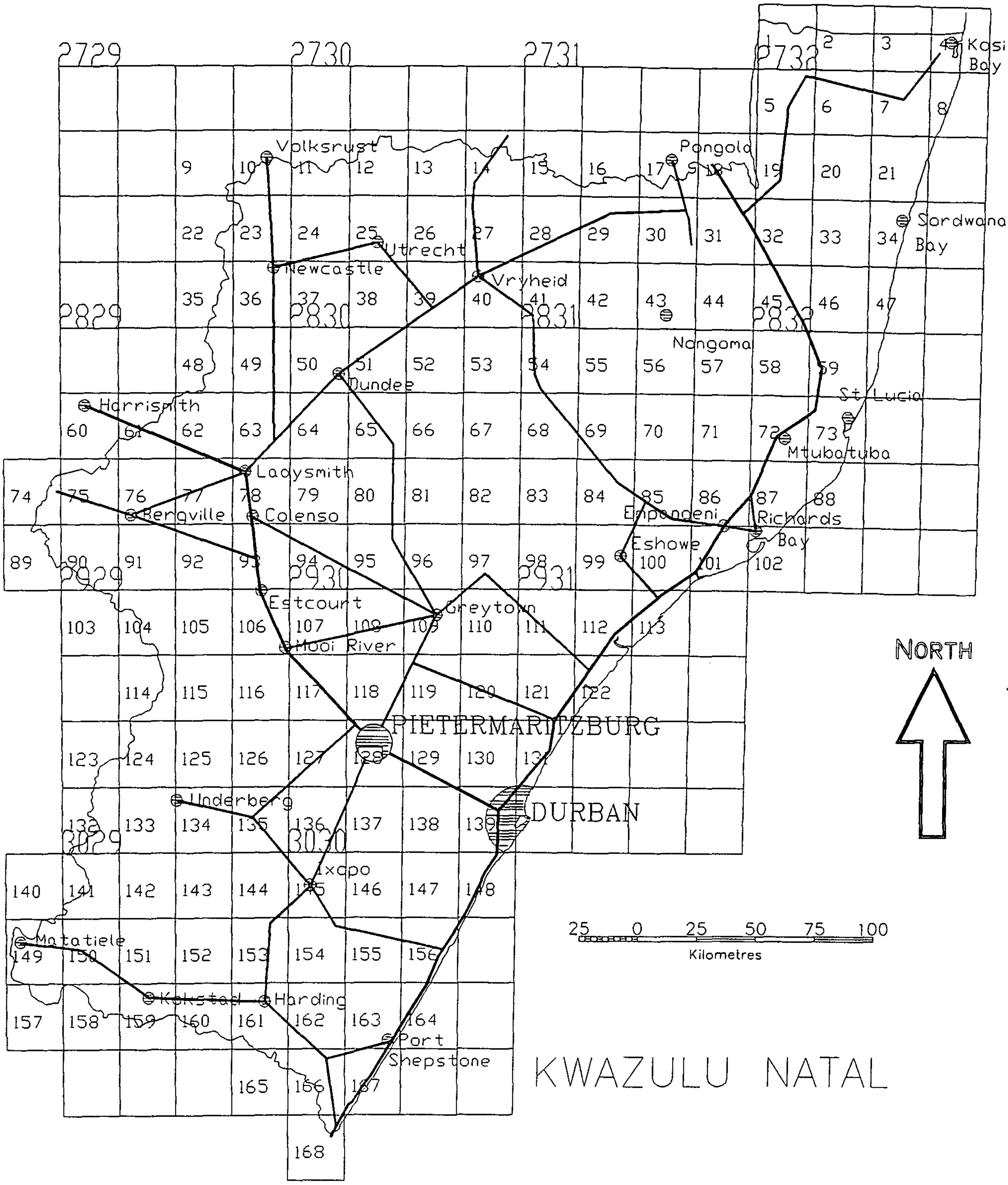


Figure 3.1: Map of Kwazulu Natal, showing major towns and cities, routes and Kwazulu Natal Provincial Administration Roads Branch 1:50000 sheet references

3.3 Criteria governing the admissibility of the data

Since the results used in this investigation had been produced by a number of people over a period of time, the following criteria were applied to the data used in the study:

1. Only soils that can be positively identified and classified were used.

2. Soils having Atterberg limits which plotted above the U-Line on the plasticity chart (Rowlands, 1984, p 93) were investigated with a view to rejecting them. There were 13 such soils making up 0,24% of the total. All were close to the U-Line and were consistent with the remainder. Since there was no clear reason to reject them, they were admitted to the database. This is shown in Figure 3.2(a). Many of the dots on the chart represent more than one value, since many of the points plot directly over each other. This is illustrated in the three dimensional frequency chart of the same data in Figure 3.2(b).

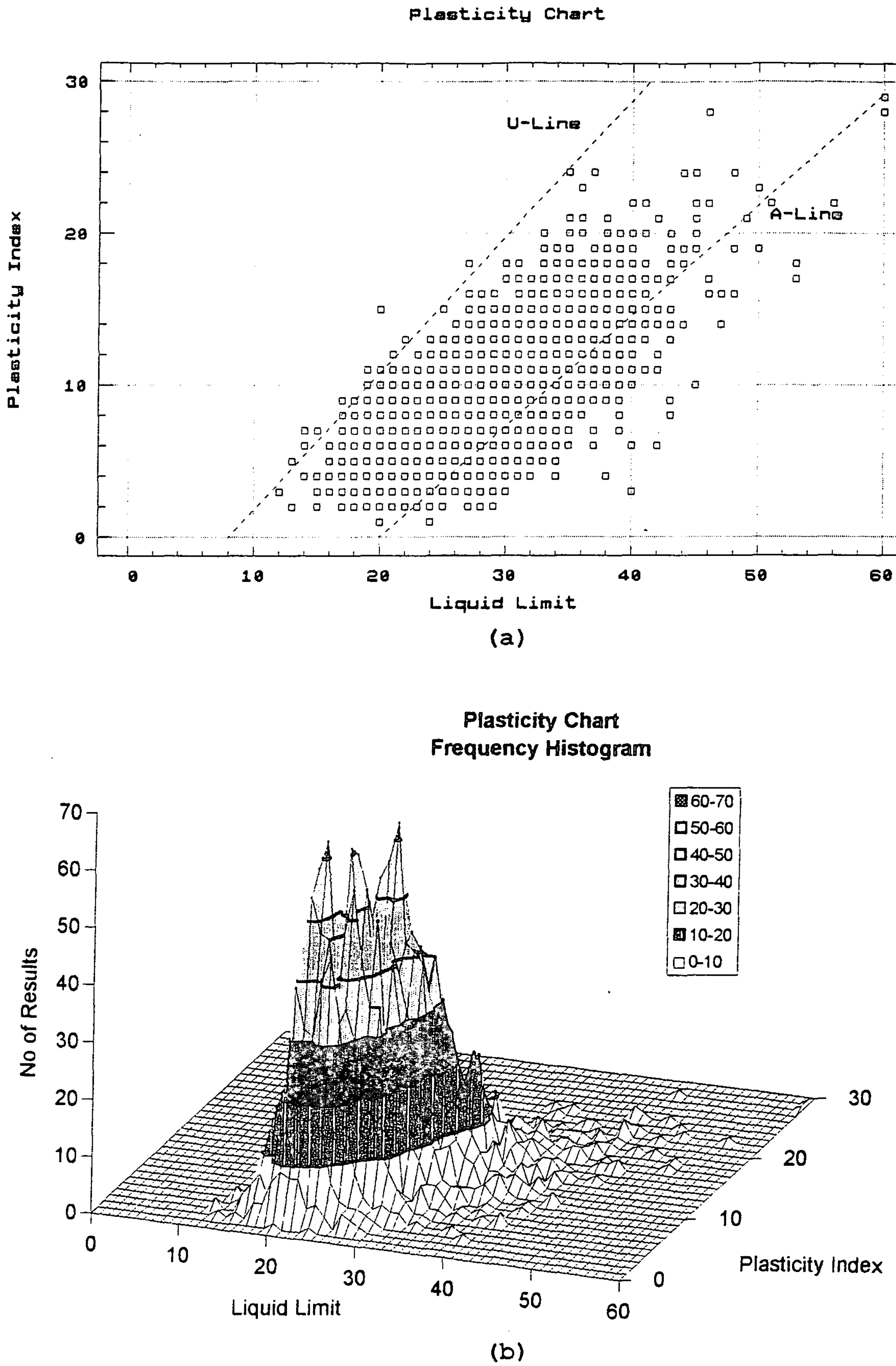


Figure 3.2: Plasticity Chart - all plastic samples

3. It was originally intended that soils whose optimum moisture content and maximum dry density plotted a significant distance from the 5 per cent air voids line, indicating a false optimum sometimes encountered in cohesionless soils would be rejected. It was found that for plastic soils this criterion was generally met. A few single sized, sandy soils with a low clay content, and many non-plastic soils appeared not to meet the criterion. However, it was not possible to draw a distinct boundary between those that met the criterion and those that did not, because there was a continuous gradation of results (see Figure 3.3) and insufficient data was available to calculate the exact air voids line. The alternatives were either to reject all single size soils, or to keep them all. Since the soils were to be separated into groups for analysis, the decision was made to retain these samples.

3. Only the results of standard tests carried out according to the methods of test laid down in TMH1 (TMH1 1986) were admitted.

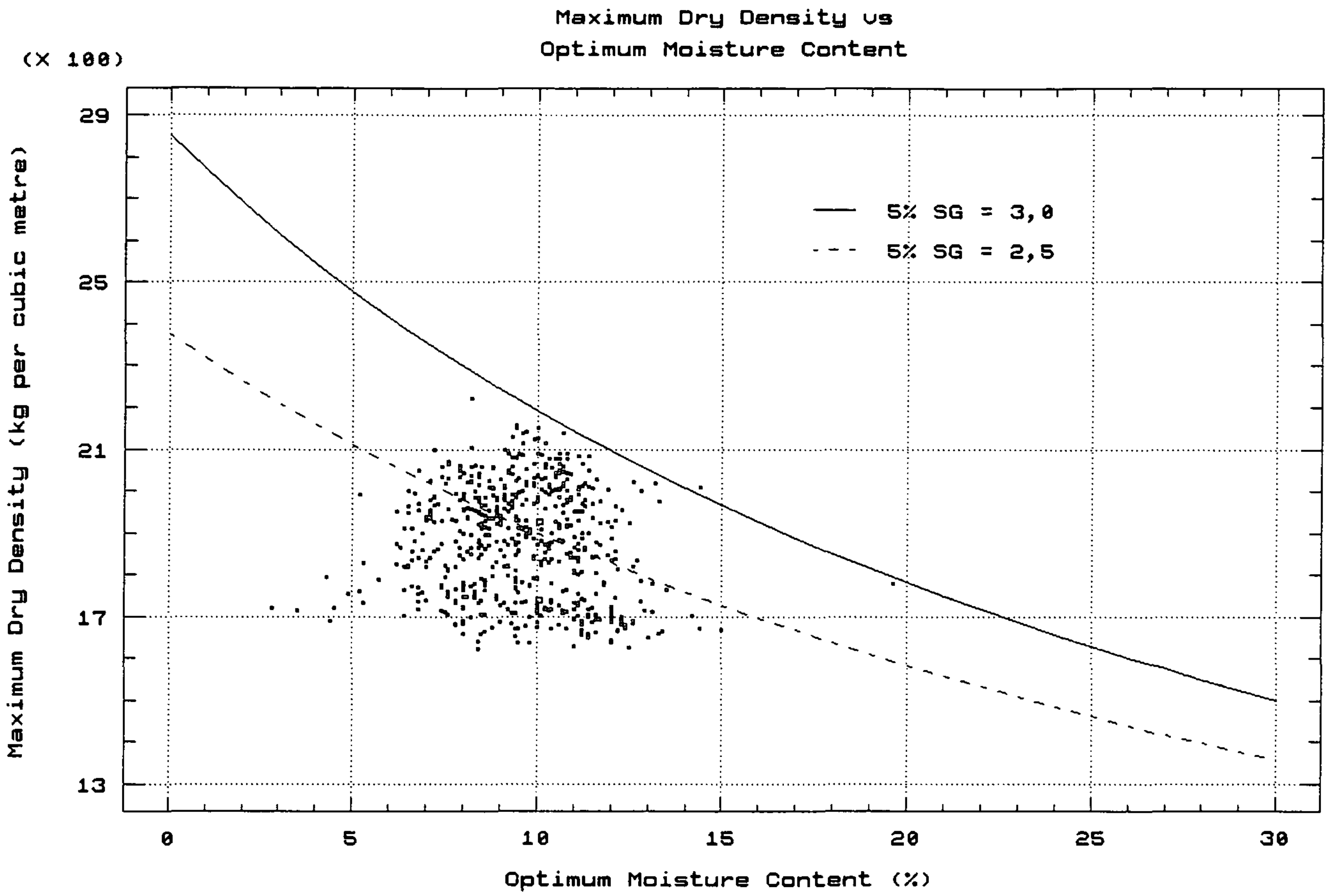


Figure 3.3: Plot of maximum dry density vs optimum moisture content for Quaternary sands

3.4 Geographical distribution of the data

The geographical distribution of the data is illustrated in Figure 3.4 and tabulated in Table 3.4. It can be seen that, although there is some concentration of results along the main routes from Durban to the South Coast and to Harrismith, the results are well distributed. Results were obtained from 70 of the 168 areas into which the province was divided for this study. The maximum proportion of results in any one area was 6,7% (Sheet 131 which includes the N2 from La Lucia to Umhlali), and most of the areas from which results were obtained yielded less than 2% of the total number of results.

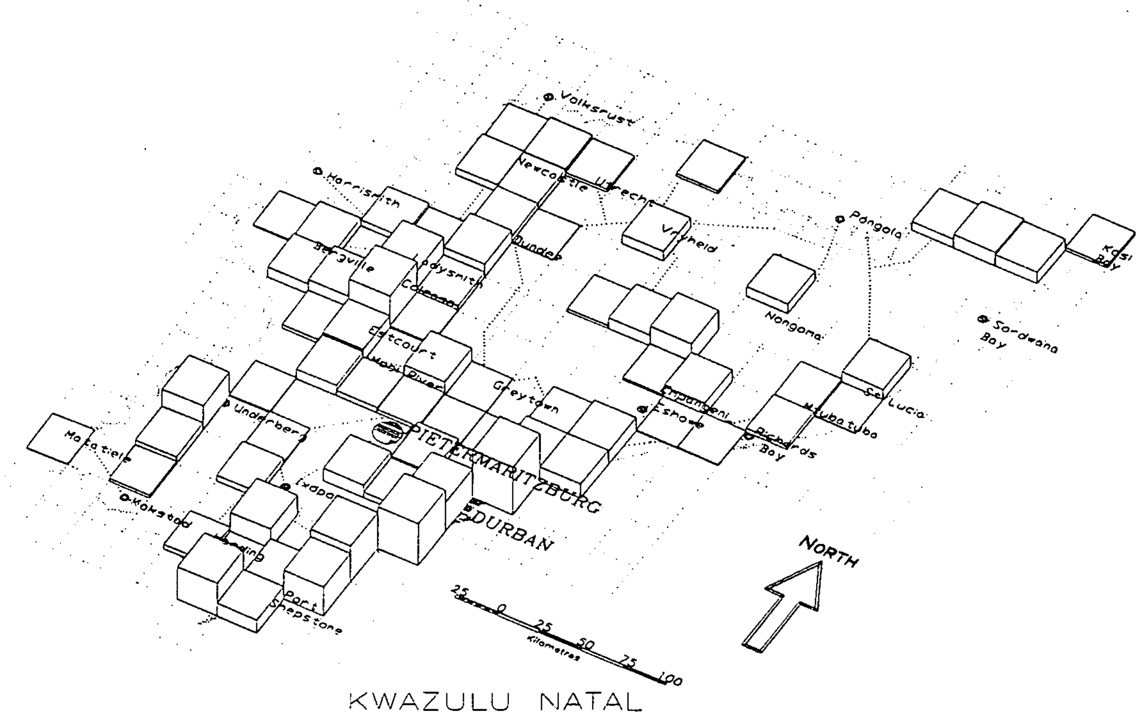


Figure 3.4: Geographical distribution of samples

Table 3.4: Geographical distribution of data

Position	Frequency	Percent	Position	Frequency	Percent
4	20	0.4	101	12	0.2
5	63	1.2	105	29	0.5
6	105	1.9	106	90	1.7
7	85	1.6	108	106	2.0
14	24	0.4	109	4	0.1
23	26	0.5	111	73	1.4
24	49	0.9	112	101	1.9
25	21	0.4	116	75	1.4
36	55	1.0	117	38	0.7
37	45	0.8	118	28	0.5
40	68	1.3	119	13	0.2
43	70	1.3	120	8	0.1
50	43	0.8	121	108	2.0
52	8	0.1	122	110	2.0
59	81	1.5	125	10	0.2
62	45	0.8	129	59	1.1
63	18	0.3	130	16	0.3
64	96	1.8	131	364	6.7
67	22	0.4	133	184	3.4
68	82	1.5	135	12	0.2
69	150	2.8	137	93	1.7
72	27	0.5	138	45	0.8
73	6	0.1	139	219	4.1
75	9	0.2	142	52	1.0
76	60	1.1	144	44	0.8
78	172	3.2	148	317	5.9
79	37	0.7	149	7	0.1
84	18	0.3	151	21	0.4
85	87	1.6	154	146	2.7
87	33	0.6	156	277	5.1
91	75	1.4	161	33	0.6
92	106	2.0	163	76	1.4
93	244	4.5	164	220	4.1
94	12	0.2	166	249	4.6
100	8	0.1	167	96	1.8
			TOTAL	5405	100.0

3.5 Distribution of data by type

The data was classified for the purposes of this study according to geological horizon, rock type, Weinert's classification of natural road building materials into groups (Table 2, Weinert 1980) and the AASHTO classification (AASHTO 1982). The description of the materials used in the study is organized by geological horizon. Details of rock type, Weinert's classification and AASHTO classification are described for each geological horizon.

3.5.1 Distribution of data by geological horizon

The distribution of the data classified by geological horizon is tabulated in Table 3.5 and shown as a "pie" chart in Figure 3.5. The abbreviations used for the horizons are those used on the 1:1 000 000 Geological Map of South Africa (Geological Survey 1984), and the 1:250 000 Geological Map Sheet 2930 Durban (Geological Survey 1988).

Table 3.5: Distribution of data by geological horizon

Horizon	Description	Frequency	Percent
Jd	Jurassic intrusives	1305	24.1
O-Sn	Natal Group	763	14.1
Nmp	Namibian intrusives and metamorphics	616	11.4
Qb	Berea Formation sands	613	11.3
Pv	Vryheid Formation	503	9.3
Pa	Adelaide Formation	327	6.0
Pvo	Volksrust Shale Formation	278	5.1
ZB	Archaean Granites	269	5.0
TRt	Tarkastad Formation	261	4.8
Pp	Pietermaritzburg Shale Formation	240	4.4
C-Pd	Dwyka Formation	177	3.3
Q	Recent sands	53	1.0
	TOTAL	5405	100.0

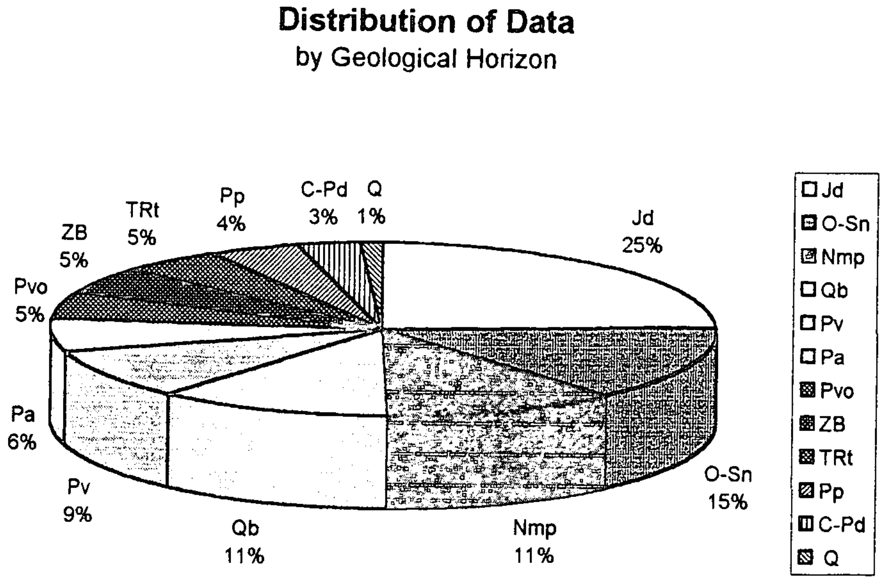


Figure 3.5: Distribution of data by geological horizon

3.5.1.1 Jurassic Intrusives

Nearly one quarter of the samples investigated were classified as Jurassic intrusives. The samples consisted entirely of dolerite, and this group is therefore identical to the group classified as Dolerite under Rock Type, and to the group Basic Crystalline Rocks using Weinert's classification. It varied from crushed, fresh rock through to weathered and decomposed rock, according to various descriptions given on the completion drawings. In some cases weathered dolerite was lightly crushed in order to meet grading requirements. Dolerite in the province of Kwazulu Natal usually occurs in concordant or semiconcordant intrusions (Geological Survey 1989). It is usually fine to medium grained, but sometimes coarse grained and is composed of about equal proportions of labradorite and augite, with olivine sometimes present, and magnetite nearly always present (Geological Survey 1989).

Over 98% of the dolerite examined in this study is granular material, and of this one quarter is classified as A-1 and the remainder as A-2-4 or A-2-6. Details of the classes of material are shown in Table 3.6.

Table 3.6: Classification of Jd horizon

AASHO Class	Frequency	Relative Frequency %
A-2-4	474	36.3
A-2-6	448	34.3
A-1-a	190	14.6
A-1-b	151	11.6
A-2-7	23	1.8
A-4	7	0.5
A-7-5	6	0.5
A-6	5	0.4
A-2-5	1	0.1

The maximum dry density of the material is plotted against its optimum moisture content in Figure 3.6. The points tend to follow the 5% air voids line corresponding to a specific gravity of about 2,8. Optimum moisture content is generally between 5 and 15%, although a few samples show an optimum moisture content in the range 15 to 30%.

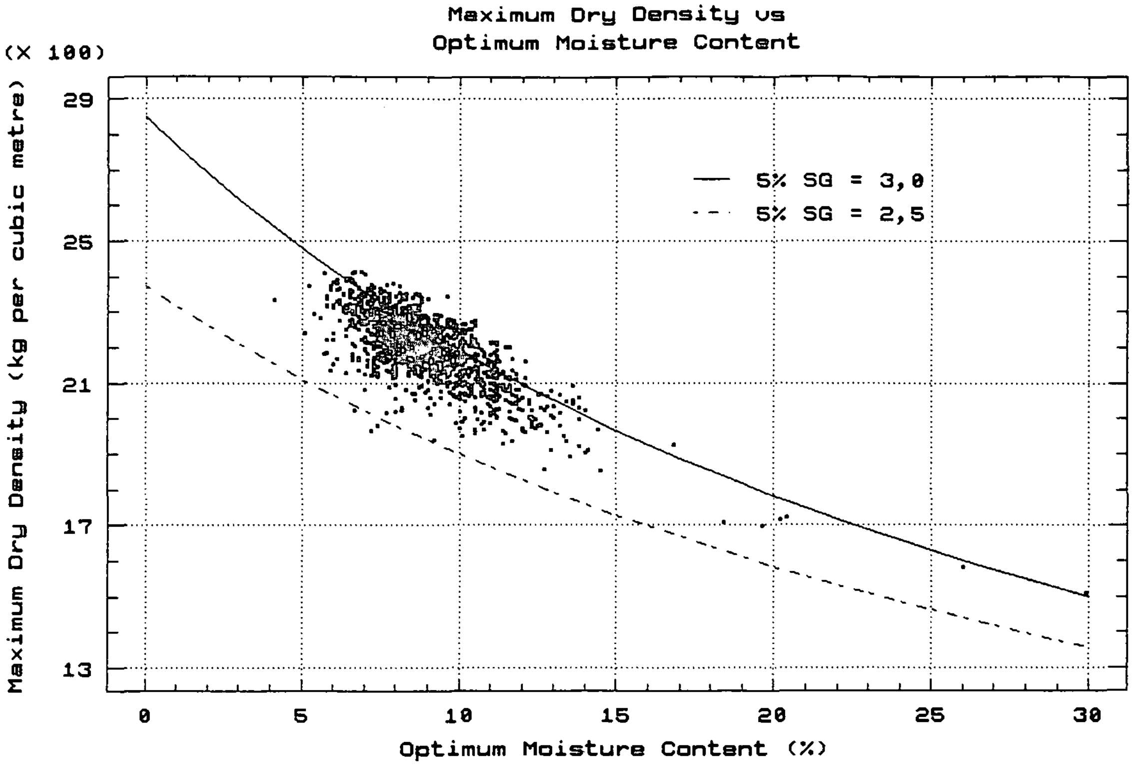


Figure 3.6: Maximum dry density vs optimum moisture content for soils from horizon Jd

The mean optimum moisture content is 9,0% with a standard deviation of 1,95%. The remaining pertinent statistics appear in Table 3.7.

Table 3.7: Basic statistics for horizon Jd

Variable: Units where applicable	**Maximum Dry Density** kg/m³	**Optimum Moisture Content** %
Sample size	1305	1305
Average	2194	8.98
Variance	11050	3.80
Standard deviation	105	1.95
Standard error	2.9	0.054
Minimum	1508	4.1
Maximum	2414	29.9
Range	906	25.8

Most of the plasticity results of this group when plotted on a plasticity chart (Figure 3.7) fall between the 'U' line and the 'A' line, within the region classified as low to medium plastic inorganic clays, with some results plotting slightly below the 'A' line. This indicates that the clay present in the group as a whole includes kaolinite, illite and montmorillonite (Rowlands 1984). Two results plot very slightly above the 'U' line.

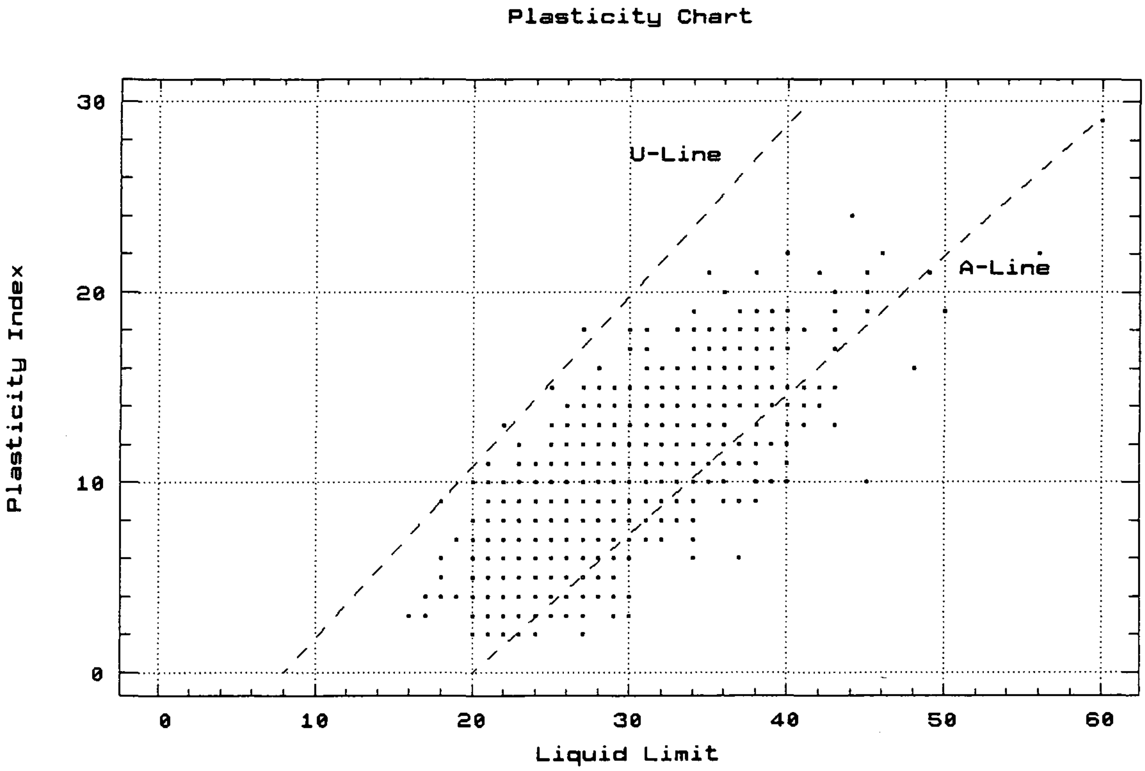


Figure 3.7: Plasticity chart for horizon Jd

The particle size distribution curves (Fig 3.8) also reflect the granular nature of the material. The shaded area of the figure shows the envelope into which 90% of the results fall, and indicates that the material, although well graded, exhibits considerable variability.

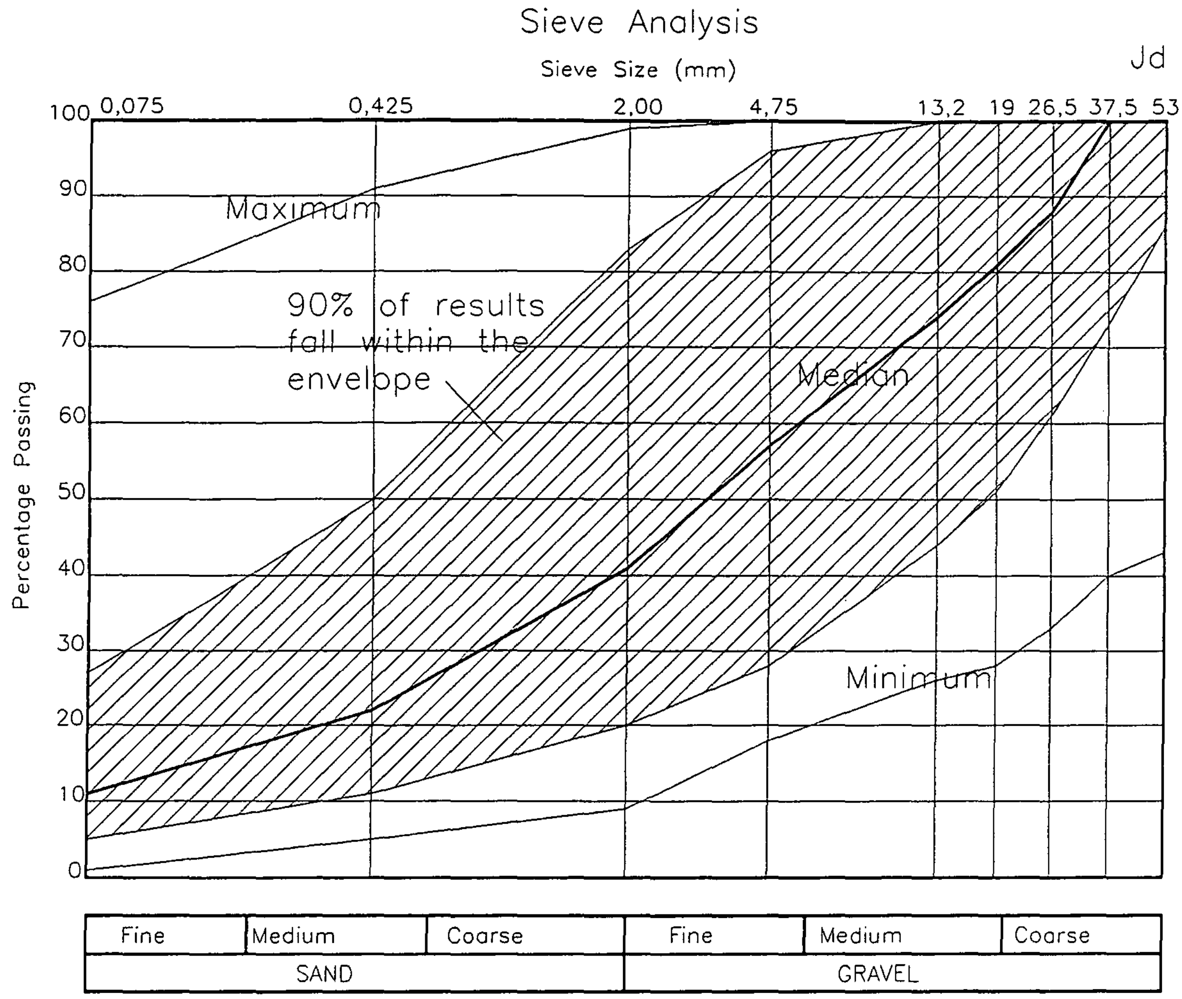


Figure 3.8: Particle size distribution for horizon Jd

3.5.1.2 Natal Group

Materials derived from rocks of the Natal Group, for the most part sandstones, comprise 14% of the materials considered in this study. The sediments of this group are described (Geological Survey 1989) as coarse in the north of the Kwazulu Natal Coastal belt grading to arenaceous in the south. The group consists of some conglomerates, feldspathic sandstones and grits, and quartzitic sandstones. Some of the formations making up the group contain mica.

Over 95% of the material in this group classifies as granular. One third is classified as A-1 and 60% as A-2-4 or A-2-6. One percent is classified as A-3, reflecting decomposition of the rock to its original granular components. Some 5% has weathered to silty or clayey material. The classification of the material is shown in Table 3.8.

Table 3.8: Classification of O-Sn horizon

AASHO Class	Frequency	Relative Frequency %
A-2-4	424	55.6
A-1-b	235	30.8
A-2-6	39	5.1
A-1-a	19	2.5
A-4	19	2.5
A-6	18	2.4
A-3	8	1.0
A-2-7	1	0.1

The maximum dry density of the material is plotted against optimum moisture content in Fig 3.9. The points tend to follow the 5% air voids line correspomding to a specific gravity of approximately 2,65.

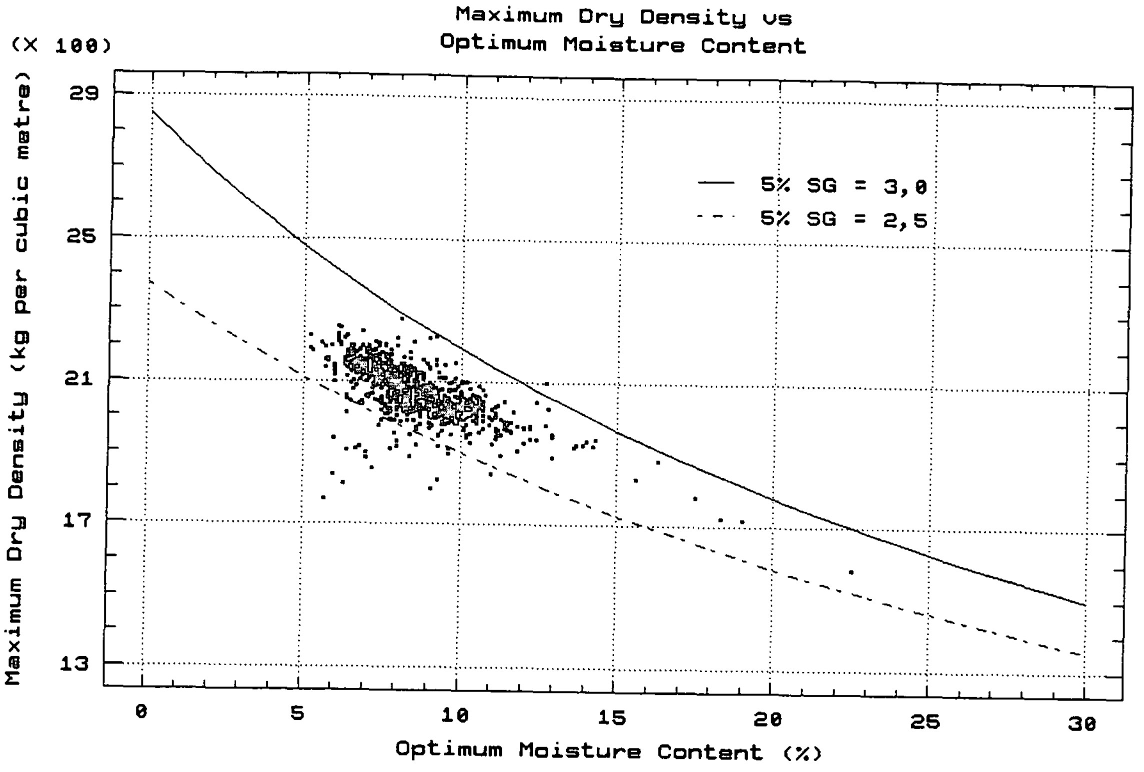


Figure 3.9: Maximum dry density vs optimum moisture content for soils from horizon O-Sn

Optimum moisture content is generally between 5% and 12%, with a mean of 8,7% and a standard deviation of 1,75%. Other statistics are shown in Table 3.9.

Table 3.9: Basic statistics for horizon O-Sn

Variable: Units where applicable	**Maximum Dry Density** kg/m³	**Optimum Moisture Content** %
Sample size	763	763
Average	2062	8.72
Variance	6255	3.06
Standard deviation	79	1.75
Standard error	2.9	0.063
Minimum	1583	5.2
Maximum	2275	22.5
Range	692	17.3

The plasticity results plot mostly below the 'U' line, and both above and below the 'A' line in the region of low to medium plastic inorganic clays, as shown in Figure 3.10.

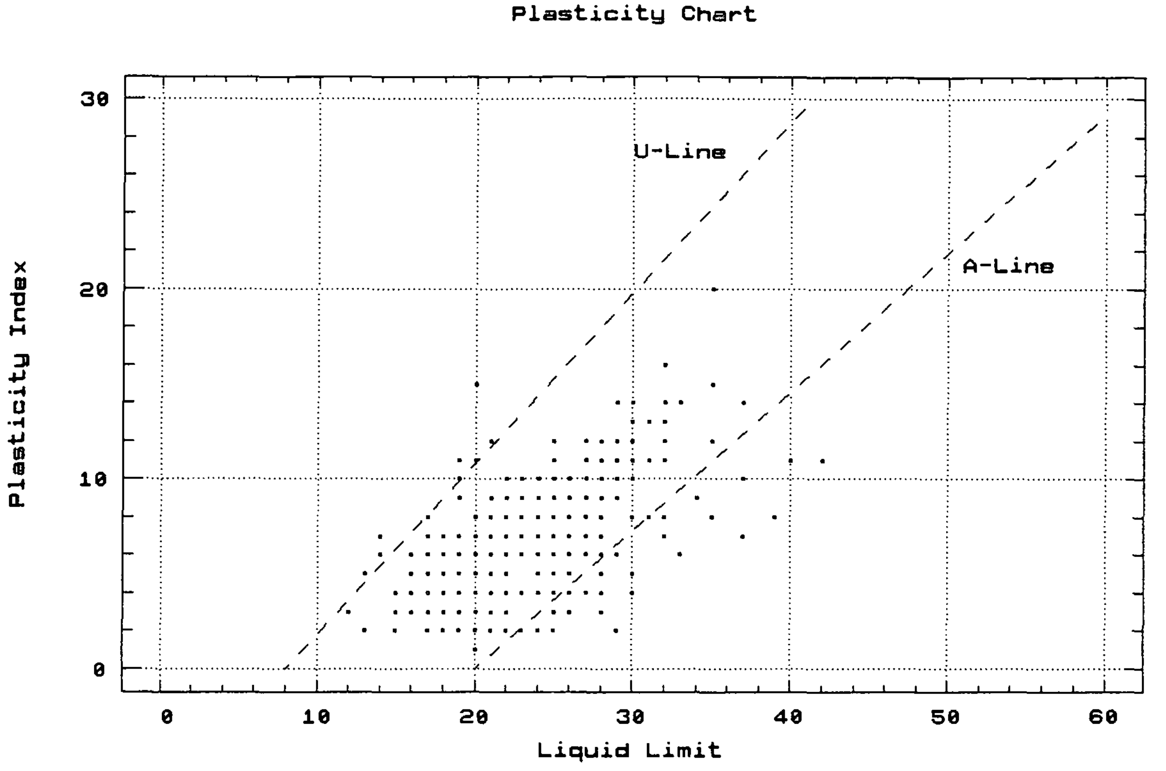


Figure 3.10: Plasticity chart for horizon O-Sn

The particle size distribution curves (Fig 3.5.1.2) correspond to the origin of the material. D_{50} of the median curve is just less than 0,425mm, and the median curve has a silt and clay content of 19%, reflecting the arkosic nature of some of the parent rock. The median curve is that of a gravelly sand, having a ratio of 85% sand, silt and clay to 15% gravel, but the wide range of particle sizes indicates that there is a substantial proportion of gravel samples within this group, supported by the classification of 33% of the samples as A-1.

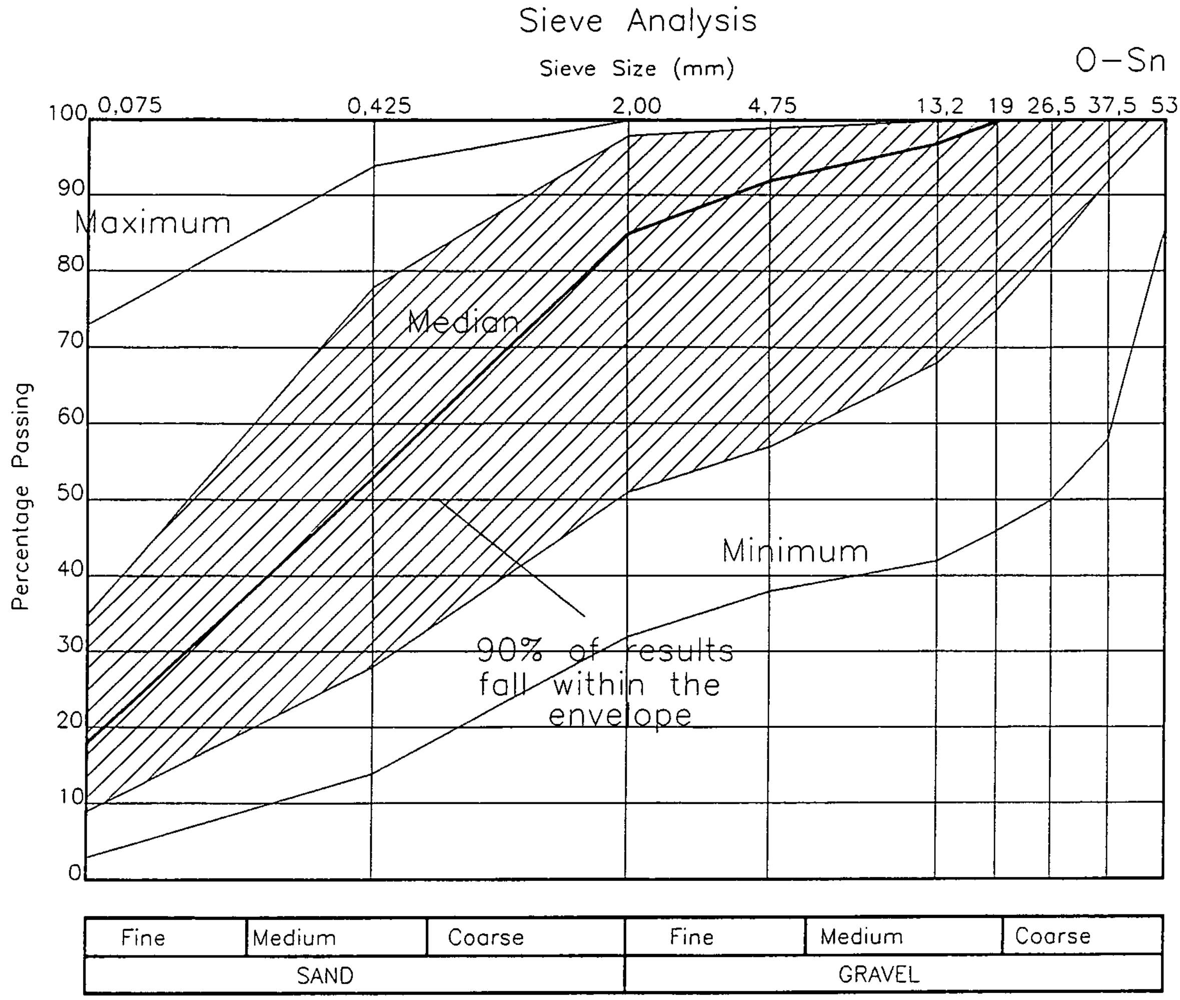


Figure 3.11: Particle size distribution for horizon O-Sn

3.5.1.3 Namibian Intrusives and Metamorphics

This group consists of rocks described as granites in the source documents, but since no distinction is made in them between intrusive and metamorphic rocks, it is likely to include a variety of granitic and gneissic metamorphic rocks. Apart from twelve samples from the Empangeni and Eshowe area which can be classified as belonging to the Tugela group, the samples belong to the Mapumulo group. The rocks of the Mapumulo group are described (Geological Survey 1989) as banded gneiss and granitic rocks and massive granitic rocks, formed by metamorphism of sedimentary and volcanic rocks, and mobilised basement granites. The material is granular, less than 2% being classified as silty or clayey. Some 62% is classed as A-1 and the remaining 36% as A-2. The classification is shown in Table 3.10.

Table 3.10: Classification of Nmp horizon

AASHTO Class	Frequency	Relative Frequency %
A-1-b	334	54.2
A-2-4	192	31.2
A-1-a	48	7.8
A-2-6	29	4.7
A-6	7	1.1
A-4	3	0.5
A-2-7	2	0.3
A-7-5	1	0.2

The maximum dry density of the material is plotted against its optimum moisture content in Figure 3.12. The points tend to follow the 5% air voids line corresponding to a specific gravity of about 2,65. Optimum moisture content is generally in a fairly narrow range between 5 and 10%, although a few samples show an optimum moisture content in the range 10 to 15%.

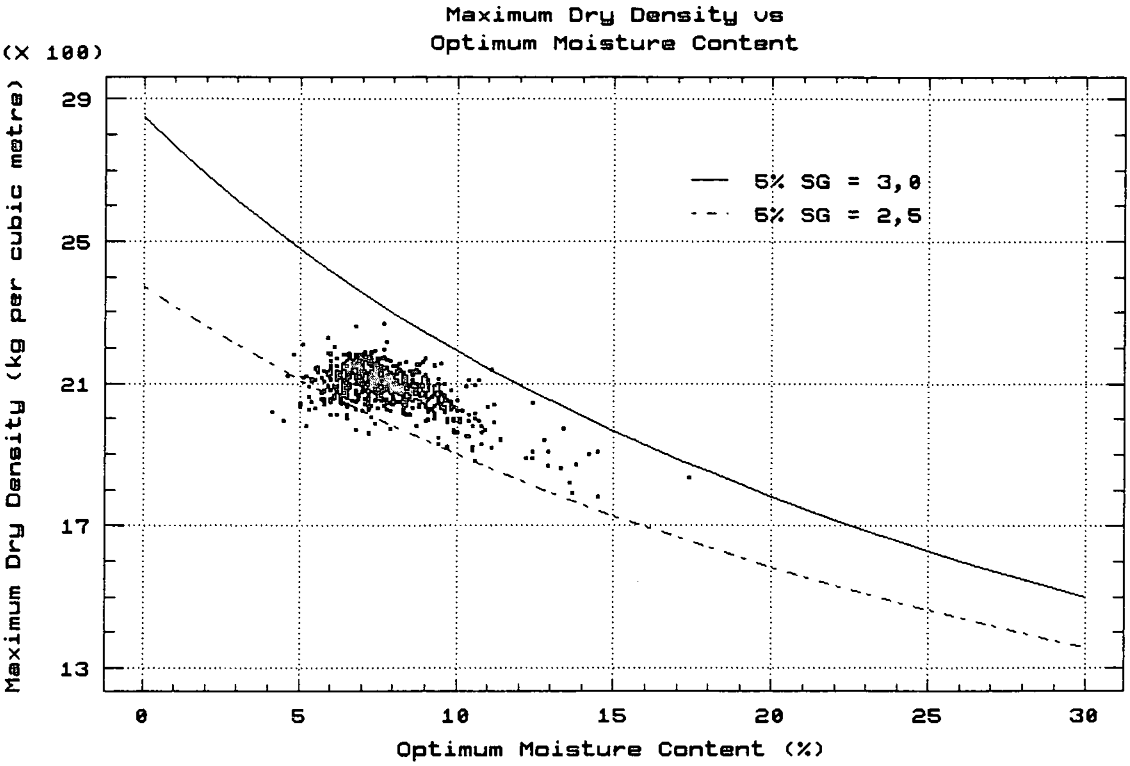


Figure 3.12: Maximum dry density vs optimum moisture content for soils from horizon Nmp

The mean optimum moisture content is 7,9% with a standard deviation of 1,59%. The remaining pertinent statistics appear in Table 3.11.

Table 3.11: Basic statistics for horizon Nmp

Variable: **Units where applicable**	**Maximum Dry Density** **kg/m³**	**Optimum Moisture Content** **%**
Sample size	616	616
Average	2087	7.90
Variance	4264	2.52
Standard deviation	65	1.59
Standard error	2.6	0.064
Minimum	1780	4.1
Maximum	2270	17.4
Range	490	13.3

All of the plasticity results of this group when plotted on a plasticity chart (Figure 3.13) fall between the 'U' line and the 'A' line, within the region classified as low to medium plastic inorganic clays, with many results plotting below the 'A' line. This reflects the normal weathering process of granitic rocks which produces kaolinite as the predominant clay weathering product. The liquid limit is generally below 35.

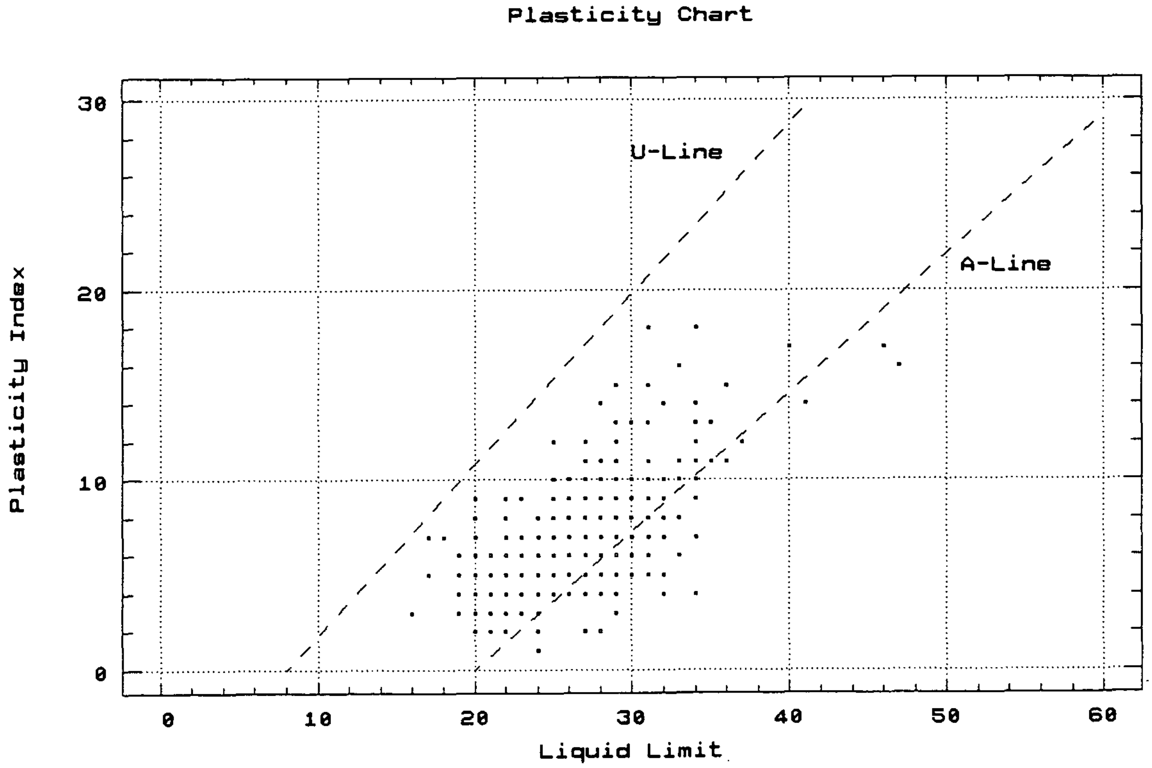


Figure 3.13: Plasticity chart for horizon Nmp

The particle size distribution curves (Fig 3.14) show that although the material is granular, it tends to be sandy rather than gravelly. The shaded area of the figure shows the envelope into which 90% of the results fall, and indicates that the material is well graded and exhibits moderate variability.

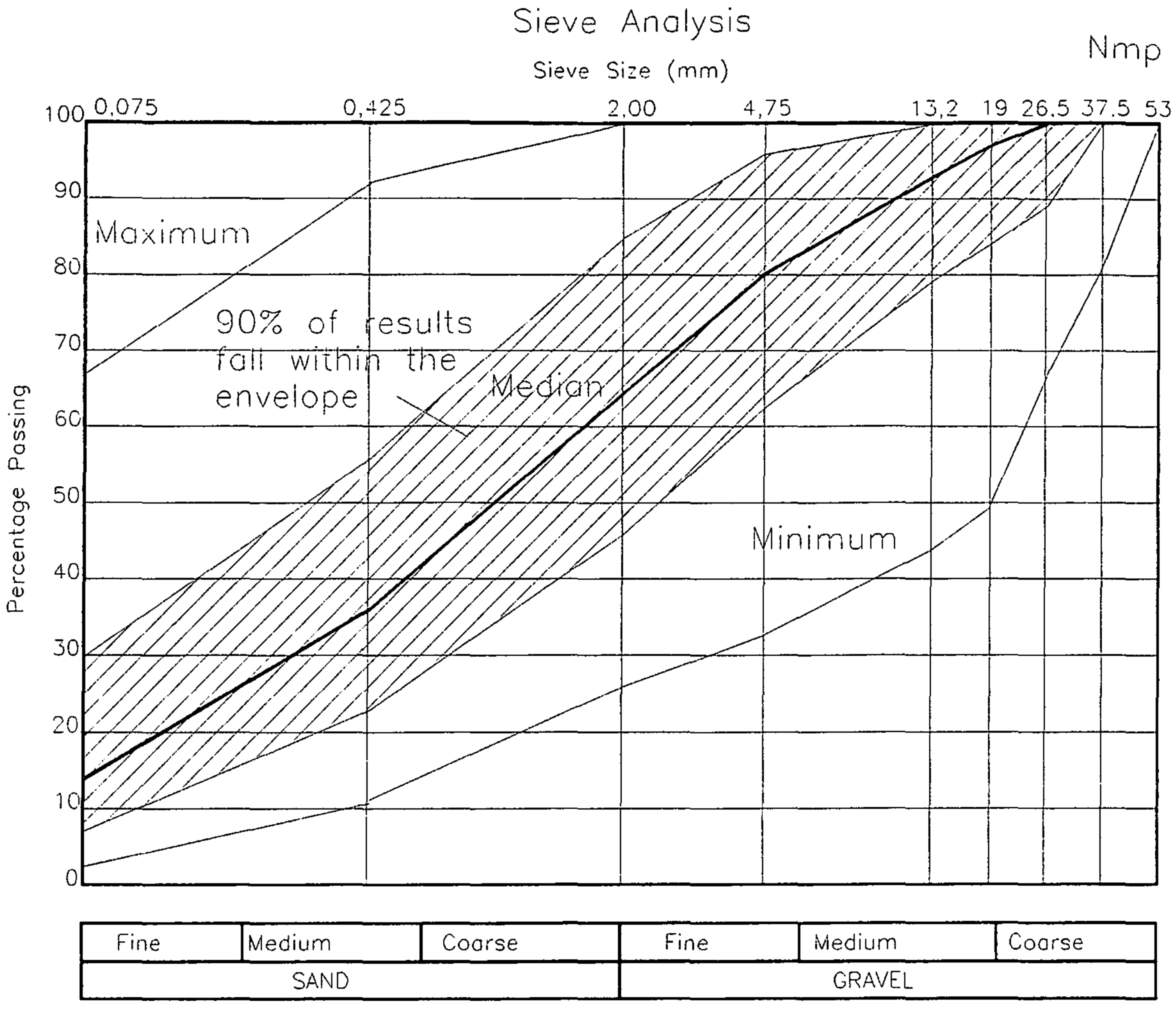


Figure 3.14: Particle size distribution for horizon Nmp

3.5.1.4 Berea Formation

The soils of the Berea Formation consist of almost single size aeolian sands with clay contents ranging up to 40% (Brink 1985), derived from dune cordons along the coast during periods of marine regression. The clay content is due to the weathering of the feldspar component of the sand. Weathering of ferrous and ferric minerals causes the sand to be stained to a characteristic orange to dark red colour. Because of its particle size distribution, non-plastic varieties classify as A-3 and plastic varieties classify as A-2-4. A few more clayey samples with higher plasticity indices classify as A-2-6 or A-4. The classification is shown in Table 3.12.

Table 3.12: Classification of Qb horizon

AASHTO Class	Frequency	Relative Frequency %
A-2-4	360	58.8
A-3	238	38.8
A-2-6	8	1.3
A-4	5	0.8
A-2-5	1	0.2
A-2-7	1	0.2

The maximum dry density of the material is plotted against its optimum moisture content in Figure 3.15. The points are randomly scattered between 5 and 15% optimum moisture content and 1700 and 2100 kg/m^3 maximum dry density, but with all points but one lying below the 5% air voids line corresponding to a specific gravity of 3,0. This distribution of data has already been remarked upon on page 3.8 in connection with rejecting invalid results. Stephens (1988) has noted the lack of correlation between CBR and a number of parameters, including moisture content and density. Although the range of maximum density agrees well with results reported by Brink (1985), the range of optimum moisture content appears to be lower than the 10 to 18% reported by Brink.

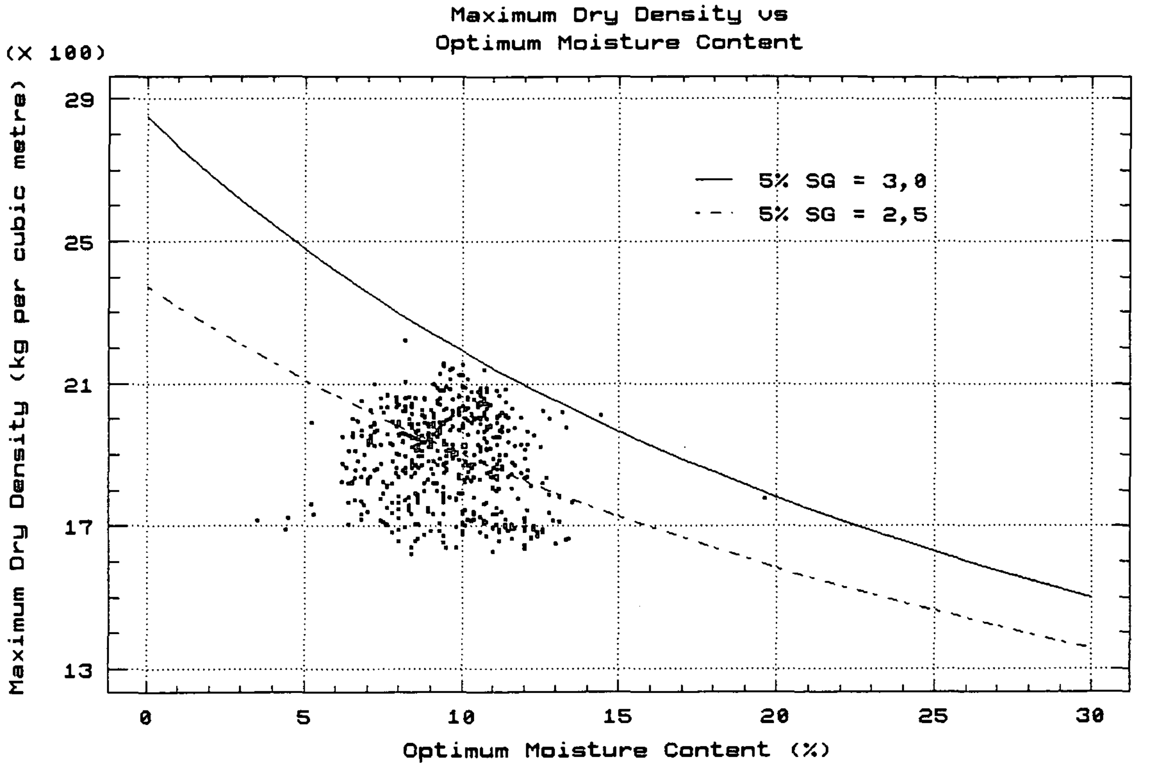


Figure 3.15: Maximum dry density vs optimum moisture content for soils from horizon Qb

The mean optimum moisture content is 7,9% with a standard deviation of 1,59%. The remaining pertinent statistics appear in Table 3.13.

Table 3.13: Basic statistics for horizon Qb

Variable: **Units where applicable**	**Maximum Dry Density** **kg/m^3**	**Optimum Moisture Content** **%**
Sample size	613	613
Average	1898	9.59
Variance	16659	2.94
Standard deviation	129	1.72
Standard error	5.2	0.069
Minimum	1622	3.5
Maximum	2220	19.6
Range	598	16.1

All of the plasticity results of this group when plotted on a plasticity chart (Figure 3.16) fall between the 'U' line and the 'A' line, within the region classified as low to medium plastic inorganic clays, with very few results plotting below the 'A' line. The results in general plot in the central portion between 'A' line and the 'U' line. The plasticity is low, with plasticity indices less than 14, and liquid limits below 30. This is less than that reported by Brink (Brink 1985) and may explain the lower, by comparison, optimum moisture contents.

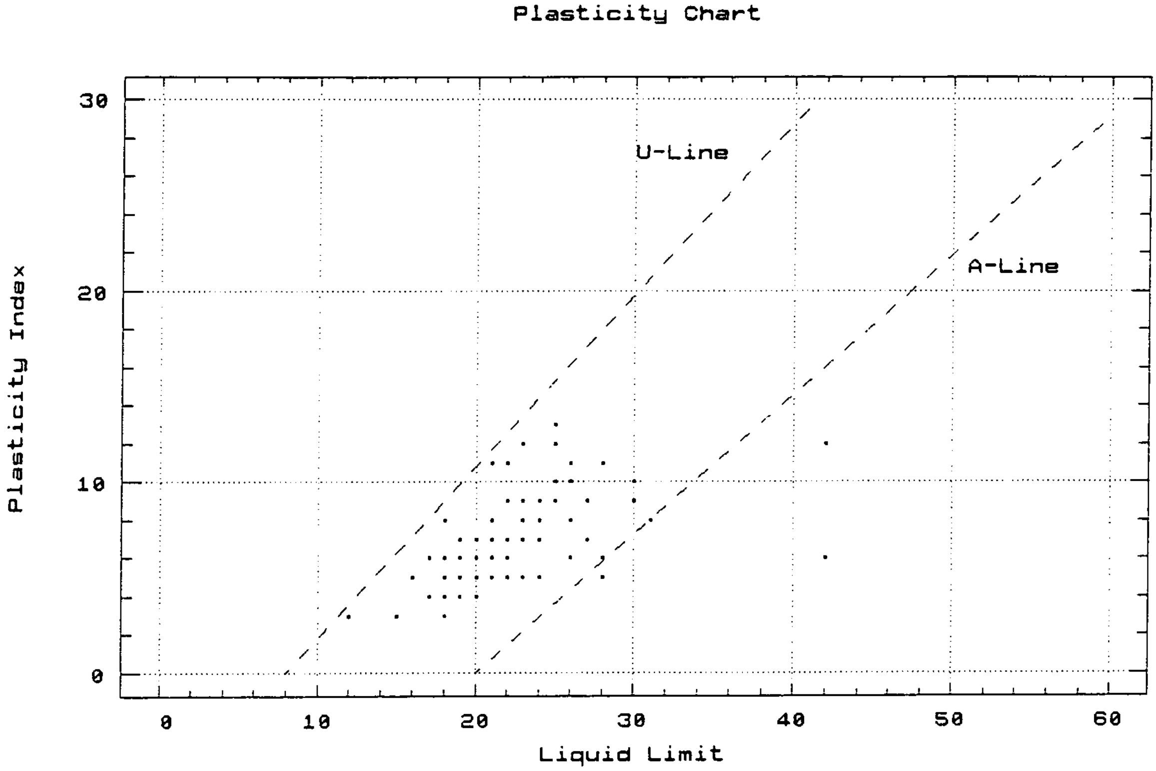


Figure 3.16: Plasticity chart for horizon Qb

The particle size distribution curves (Fig 3.17) illustrate very clearly the single size nature of the soil. Although there is a wide range of particle size distribution, the great majority of the results lie within a very narrow envelope between 0,425 mm and 0,075 mm. The soil is typically a fine to medium grained sand.

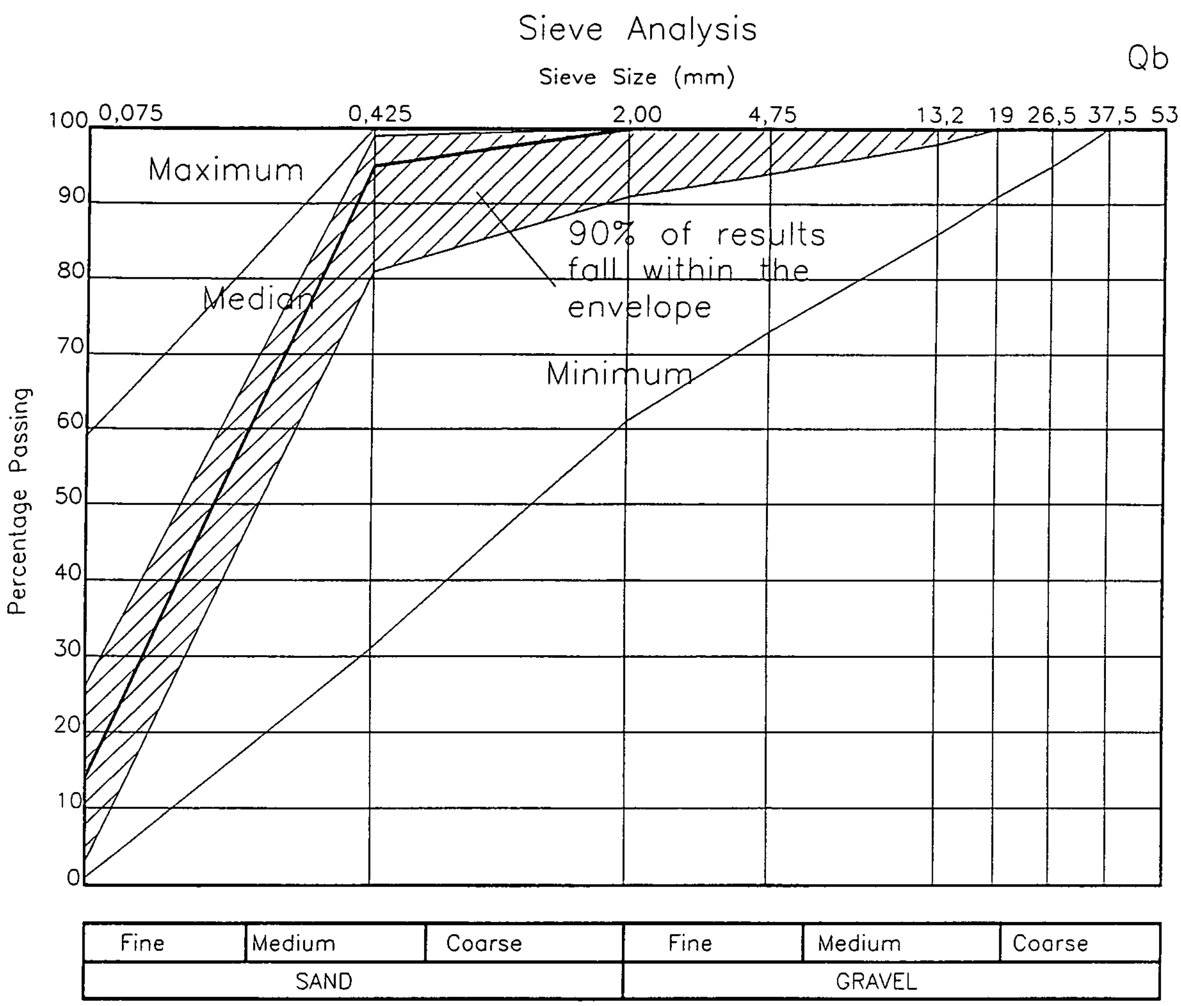


Figure 3.17: Particle size distribution for horizon Qb

3.5.1.5 Vryheid Formation

The Vryheid Formation is part of the Ecca Group of the Karoo Sequence (South African Committee for Stratigraphy 1980) and is composed predominantly of sandstone, other rock types present being grit and soft, sandy shale (Geological Survey 1989). The proportions in the materials studied are 73% sandstone to 27% of shale, mudstone, silt and clay. Some 85% of the materials are granular, the rest are classified as silty or clayey. Most of the granular material is classified as A-2 (81%) and the silty or clayey material as A-4 and A-6 (14%). A-1 materials comprise 15%. The classification is shown in Table 3.14.

Table 3.14: Classification of Pv horizon.

AASHTO Class	**Frequency**	**Relative Frequency %**
A-1-a	11	2.2
A-1-b	62	12.3
A-2-4	273	54.3
A-2-6	82	16.3
A-4	41	8.2
A-6	30	6.0
A-7-5	4	0.8

The maximum dry density of the material is plotted against optimum moisture content in Figure 3.18. The points tend to follow the 5% air voids line corresponding to a specific gravity of 2,65. The optimum moisture content generally falls between 5 and 15%, but ranges as high as 20%. The mean optimum moisture content is 9,6% with a standard deviation of 1,98%.

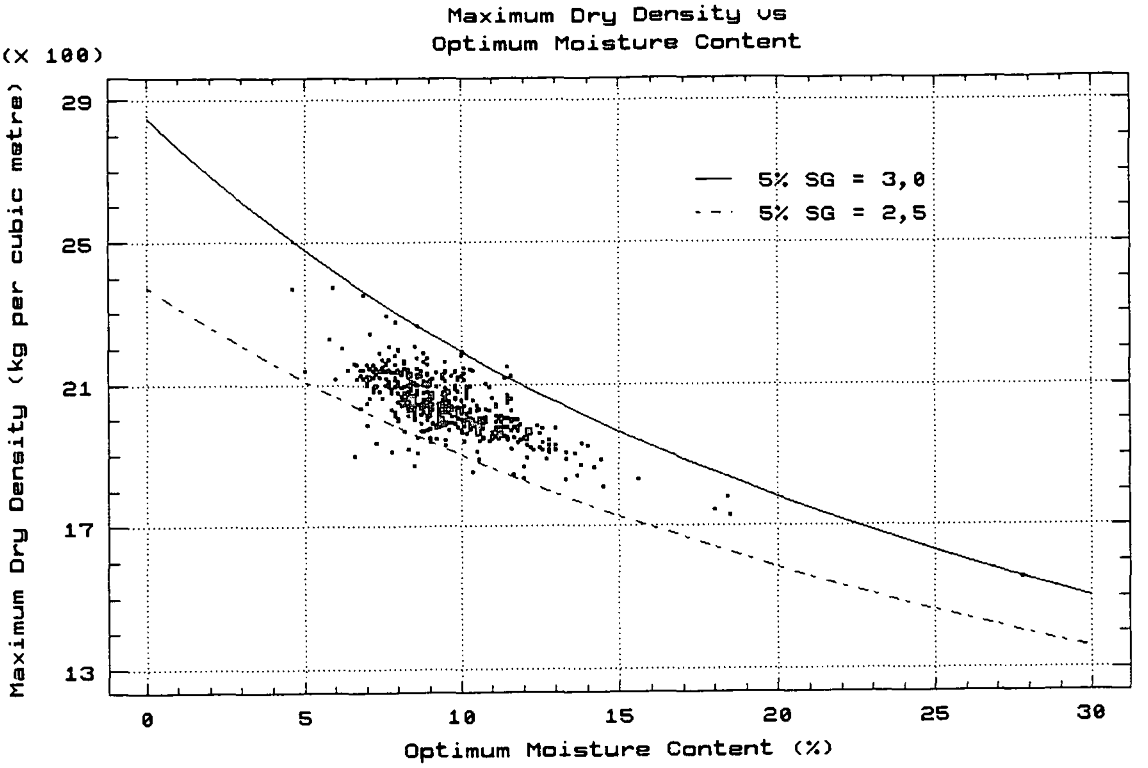


Figure 3.18: Maximum dry density vs optimum moisture content for soils from horizon Pv

Other statistics are presented in Table 3.15.

Table 3.15: Basic statistics for horizon Pv

Variable: **Units where applicable**	**Maximum Dry Density** **kg/m^3**	**Optimum Moisture Content** **%**
Sample size	503	503
Average	2041	9.61
Variance	8169	3.90
Standard deviation	90	1.98
Standard error	4.03	0.088
Minimum	1554	4.6
Maximum	2372	27.8
Range	818	23.2

All the plasticity results when plotted on a plasticity chart, shown in Figure 3.19, fall below, and generally well below, the 'U' line. Only a few plot below the 'A' line. This corresponds to clays and silts of low plasticity, and is consistent with the clay fraction consisting predominantly of illite. The liquid limit is generally less than 40.

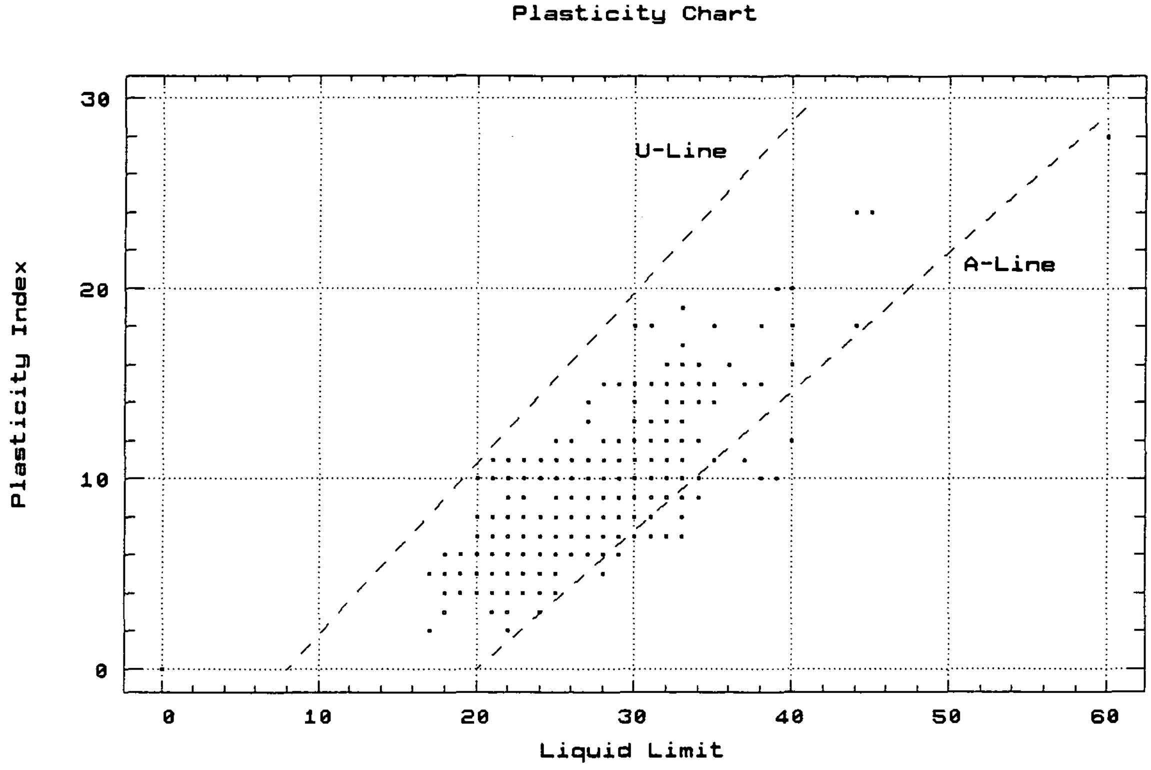


Figure 3.19: Plasticity chart for horizon Pv

The particle size distribution, shown in Figure 3.20, exhibits a wide range of particle size, which reflects the variable nature of the parent materials. The shape of the curves, particularly the change in gradient at the 2mm size, indicates that some of the material has broken down to its original sand sized particles.

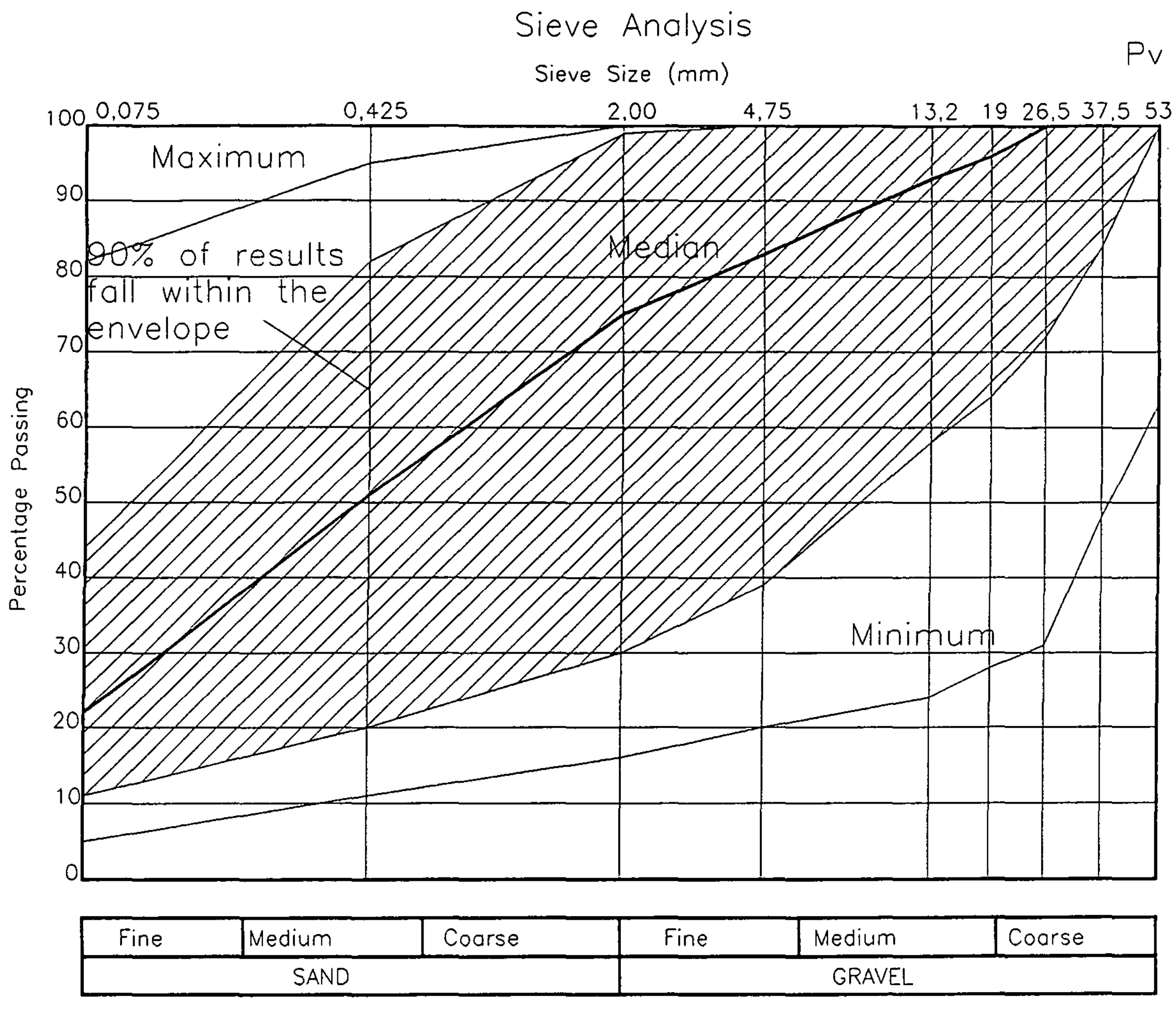


Figure 3.20: Particle size distribution for horizon Pv

3.5.1.6 Adelaide Formation

The Adelaide Formation consists of mudstones and immature sandstones of terrestrial origin (Geological Survey 1989). The materials studied were 84% argillaceous, consisting of mudstones, shales and clay, and 16% arenaceous. Although the soils were mostly granular (72%), there was a substantial proportion (28%) of silty or clayey material. Most of the granular material was classified as A-2, with barely 4% of it being classified as A-1. Most of the silty or clayey material was classified as A-6. The classification is shown in Table 3.16.

Table 3.16: Classification of Pa horizon.

AASHTO Class	Frequency	Relative Frequency %
A-1-a	1	0.3
A-1-b	13	4.0
A-2-4	116	35.5
A-2-6	106	32.4
A-4	28	8.6
A-6	57	17.4
A-7-5	6	1.8

A plot of maximum dry density vs optimum moisture content is shown in Figure 3.21. The plotted points tend to follow the 5% air voids line corresponding to a specific gravity of 2,65.

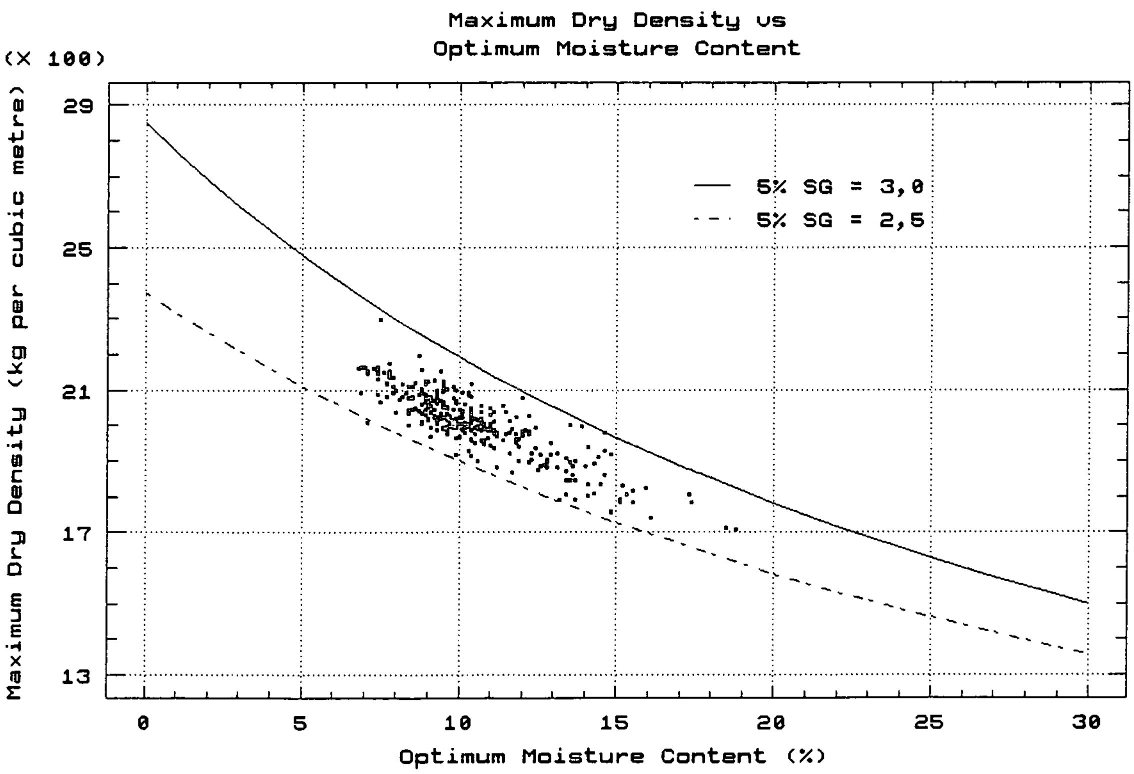


Figure 3.21: Maximum dry density vs optimum moisture content for soils from horizon Pa

The optimum moisture content averages 10,5% with a standard deviation of 2,1%, and ranges from 7 to 19%. These and other statistics appear in Table 3.17.

Table 3.17: Basic statistics for horizon Pa

Variable: **Units where applicable**	**Maximum Dry Density** **kg/m³**	**Optimum Moisture Content** **%**
Sample size	327	327
Average	2004	10.47
Variance	8382	4.43
Standard deviation	92	2.10
Standard error	5.06	0.116
Minimum	1707	6.8
Maximum	2297	18.8
Range	590	12.0

All the plasticity results when plotted on the plasticity chart, Figure 3.22, fall below the U-line. The majority fall in the central area between the U-line and the A-line, well below the U-line and well above the A-line, in the region of clays of low plasticity. Very few points fall below the A-line. The liquid limit of most of the soils is less than 40.

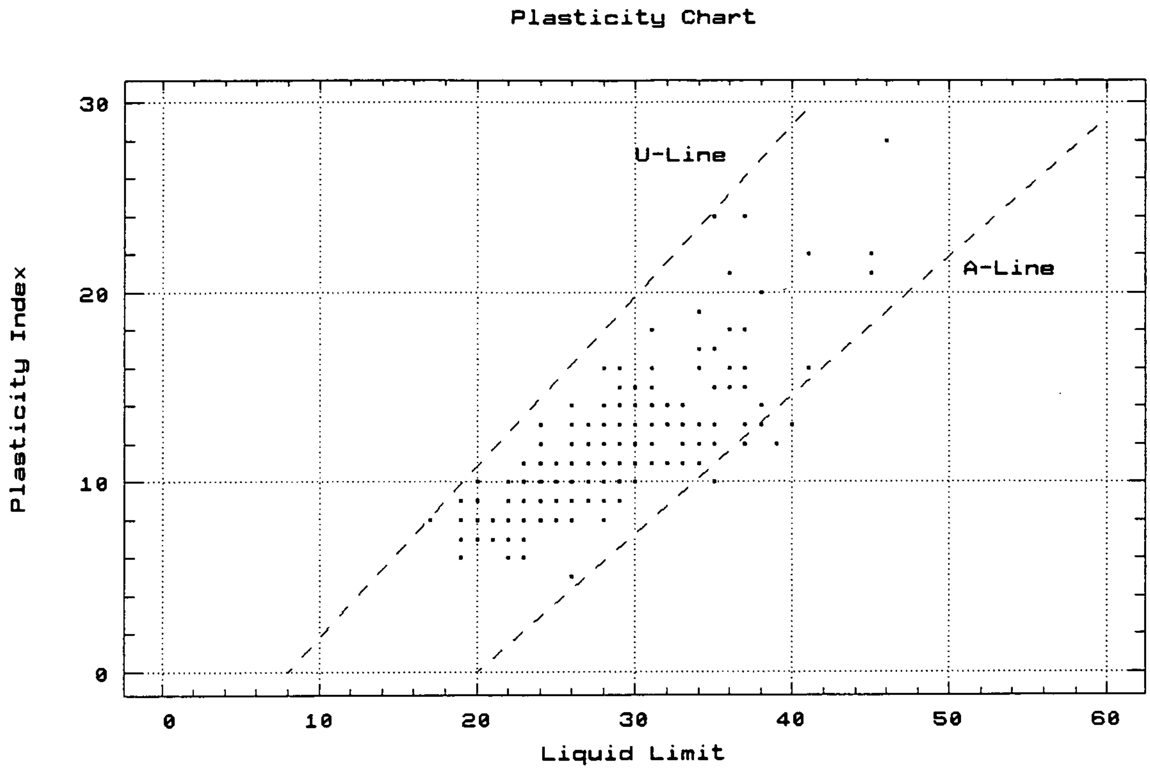


Figure 3.22: Plasticity chart for horizon Pa

The particle size distribution shows a wide range of particle size reflecting the mixture of argillaceous and arenaceous sediments from which the soils are derived. There is a large proportion of silt and clay. A kink in the curve may indicate some of the rock breaking down to fine sand particles of about 0,425 mm composing the parent rock. The particle size distribution curves appear in Figure 3.23.

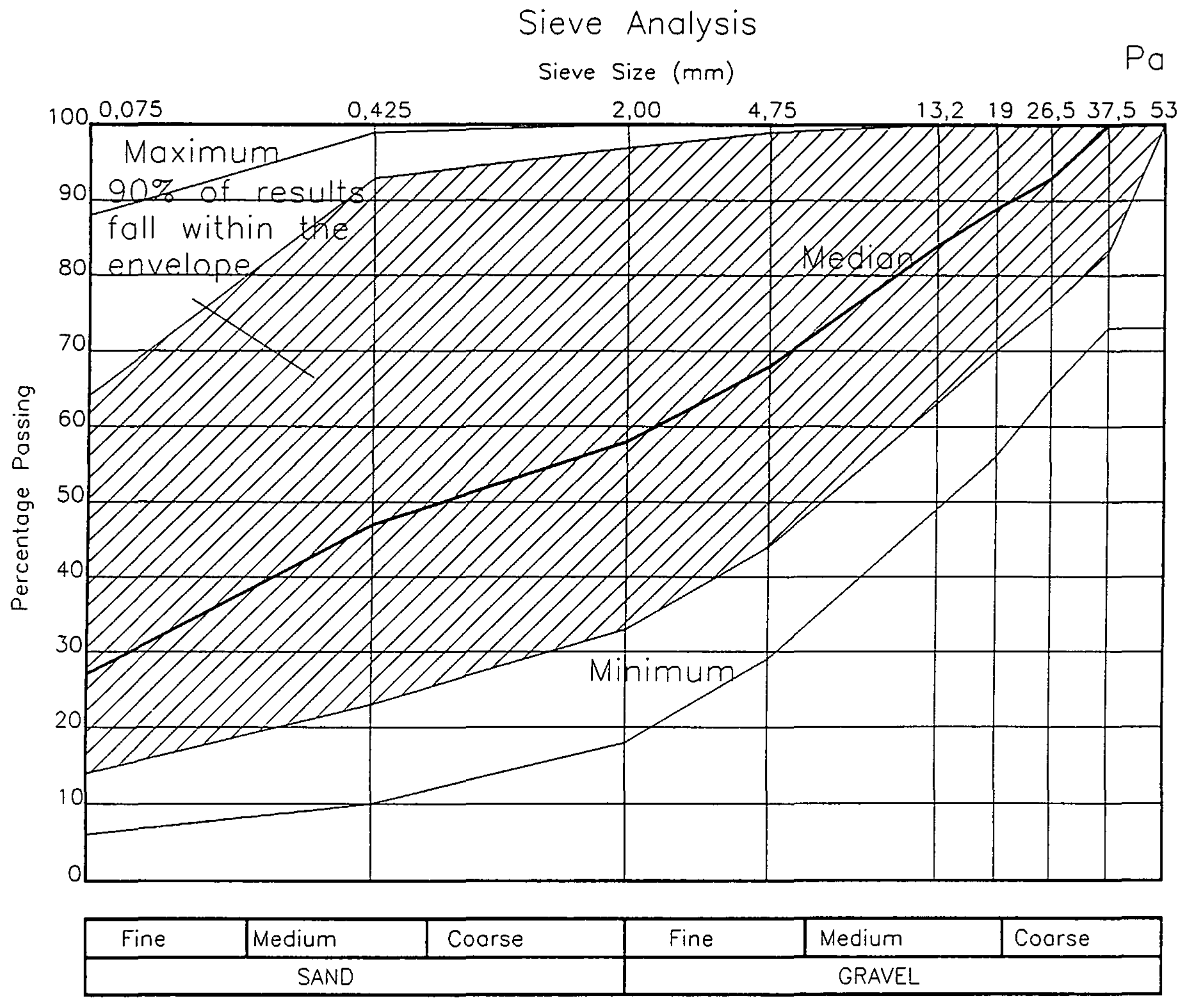


Figure 3.23: Particle size distribution for horizon Pa

3.5.1.7 Volksrust Shale Formation

The Volksrust Shale Formation consists entirely of soft shale, very much like that of the Pietermaritzburg Shale Formation (Geological Survey 1989), but contains numerous nodules, lenses and lenticular beds of calcium phosphate. Most of the materials were granular, largely (72%) classified as A-2, but 10% of the materials were classified as silty or clayey. All the soils studied were argillaceous. Twelve of the samples were described in the original documentation as "brown decomposed sandstone".

However the soil properties indicate that they are argillaceous rather than arenaceous. Most were shales (84%), the remainder being described as mudstone and silt. The classification appears in Table 3.18.

Table 3.18: Classification of Pvo horizon

AASHTO Class	Frequency	Relative Frequency %
A-1-a	16	5.8
A-1-b	10	3.6
A-2-4	108	38.8
A-2-6	103	37.1
A-2-7	14	5.0
A-4	14	5.0
A-5	3	1.0
A-6	8	2.8
A-7-5	2	0.7

The maximum dry density is plotted against optimum moisture content in Figure 3.24. The points cluster around the 5% air voids line corresponding to a specific gravity of 2,75, and a number lie above the 5% air voids line corresponding to a specific gravity of 3,0. This specific gravity is larger than would normally be expected in an argillaceous soil, and may possibly be due to the presence of calcium phosphate.

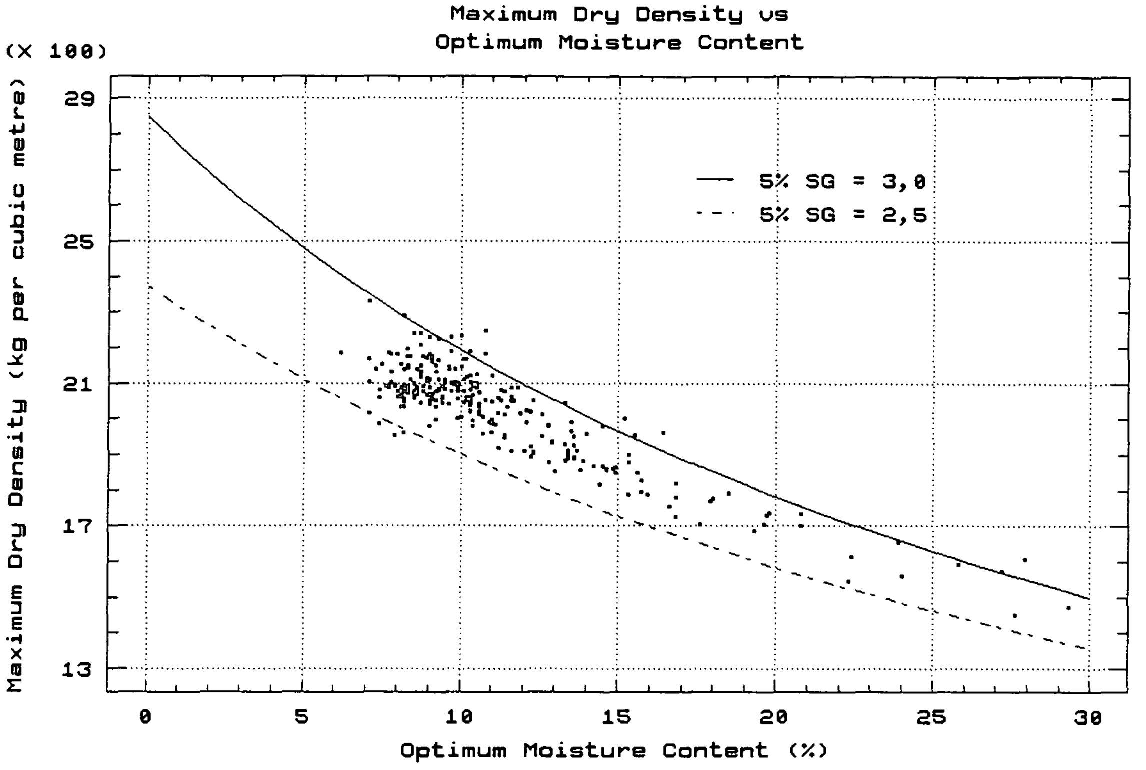


Figure 3.24: Maximum dry density vs optimum moisture content for soils from horizon Pvo

The optimum moisture content ranges between 7 and 30%, with some concentration between 7 and 11%. Other statistics appear in Table 3.19.

Table 3.19: Basic statistics for horizon Pvo

Variable: **Units where applicable**	**Maximum Dry Density** **kg/m³**	**Optimum Moisture Content** **%**
Sample size	278	278
Average	2019	11.20
Variance	20378	14.73
Standard deviation	143	3.84
Standard error	8.56	0.230
Minimum	1451	6.2
Maximum	2330	29.3
Range	879	23.1

On the plasticity chart, Figure 3.25, the plasticity results all plot well below the U-line. Most plot above the

A-line, in the region of clays of low plasticity, but some plot below the A-line in the region of silts of low and intermediate plasticity. The liquid limit of the soils ranges up to 50.

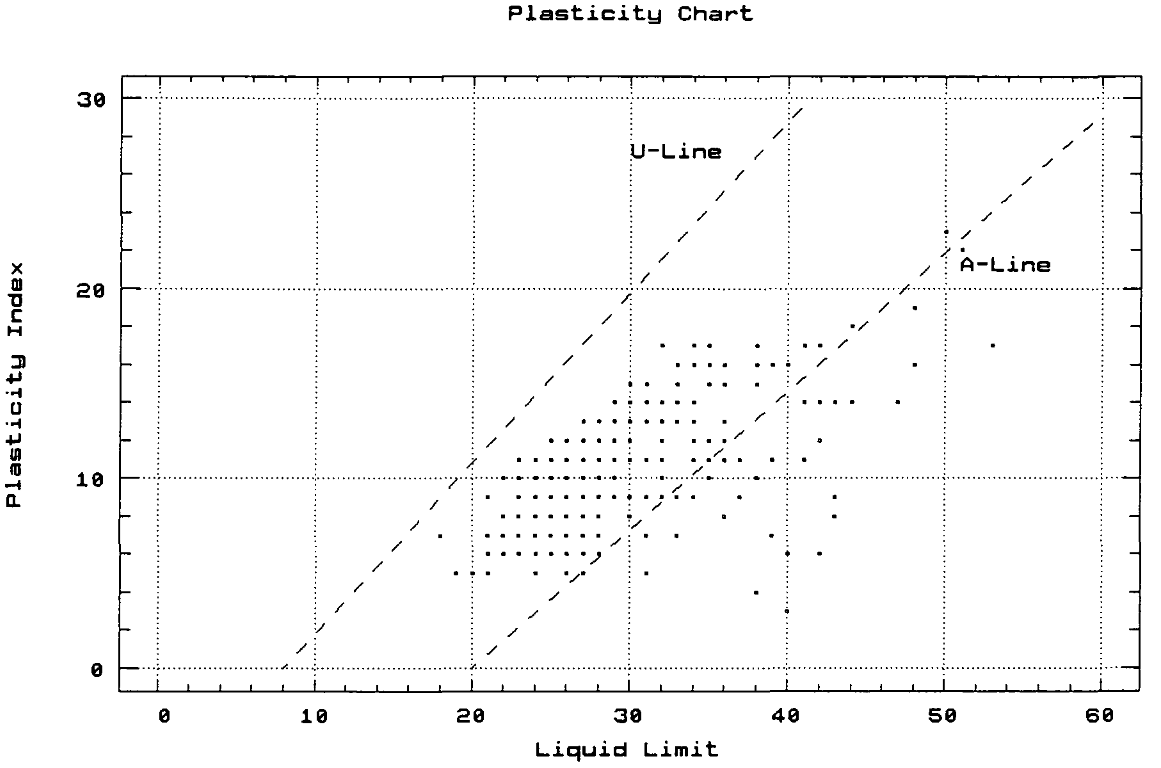


Figure 3.25: Plasticity chart for horizon Pvo

The particle size distribution, appearing in Figure 3.26,shows the wide range of particle sizes exhibited by this material.

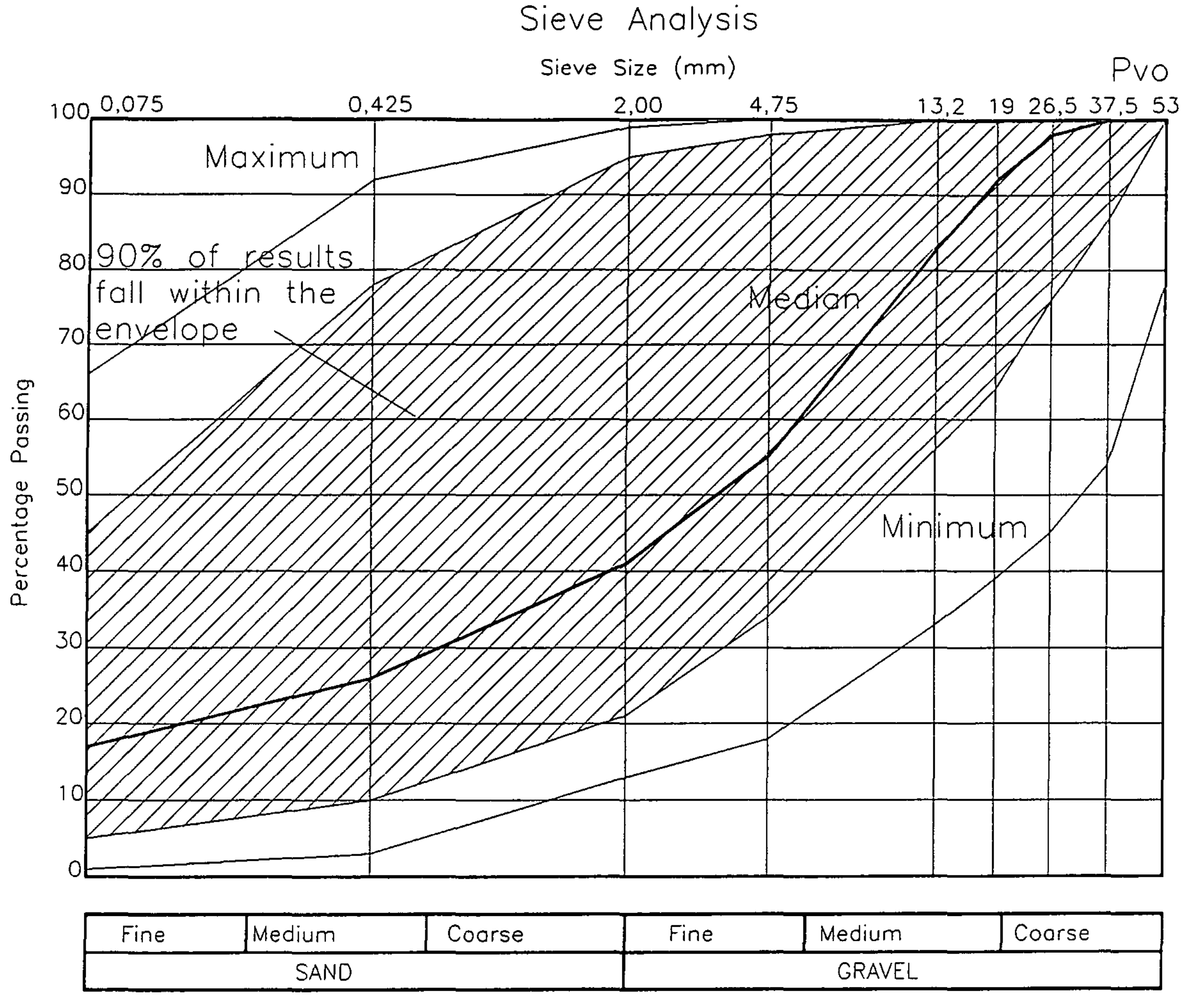


Figure 3.26: Particle size distribution for horizon Pvo

3.5.1.8 Archaean Granites

This group consists of all rocks north of the latitude of Empangeni described as granites in the source documents. They must be distinguished from the granites and metamorphosed sediments of the Natal Metamorphic Province. They consist of granites and granodiorites (Geological Survey 1989) not differentiated on the 1:1 000 000 geological map (Geological Survey 1984). The material is granular (96%), and consists largely of A-1 (48%) and A-2 (48%). The classification is shown in Table 3.20.

Table 3.20: Classification of ZB horizon

AASHTO Class	Frequency	Relative Frequency %
A-1-a	16	6.0
A-1-b	113	42.0
A-2-4	96	35.7
A-2-6	30	11.2
A-2-7	1	0.4
A-4	5	1.9
A-6	6	2.2
A-7-5	2	0.7

The maximum dry density of the material is plotted against its optimum moisture content in Figure 3.27. The points tend to follow the 5% air voids line corresponding to a specific gravity of about 2,65. Optimum moisture content is generally in a fairly narrow range between 5 and 10%, although a few samples show an optimum moisture content in the range 10 to 15%.

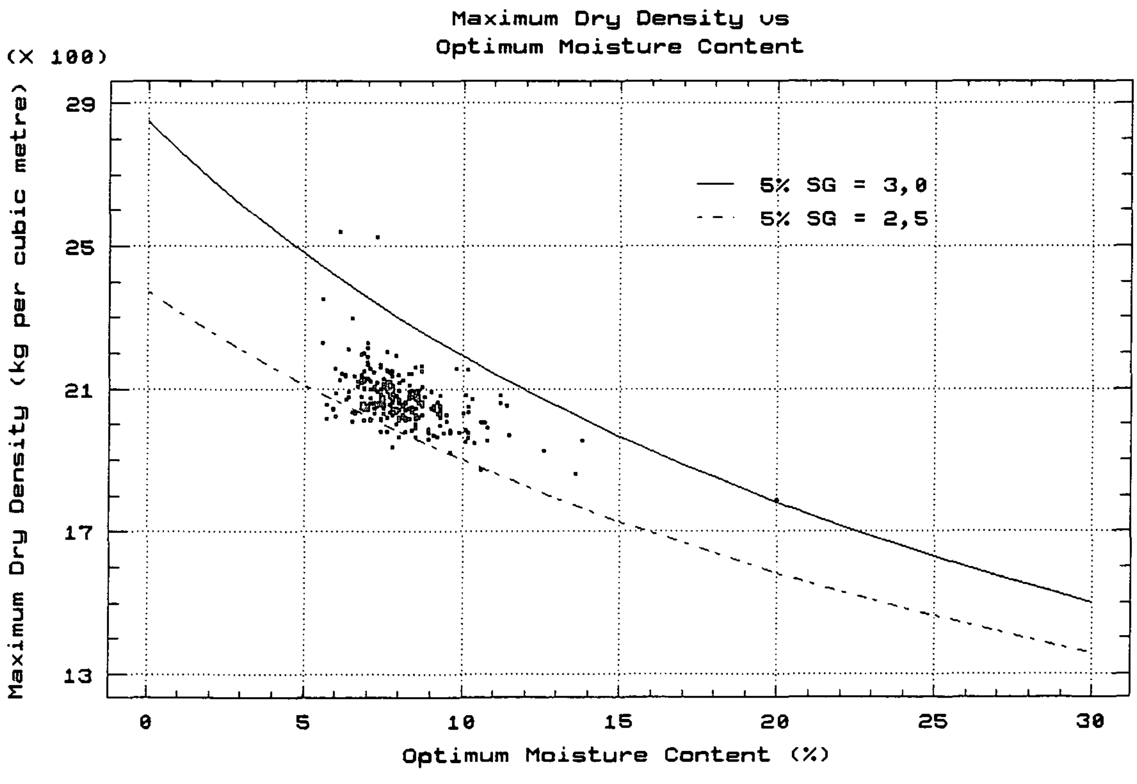


Figure 3.27: Maximum dry density vs optimum moisture content for soils from horizon ZB

The average optimum moisture content is 8,1%, with a standard deviation of 2,2%. Other statistics appear in Table 3.21.

Table 3.21: Basic statistics for horizon ZB

Variable: **Units where applicable**	**Maximum Dry Density** **kg/m³**	**Optimum Moisture Content** **%**
Sample size	269	269
Average	2068	8.09
Variance	6223	2.17
Standard deviation	78.9	1.47
Standard error	4.810	0.090
Minimum	1787	5.6
Maximum	2539	20
Range	752	14.4

All of the plasticity results of this group when plotted on a plasticity chart (Figure 3.28) fall well below the 'U' line and straddle the 'A' line, within the region classified as low to medium plastic inorganic clays and low plastic silts. This is consistent with the clay being predominantly kaolinite or kaolinite and illite which can be expected from the weathering of granitic rocks. The liquid limit is generally below 40.

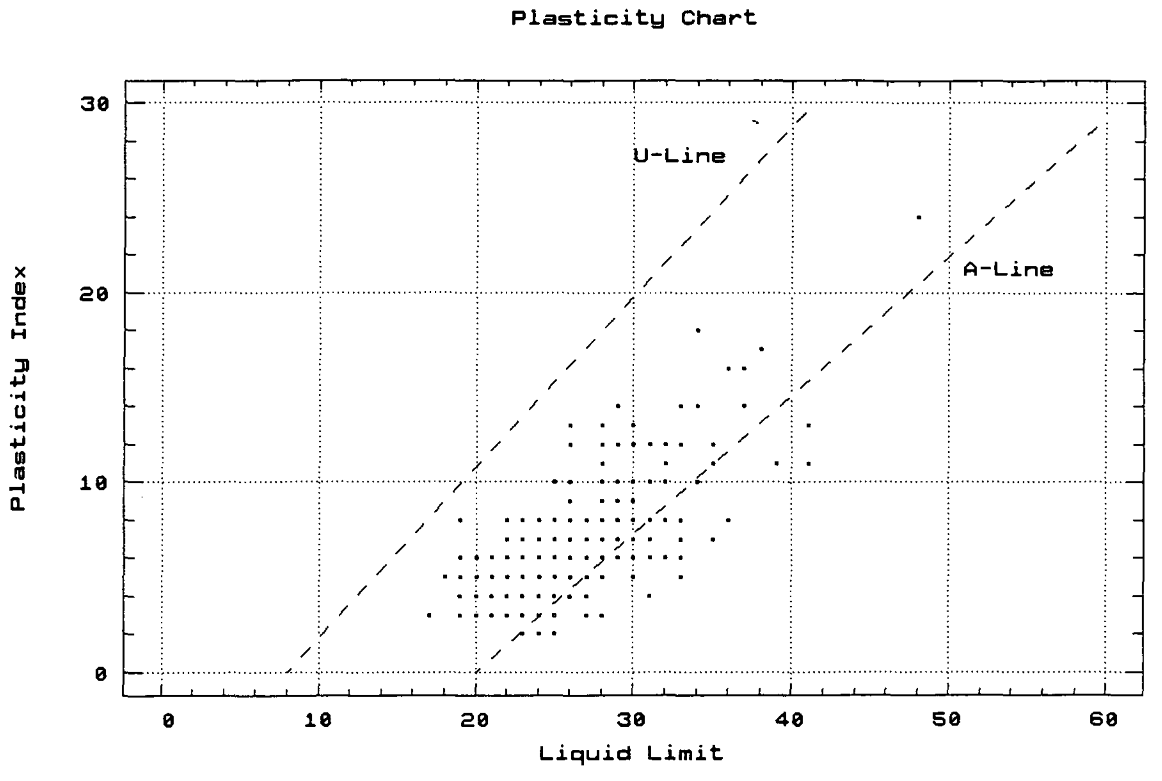


Figure 3.28: Plasticity chart for horizon ZB

The particle size distribution curves (Fig 3.29) indicate granular materials that are sandy, again reflecting the normal weathering products of granitic rocks. The material is well graded, with a moderate variation in particle size.

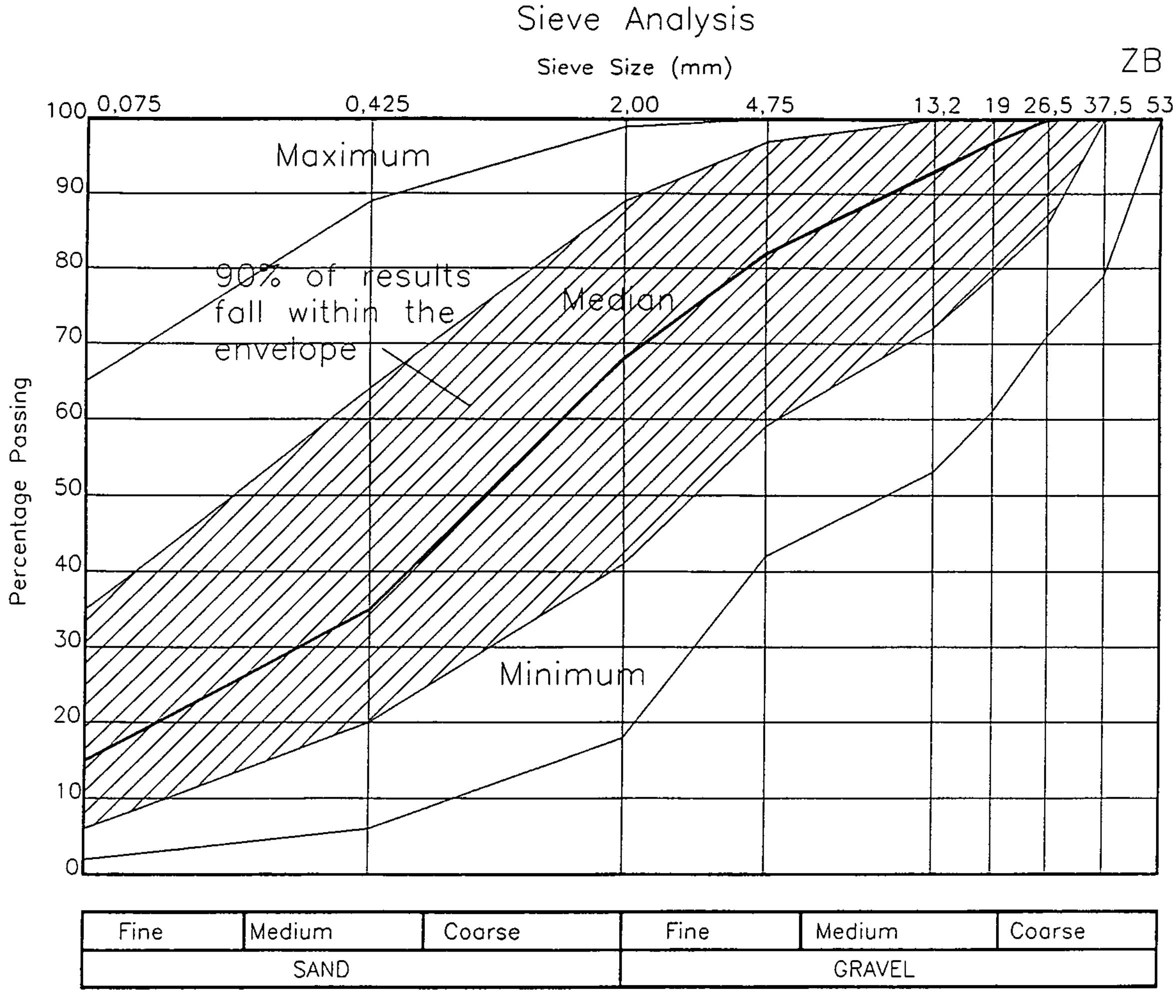


Figure 3.29: Particle size distribution for horizon ZB

3.5.1.9 Tarkastad Formation

The Tarkastad Formation consists sandstones and mudstones (Geological Survey 1989). The greater proportion (90%) of the materials were granular, with 85% classified as A-2. Argillaceous rocks constituted 36% of the materials studied, the remainder being described as sandstones. The classification appears in Table 3.22.

Table 3.22: Classification of TRt horizon

AASHTO Class	Frequency	Relative Frequency %
A-1-a	1	0.8
A-1-b	10	3.3
A-2-4	179	68.8
A-2-6	43	16.8
A-2-7	1	0.8
A-4	25	9.8
A-6	1	0.8
A-7-5	1	0.8

The maximum dry density is plotted against optimum moisture content in Figure 3.30. The points lie approximately along the 5% air voids line corresponding to a specific gravity of 2,8, which is rather higher than would be expected, but may be due to the presence of calcareous nodules.

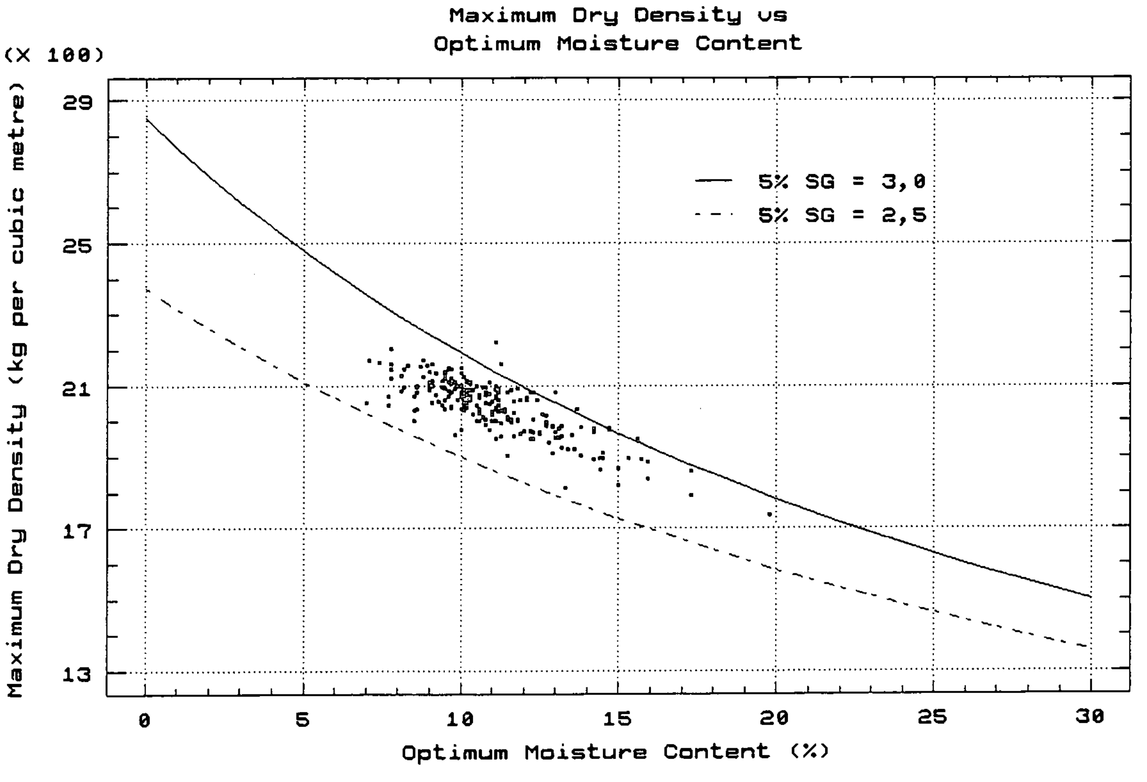


Figure 3.30: Maximum dry density vs optimum moisture content for soils from horizon TRt

The optimum moisture content ranges between 7 and 20%, with some concentration of points at about 10%. Other statistics appear in Table 3.23.

Table 3.23: Basic statistics for horizon TRt

Variable: Units where applicable	Maximum Dry Density kg/m^3	Optimum Moisture Content %
Sample size	261	261
Average	1974.68	11.13
Variance	11311.6	7.00
Standard deviation	106.351	2.65
Standard error	6.58298	0.164
Minimum	1600	5.4
Maximum	2230	24.8
Range	630	19.4

On the plasticity chart, Figure 3.31, the plasticity results all plot well below the U-line, and most plot above the A-line, in the region of clays of low plasticity. The liquid limit of most of the soils is less than 40.

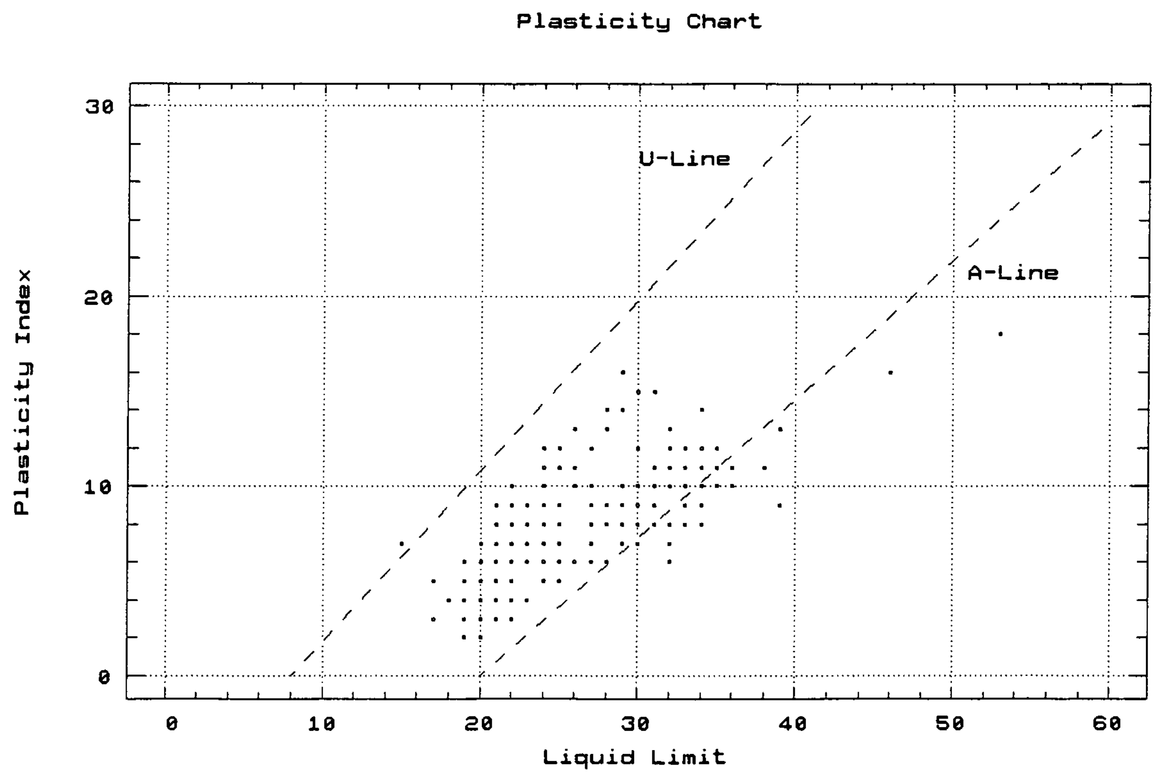


Figure 3.31: Plasticity chart for horizon TRt

The particle size distribution, appearing in Figure 3.32,shows the wide range of particle sizes exhibited by this material, and a high proportion of silt and clay. A change in gradient of the median curve at 0,425 mm indicates that some of the arenaceous parent material may have decomposed to its original fine sand size particles.

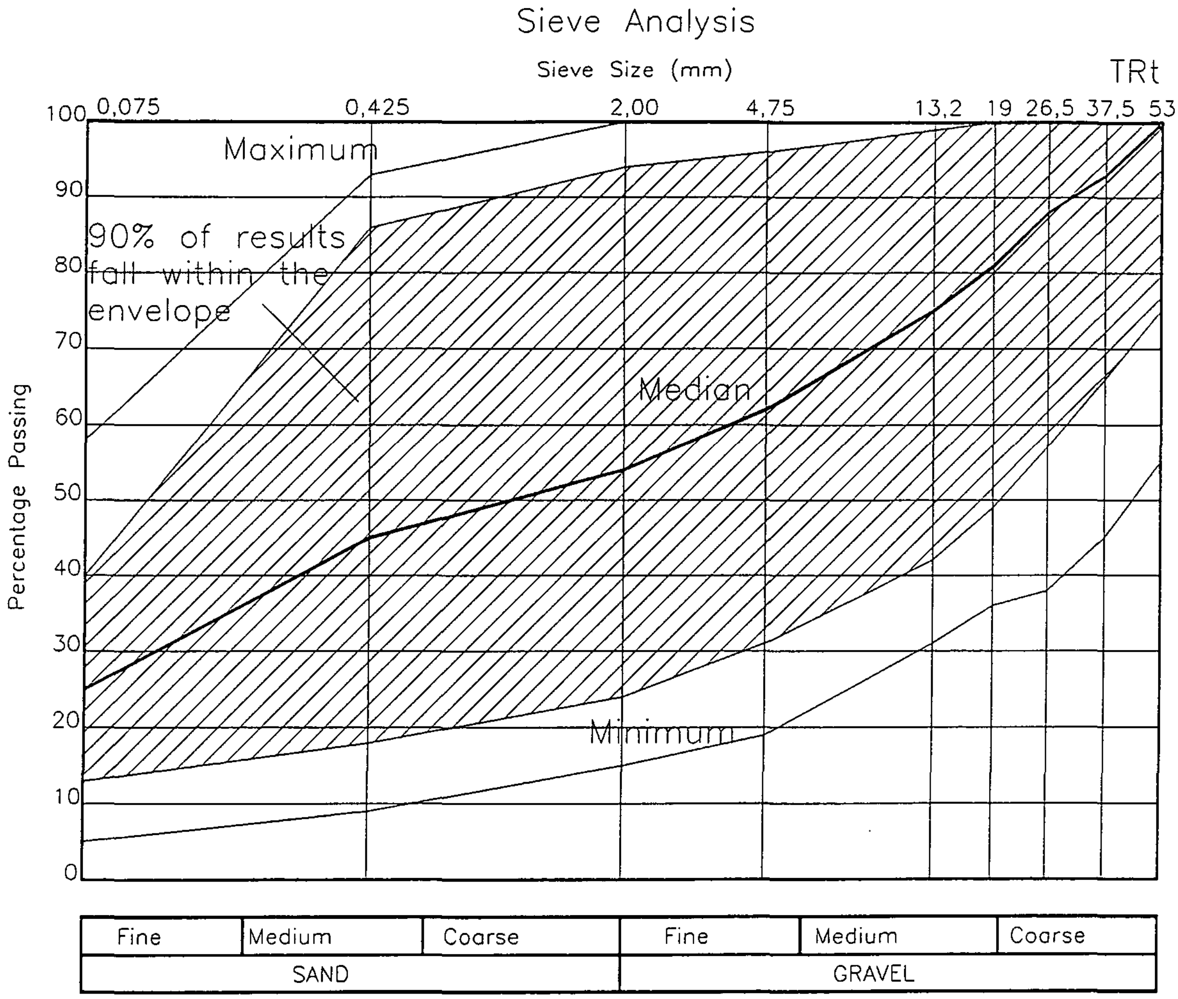


Figure 3.32: Particle size distribution for horizon TRt

3.5.1.10 Pietermaritzburg Shale Formation

The Pietermaritzburg Shale Formation is part of the Ecca Group of the Karoo Sequence (South African Committee for Stratigraphy 1980) and is composed entirely of fissile shales and mudstones (Geological Survey 1989). The materials studied were all described as shales or mudstones. Some 91% of the materials are granular, the rest being classified as silty or clayey. Most of the granular material is classified as A-2 (84%). The classification is shown in Table 3.24.

Table 3.24: Classification of Pp horizon.

AASHTO Class	**Frequency**	**Relative Frequency %**
A-1-a	5	2.8
A-1-b	9	3.5
A-2-4	103	42.2
A-2-5	1	0.2
A-2-6	99	41.5
A-2-7	1	0.2
A-4	13	5.2
A-6	9	3.5

The maximum dry density of the material is plotted against optimum moisture content in Figure 3.33. The points tend to follow the 5% air voids line corresponding to a specific gravity of about 2,8. This figure may appear to be high for an argillaceous material, but it is consistent with published values of specific gravity of about 2,77 (Rowlands 1984).

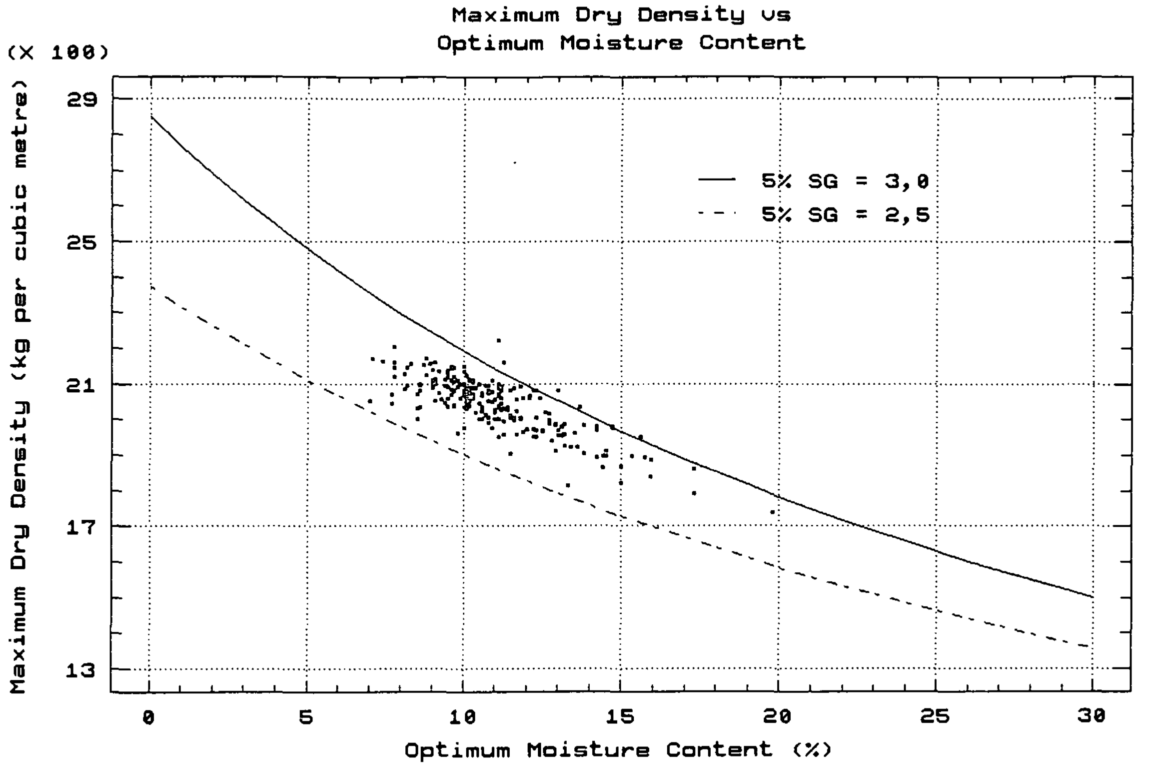


Figure 3.33: Maximum dry density vs optimum moisture content for soils from horizon Pp

The optimum moisture content generally falls between 7 and 15%, but ranges as high as 20%. The mean optimum moisture content is 10,9% with a standard deviation of 1,95%. Other statistics are presented in Table 3.25.

Table 3.25: Basic statistics for horizon Pp

Variable: **Units where applicable**	**Maximum Dry Density** **kg/m³**	**Optimum Moisture Content** **%**
Sample size	240	240
Average	2043	10.94
Variance	5939	3.80
Standard deviation	77	1.95
Standard error	4.97	0.126
Minimum	1736	7.0
Maximum	2223	19.8
Range	487	12.8

All the plasticity results when plotted on a plasticity chart, shown in Figure 3.34, fall below, and generally well below, the 'U' line. The majority plot above the 'A' line, but a considerable number fall below it. This corresponds to clays and silts of low plasticity. The liquid limit is generally less than 40.

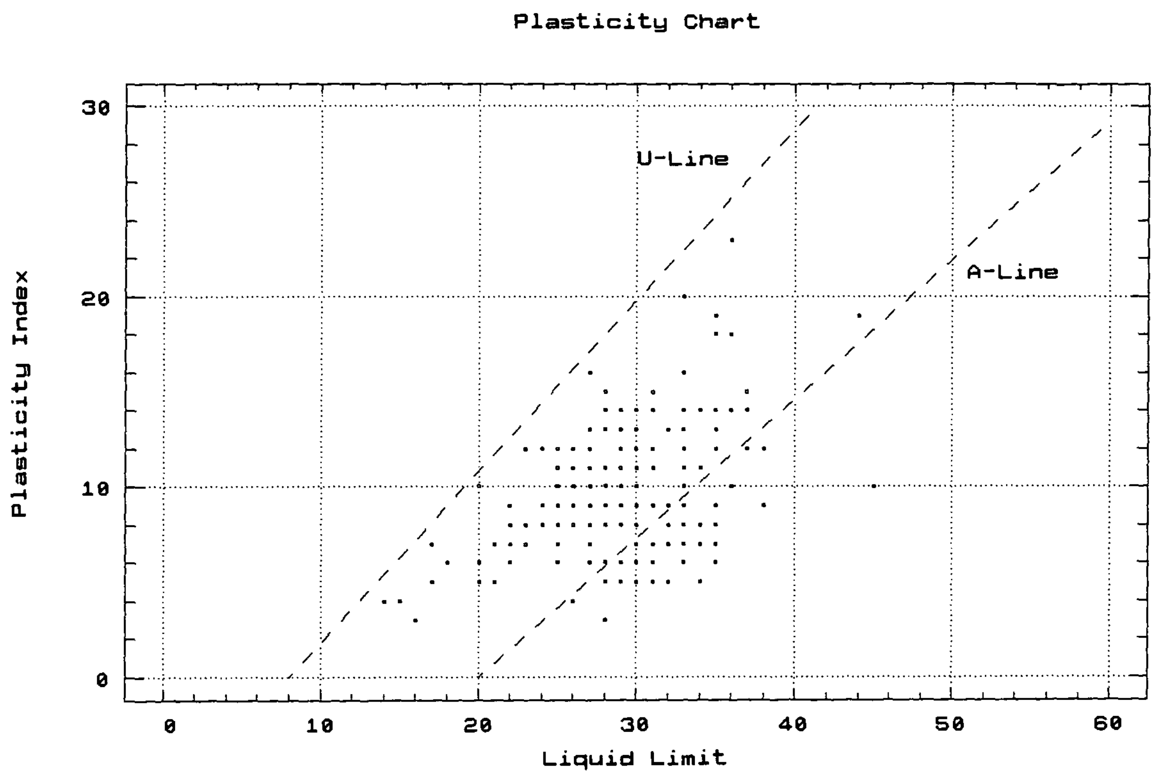


Figure 3.34: Plasticity chart for horizon Pp

The particle size distribution, shown in Figure 3.35, exhibits a wide range of particle size, which reflects the variable nature of the parent materials. The median curve shows equal proportions of gravel to sand, silt and clay. There is generally a high proportion of silt and clay.

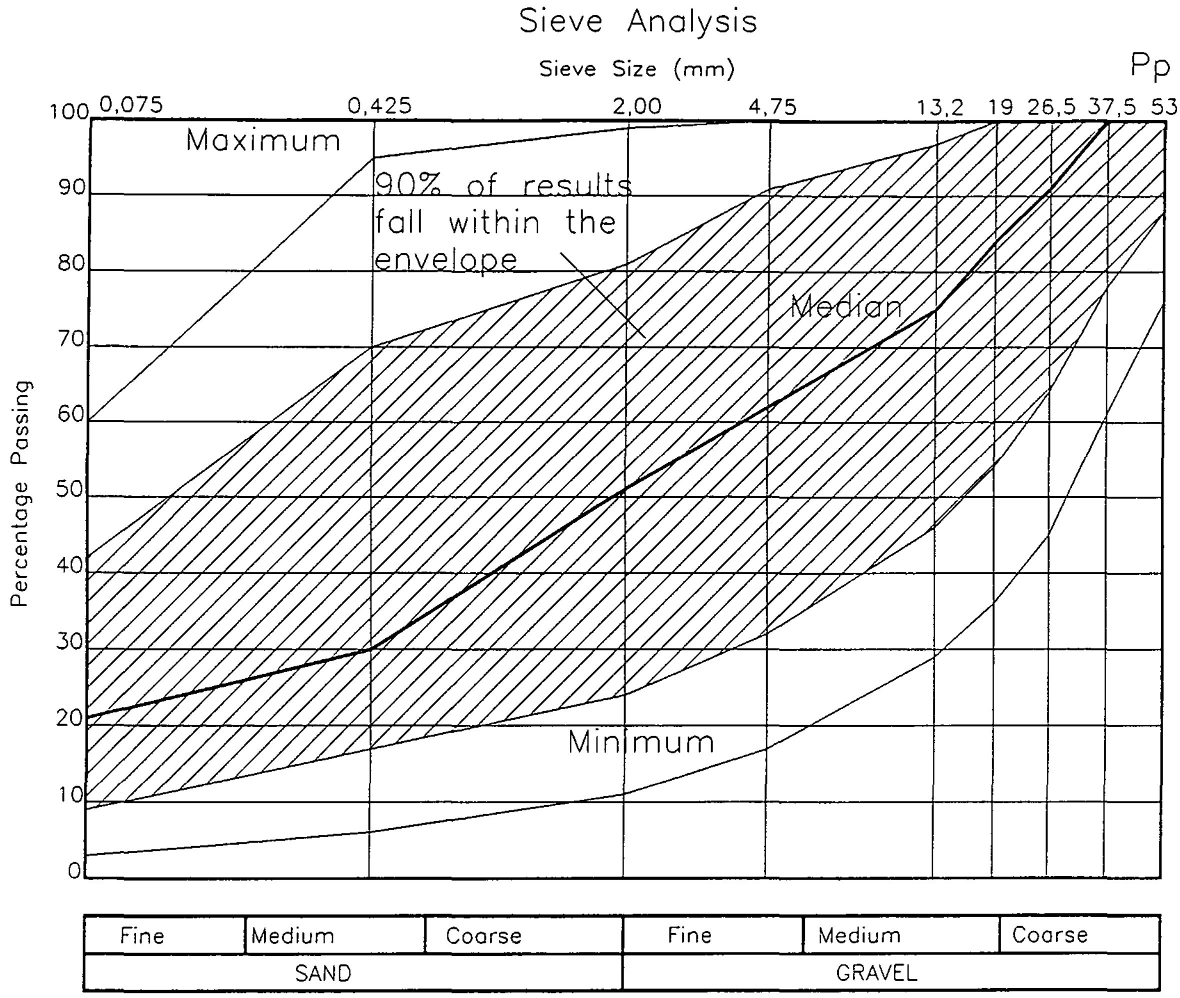


Figure 3.35: Particle size distribution for horizon Pp

3.5.1.11 Dwyka Formation

The Dwyka Formation forms the base of the Ecca Group of the Karoo Sequence (South African Committee for Stratigraphy 1980) and is composed of diamictite and mudstone of glacial origin (Geological Survey 1989). The materials studied were all described as tillite. Most of the materials of this group were granular (81%) and classified as A-2 (67%) but 19% was classified as silty or clayey. The classification is shown in Table 3.26.

Table 3.26: Classification of C-Pd horizon.

AASHTO Class	Frequency	Relative Frequency %
A-1-a	6	3.4
A-1-b	19	10.7
A-2-4	98	55.4
A-2-6	21	11.9
A-4	20	11.3
A-6	11	6.2
A-7-5	2	1.1

The maximum dry density of the material is plotted against optimum moisture content in Figure 3.36. The points tend to follow the 5% air voids line corresponding to a specific gravity of about 2,7.

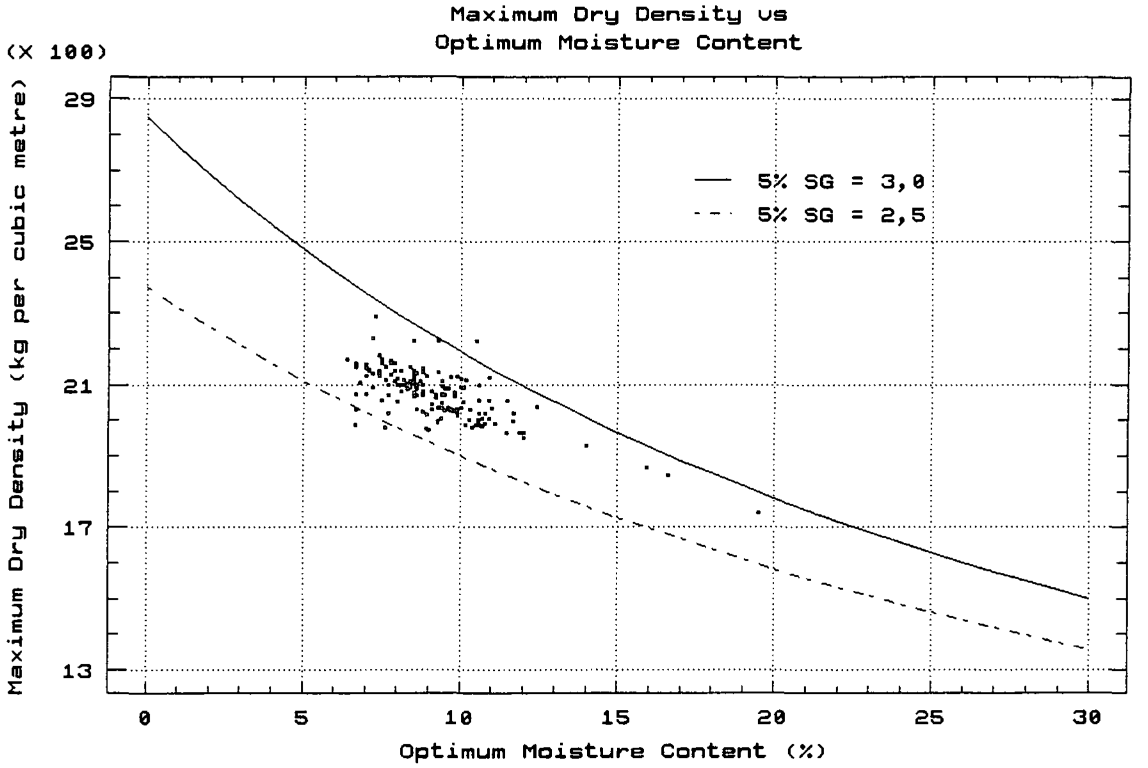


Figure 3.36: Maximum dry density vs optimum moisture content for soils from horizon C-Pd

The optimum moisture content generally falls between 5 and 12%, with a few results reaching 20%. The mean optimum moisture content is 9,3% with a standard deviation of 1,79%. Other statistics are presented in Table 3.27.

Table 3.27: Basic statistics for horizon C-Pd

Variable: Units where applicable	Maximum Dry Density kg/m^3	Optimum Moisture Content %
Sample size	177	177
Average	2075	9.27
Variance	5656	3.19
Standard deviation	75	1.79
Standard error	5.65	0.134
Minimum	1740	6.4
Maximum	2291	19.5
Range	551	13.1

With the exception of a single value, all the plasticity results when plotted on a plasticity chart, shown in Figure 3.37, fall below, and generally well below, the 'U' line. The majority plot above the 'A' line, but a few straddle it, corresponding to clays and silts of low plasticity. The liquid limit is generally less than 30, but a few values of liquid limit do lie between 30 and 41.

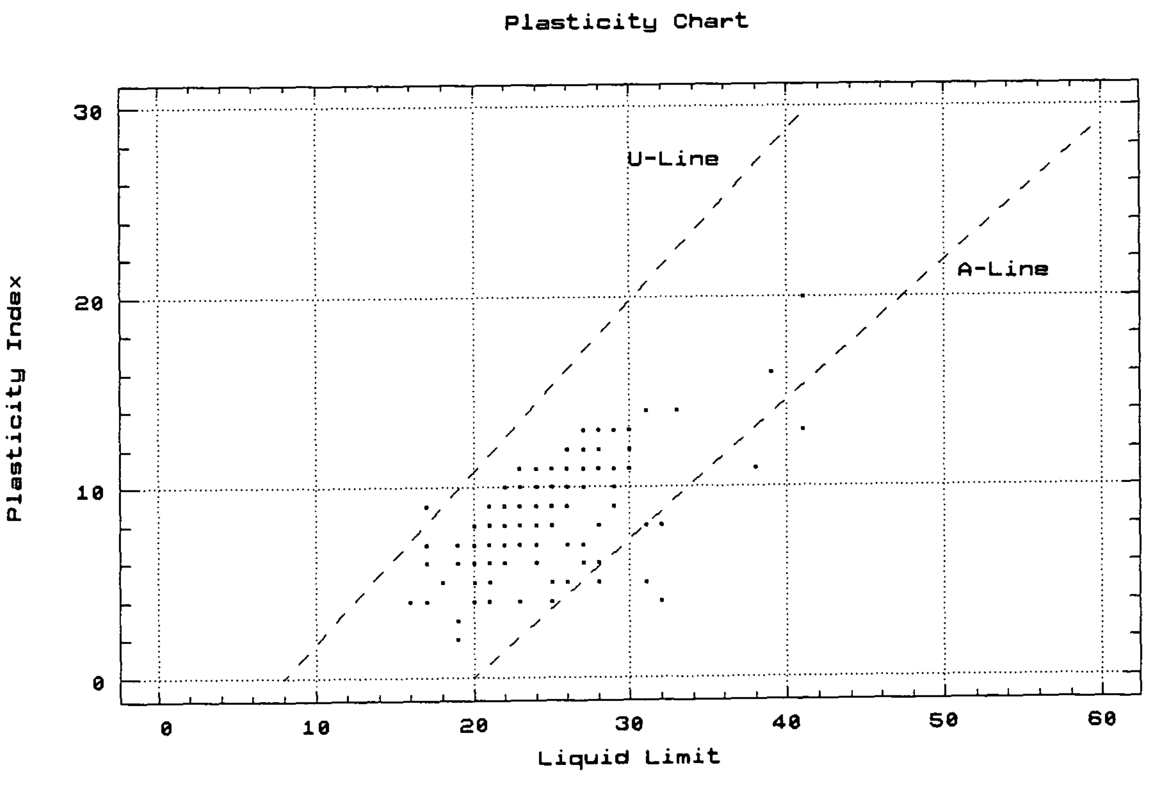


Figure 3.37: Plasticity chart for horizon C-Pd

The particle size distribution, shown in Figure 3.38, exhibits a moderate range of particle size. There is generally a high proportion of silt and clay.

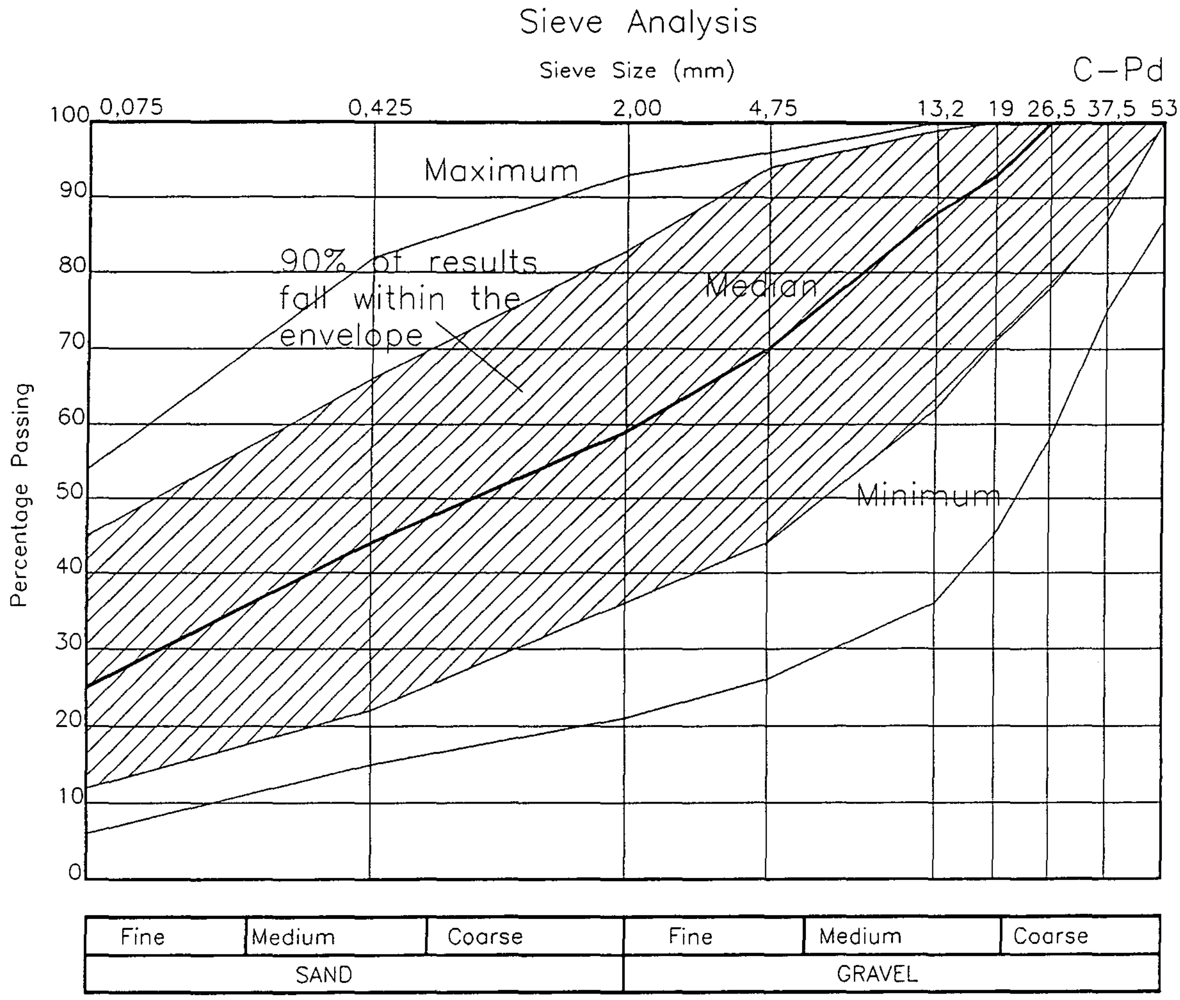


Figure 3.38: Particle size distribution for horizon C-Pd

3.5.1.12 Recent Sands

All the materials of this group used in this study were obtained from a single location, the route of MR 572 between the Pongola River and Kosi Bay, on the Zululand coastal plain 20 to 30 km south of the Mozambique border. They consist of aeolian sand similar to the Berea Formation sand from which they are derived (Geological Survey 1989). For this reason, the results do not apply to other Recent deposits, which may have totally different origins and properties. The soil is a single size non-plastic fine sand, classified as A-3. This is exhibited clearly in the particle size distribution curves of Figure 3.39.

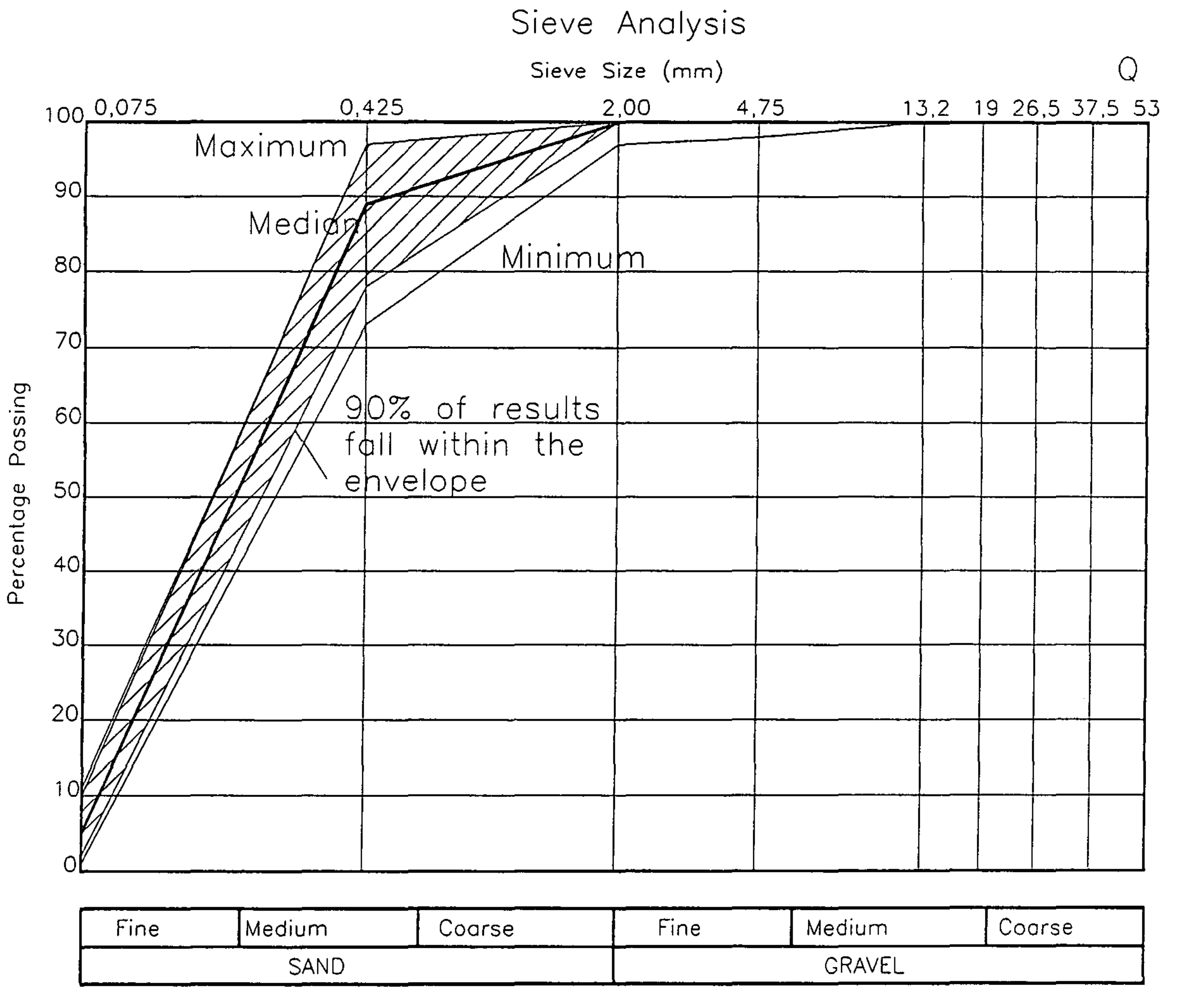


Figure 3.39: Particle size distribution for horizon Q

The plot of maximum dry density against optimum moisture content, Figure 3.40, shows no correlation at all to any constant air voids line. The maximum dry density appears to be more or less constant at 1700 kg/m^3, and independent of the optimum moisture content.

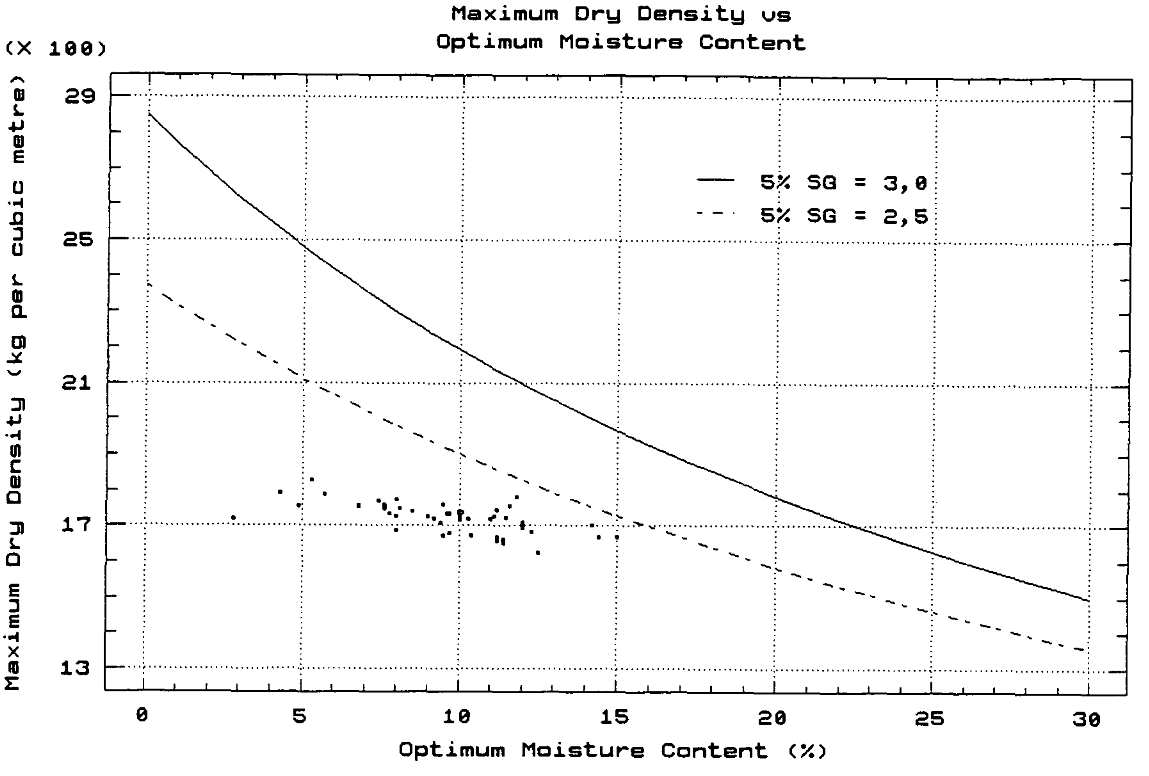


Figure 3.40: Maximum dry density vs optimum moisture content for soils from horizon Q

The optimum moisture content varies from 3 to 15%, an optimum moisture content of 15% corresponding to a soil having a specific gravity of 2,5 and an air voids content of 5%. The average optimum moisture content is 9,6%, with a standard deviation of 2,5%. The remaining statistics are presented in Table 3.28.

Table 3.28: Basic statistics for horizon Q

Variable: **Units where applicable**	**Maximum Dry Density** **kg/m³**	**Optimum Moisture Content** **%**
Sample size	53	53
Average	1720	9.60
Variance	1689	6.19
Standard deviation	41	2.49
Standard error	5.64	0.342
Minimum	1626	2.8
Maximum	1828	15
Range	202	12.2

3.5.2 A comparison of Karoo mudstones and sandstones

The sedimentary formations of the Karoo Sequence that form part of this study are shown in chronological order in Table 3.29.

Table 3.29: Formations of the Karoo Sequence included in this study

Group	Formation	Rock type
Beaufort	Tarkastad	Sandstone, Mudstone
	Adelaide	Mudstone, Sandstone
Ecca	Volksrust Shale	Shale
	Vryheid	Sandstone
	Pietermaritzburg Shale	Shale

All the Karoo Sequence materials exhibit a wide range of particle size distribution. The shape of the median curve of the two shale formations (Figures 3.26 and 3.35) differs markedly from the single sandstone formation. The shale curve slopes steeply in the gravel sizes, then the slope flattens at the 2,00 mm size, with gravel contents of 50 to 60 %, indicating relatively fresh material which would be required to meet subgrade specifications. The median curve of the sandstone (Figure 3.20) has a completely different shape, with a gentle slope as far as the 2,00 mm size and a gravel content of only 25%, and then a steep slope between 2,00 mm and 0,075 mm. This may be due to the sandstone having weathered to a greater degree than the shale. The median particle size distribution curves of the Beaufort Group materials (Figures 3.23 and 3.32) show characteristics similar to the shale curves in the gravel sizes, and to the sandstone in the sand sizes. Most of the material from all the formations is classified as A-2. The

A-2 portion is almost equally divided between A-2-4 and A-2-6, except for the Vryheid Formation sandstone and the Tarkastad Formation sandstone and shale, where the preponderance of sandstone and the corresponding lower plasticity results in a higher proportion of A-2-4 material.

3.5.3 Comparison of granitic materials

All the materials classified as Namibian Intrusives and Metamorphics, and Archaean Granites were described as granites. Both groups of material show a similar distribution of points on the plot of maximum dry density versus optimum moisture content and the plasticity chart, while the median curves of the two particle size distributions are almost identical, although the particle size distribution of Archaean Granites samples has a greater variation, notwithstanding the smaller sample size.

3.5.4 Comparison of Berea Formation and Recent sands

Both of these materials are very similar, as a result of the Recent sands being derived from the Berea Formation Sands. This observation is not necessarily true for Recent sands derived from other sources, and it should be noted that the Recent sands in this study constituted a small sample from a single location. Both types of sand were single sized. Some of the Berea Formation sands were clayey and plastic, but the entire sample of Recent sands was non-plastic.

3.5.5 Summary

Materials from different geological horizons show different and distinctive properties. However, materials from horizons that are related by broader geological classification, and materials that are of similar composition, show broad similarities although maintaining distinctive differences in detail. It is therefore reasonable to classify the materials by geological horizon, and to subdivide them further by rock type for further investigation. It is also reasonable to investigate the materials subdivided by rock type. However, it is expected that groups of material subdivided by both horizon and rock type will show the greatest similarity of properties. Classification of the material using Weinert's classification (Weinert 1980) will also be used, but it is not expected that this will be any better than the classification by rock type, since the two classifications overlap considerably.

That subtle differences in geological horizon were reflected in the soil test results, and that these results agree with published values, indicates that the data used in the study is valid, and supports the decision to obtain results from a single source. It also indicates that the system of check testing and supervision employed by the Kwazulu Natal Provincial Administration Roads Branch is effective. The geographical distribution of data makes it reasonable to assume that it is representative of the province as a whole.

Chapter 4

ANALYSIS OF THE DATA FOR THE FIRST SUB-PROBLEM

The first sub-problem is to analyse the factors influencing the relationship between soil properties used for classification and identification, and optimum moisture content in order to identify and quantify those that are most effective in predicting optimum moisture content.

The soil properties used for classification and identification are plasticity and particle size distribution.

4.1 Plasticity

Plasticity is described by the Plasticity Index (usually abbreviated to PI), which is obtained from two measurements of the soil, the Liquid Limit (usually abbreviated to LL) and the Plastic Limit (usually abbreviated to PL). The procedure for obtaining the liquid limit is described in Method A2 of TMH1 (1986), and is defined there as "the moisture content, expressed as a percentage of the mass of oven-dried soil, at the boundary between the liquid and the plastic states.". The boundary is established by using the Casagrande apparatus. The procedure for the determination of the plastic limit and the plasticity index is laid out in Method A3 of TMH1 (1986). The plastic limit is defined in Method A3 as "the moisture content, expressed as a percentage of the oven-dried soil, at the boundary between the plastic and semi-solid states.". The plasticity index is the range of moisture content over which the soil is plastic measured by the numerical difference between the liquid limit and the plastic limit. The plasticity data collected for this study consisted of the liquid limit and the plasticity index. If the liquid limit cannot be determined, but the soil feels slightly plastic, then both the liquid limit and the plasticity index are recorded as SP (slightly plastic). In this study, a soil classified as SP was regarded as having a plasticity index of 0, since the soil was slightly plastic but not sufficiently plastic to have a plasticity index of 1. On the basis of plasticity, the data set was divided into the three groups set out in table 4.1 below.

Table 4.1: Data groups based on plasticity.

Group	Size	Description
NPA1P	4362	Plastic samples PI > 0 and LL > 0
NPA1PS	4810	Plastic and slightly plastic samples PI ≥ 0
NPA1NP	595	Non plastic samples

Group NPA1P was used to analyse the effects of liquid limit and plastic limit, while NPA1PS was used to analyse the effects of plasticity index.

Plasticity tests are carried out on material that is finer than 0,425 mm. In order to correct for the proportion of soil used in the plasticity tests, the plasticity index and liquid limit were multiplied by the ratio of soil finer than 0,425 mm to the total amount of soil. The terms "Plasticity Index Modulus" and "Liquid Limit Modulus" were coined for these two corrected parameters respectively. The plasticity parameters used in the analyses are summarized in Table 4.2 below.

Table 4.2: Summary of plasticity parameters used in analysis.

Parameter	**Description**
PI	Plasticity Index. This included samples described as "slightly plastic", which were assigned a value of 0.
PIMOD	Plasticity Index Modulus. This is the PI, corrected for the proportion of material used in the determination of the PI. $PIMOD = \frac{\% \text{ passing } 0,425 \text{ mm} \times PI}{100}$
LL	Liquid Limit. This did not include samples described as "slightly plastic".
LLMOD	Liquid Limit Modulus. This is the liquid limit, corrected for the proportion of material used in the determination of the liquid limit. $LLMOD = \frac{\% \text{ passing } 0,425 \text{ mm} \times LL}{100}$
PL	Plastic Limit. PL = LL - PI.

4.2 Models for predicting optimum moisture content based on plasticity parameters

Two models were considered for predicting optimum moisture content from plasticity parameters. They are the *linear model* having the form

$$OMC = a_0 + a_1 P \qquad (4.1)$$

OMC = optimum moisture content

a_n = regression coefficient

P = one of PI, PIMOD, LL, LLMOD, PL

and *Semmelink's model* (Equation 2.13).

4.2.1 The linear model

The first step in the analysis was to apply Equation 4.1 to all the plastic materials. The results are shown in Table 4.3 below.

Table 4.3: Results of linear regression analysis on all plastic materials.

	Independent variable				
Statistic	**PI**	**PIMOD**	**LL**	**LLMOD**	**PL**
mean x	7,8	3,1	26,8	10,6	18,2
mean OMC	9,3	9,3	9,4	9,4	9,4
Sdv x	5,4	5,8	4,3	3,7	2,5
Sdv OMC	2,3	2,3	2,3	2,3	2,3
a_0	8,20	8,13	4,90	7,45	6,08
a_1	0,147	0,393	0,169	0,185	0,184
n	4810	4810	4362	4362	4362
r	0,276	0,431	0,388	0,459	0,294
t_r	19,9	33,1	27,8	34,1	20,3
Conf Lim	±4,30	±4,04	±4,23	±4,08	±4,39

mean x = the mean of the independent variable

mean OMC = the mean optimum moisture content

Sdv x = the standard deviation of the independent variable

Sdv OMC = the standard deviation of the optimum moisture content

a_0, a_1 = the regression coefficients

n = the size of the sample

r = the coefficient of correlation

t_r = the T-statistic for the coefficient of correlation

Conf Lim = the minimum error bound within which predictions of optimum moisture content will lie at the 95% level of confidence. This minimum occurs at the mean value of the independent variable.

In order to investigate whether the coefficients of correlation are significant, the ***t*** test can be employed. The null hypothesis is that the coefficient of correlation is zero (there is no correlation between the independent variables and optimum moisture content) and its alternative is that the coefficient of correlation is not equal to zero (there is a correlation between the independent variables and optimum moisture content). For the null hypothesis to be rejected and the alternative hypothesis accepted, the value of t_r must exceed the value of ***t*** corresponding to the level of confidence required and the number of degrees of freedom. In this case the value of ***t*** for 95% confidence limits (two tailed test) and ∞ degrees of freedom, obtained from Biometrika (1976,Table 12) is 1,96. Each of the values of t_r exceeds this, and the alternative hypothesis, that there is a correlation between optimum moisture content and the plasticity parameters must be accepted. Optimum moisture content increases with an increase of each of the plasticity parameters.

The correlation between some plasticity parameters and optimum moisture content appears to be better than others. The relative merits of each of the correlation coefficients can be investigated by calculating the statistic ***z*** due to Fisher (Biometrika 1976, p 30) for the difference between two correlation coefficients. The statistic z has a mean of 0 and a standard deviation of 1, and so can be related to the normal curve. For a confidence level of 95%, the difference between two correlation coefficients is significant if $|z| > 1,96$ (Biometrika 1976, Table 4). The values of z appear in Table 4.4 below.

Table 4.4: Table of z for differences of correlation coefficient between optimum moisture content and various plasticity parameters.

	PI	PIMOD	LL	LLMOD	PL
PI	0	-8,73	-6,02	-10,2	-0,932
PIMOD	8,73	0	2,50	- 1,66	7,59
LL	6,02	-2,50	0	- 4,06	4,97
LLMOD	10,2	1,66	4,06	0	9,02
PL	0,932	-7,59	-4,97	- 9,02	0

To read Table 4.4, select the row containing the plasticity parameter of interest. Reading along the row, the values represent z for the difference between the coefficient of correlation of the parameter in the row and the column. If the value is positive, then the coefficient of correlation of the parameter at the beginning of the row is greater than the coefficient of correlation of the parameter at the head of the column. If the absolute value of z is greater than 1,96, then the difference is significant at the 95% level of confidence.

Table 4.3 shows that the largest coefficients of correlation are between optimum moisture content and liquid limit modulus and optimum moisture content and plasticity index modulus. Table 4.4 indicates that there is no significant difference between these coefficients. It shows also that an improvement is achieved by correcting plasticity index and liquid limit for the proportion of material used in the determination of the plasticity index. The coefficient of correlation of the plastic limit is not significantly larger than the coefficient of correlation of the plasticity index, and is significantly lower than that of the liquid limit.

Although all the correlations are statistically significant, at best only just over 20% of the variation in the relationships between optimum moisture content and the plasticity parameters is explained by the correlations. As a result, at best the optimum moisture content can be predicted to ±4,1 percentage points at the 95% level of confidence. The mean and standard deviation of the optimum moisture content are 9,4% and 2,3% respectively, thus the optimum moisture content of any material represented by these results could be estimated at 9,4% ±4,6 without any further knowledge of the materials. Since all the points of a moisture density test almost always lie within ±5 percentage points of optimum, and the critical part of the moisture density curve is usually within the range 3% below optimum to 2% above optimum (see Fig 2.1) the relationships deduced thus far are not of any practical use for estimating optimum moisture content with a view to reducing the effort required for the test. In view of the wide range of properties of the materials under investigation, this was not unexpected. The recommendation in TMH1 (1986) to use plastic limit - 2 as an estimator of optimum moisture content can also be seen not to be of any practical benefit.

In an attempt to improve the precision with which the optimum moisture content could be predicted, the second step in the analysis was to subdivide the materials into their geological horizon. Regression analyses were carried out for each horizon. The results appear in Appendix D. It was hypothesized that

1. The coefficients of correlation between optimum moisture content and plasticity parameters for horizons would be different to the coefficient of correlation of the materials as a whole

2. The coefficients of correlation between optimum moisture content and the plasticity parameters of each horizon would be greater than the coefficient of correlation of the materials as a whole.

The first hypothesis was tested by calculating the chi^2 statistic for the differences between Fisher's z for the whole dataset and the individual values:

$$chi^2 = \sum_{i=1}^{k} (n_i - 3)(z_i - z)^2 \qquad (4.1)$$

k = number of groups

n_i = number of observations in group i

z_i = Fisher's z of group i

z = arc tanh(r)

r = coefficient of correlation of population

The chi^2 table is entered with k-1 degrees of freedom. The critical value at the 95% confidence level is 20,48. If the calculated value of chi^2 exceeds this, then the hypothesis that there is a common coefficient of correlation must be rejected. The results of the computation of chi^2 appear in Table 4.5 below.

Table 4.5: Chi squared for subdivision of results by horizon

Parameter	r	z	k	chi^2
LL	0,388	0,409	11	66,6
LLMOD	0,459	0,496	11	104,4
PI	0,276	0,283	11	78,7
PIMOD	0,431	0,461	11	83,1
PL	0,294	0,303	11	175,7

Critical value of chi^2 = 20,48

In each case the value of chi^2 exceeds the critical value, and it must be concluded that in each case there is at least one horizon whose coefficient of correlation differs significantly from the coefficient of correlation of all the horizons combined.

The second hypothesis was tested by calculating the statistic

$$x_i = (z_i - z)\sqrt{(n_i - 3)} \qquad (4.2)$$

x is normally distributed with $\mu=0$, $\sigma=1$

z_i = Fisher's z for any horizon

z = Fisher's z for all the results (= arc tanh(r))

n_i = number of observations in the horizon for each of the horizons. The significance of the coefficient of correlation of each of the horizons was tested using the statistic

$$x_{ri} = (z_i - 0)\sqrt{(n_i - 3)} \qquad (4.3)$$

or $$x_{ri} = z_i\sqrt{(n_i - 3)} \qquad (4.4)$$

The statistics are shown in Tables E.1 to E.5 in Appendix E.

As predicted by the results shown in Table 4.5 some horizons show a coefficient of correlation which differs significantly from the coefficient of correlation of all the materials taken together. An unexpected result is that many do not, and even more unexpectedly almost as many horizons have a coefficient of correlation that is significantly worse than that of all the materials taken as a whole. The comparisons are shown in Table 4.6 below.

Table 4.6: Coefficients of correlation for each horizon compared with the overall coefficient of correlation for various plasticity parameters

Horizon	**LL**	**LLMOD**	**PI**	**PIMOD**	**PL**
C-Pd	o	o	o	-	o
Jd	o	+	-	o	+
Nmp	-	o	o	o	-
O-Sn	o	o	o	o	o
Pa	o	+	o	o	+
Pp	o	-	-	-	o
Pv	+	+	+	+	+
Pvo	+	+	o	+	+
Qb	o	-	+	o	o
TRt	+	-	o	-	+
ZB	o	o	o	o	-

o indicates no improvement of correlation
+ indicates a better correlation
- indicates a poorer correlation

Five of the horizons, C-Pd, Nmp, O-Sn, Pp and ZB show either no difference between their individual coefficients and the overall coefficients, or a worse coefficient of correlation. These horizons each consist of a single rock type. Horizons Pa, Pv and Pvo show improved correlations. There is a variety of rock types in horizon Pa. The other three horizons, Jd, Qb and TRt show some correlations that are better than the overall correlation, some that are worse, and some that are no different. The analysis shows that materials from a single geological horizon may show a greater coefficient of correlation between plasticity parameters than for all materials taken together, but it may equally well show a lesser coefficient, or even be no different at all.

As far as being able to predict optimum moisture contents was concerned, the confidence limits for the materials grouped by horizon were more often than not reduced, but in some cases were increased. However, where the confidence limits were reduced, the amount of reduction was small.

The same analysis was carried out with materials grouped according to rock type.

Table 4.7: Chi squared for subdivision of results by rock type

Parameter	**r**	**z**	**k**	**chi^2**
LL	0,388	0,409	9	36,2
LLMOD	0,459	0,496	9	33,3
PI	0,276	0,283	9	66,2
PIMOD	0,431	0,461	9	58,1
PL	0,294	0,303	9	109,5

Critical value of chi^2 = 17,53

A comparison of the coefficients of correlation of each rock type with the overall coefficient of correlation is shown in Table 4.8 below.

Table 4.8: Coefficients of correlation for each rock type with the overall coefficient of correlation for various plasticity parameters

Rock Type	LL	LLMOD	PI	PIMOD	PL
Clay	o	o	o	o	+
Dolerite	o	+	-	o	+
Granite	-	o	o	o	-
Mudstone	+	-	o	-	+
Sand	o	-	+	o	o
Shale	o	o	-	o	+
Sandstone	o	o	o	-	+
Silt	o	-	-	-	+
Tillite	o	o	o	-	o

o indicates no improvement of correlation
+ indicates a better correlation
- indicates a poorer correlation

No improvement of correlation, and in some cases a worsening of correlation, is displayed by granites and tillites, and in only seven cases overall has the correlation been improved over that of the materials taken together. In nine cases, the coefficient of correlation has become worse. No consistent improvement of correlation has been demonstrated, either for any particular rock type or for any particular plasticity parameter.

The confidence limits within which predicted optimum moisture content would be expected to fall have been reduced in the majority of cases, albeit by a small amount, but as in the case where the grouping was done according to horizon, there are a number of instances where the confidence limits have extended.

It should be noted that the classifications Jd (horizon), dolerite (Rock Type) and Basic (Weinert's classification) consist of exactly the same set of observations, as do C-Pd, tillite and diamictites.

A third analysis, grouping the materials according to Weinert's classification was carried out.

Table 4.9: Chi squared for subdivision of results by Weinert's classification

Parameter	r	z	k	chi^2
LL	0,388	0,409	5	49,9
LLMOD	0,459	0,496	5	18,4
PI	0,276	0,283	5	43,7
PIMOD	0,431	0,461	5	18,9
PL	0,294	0,303	5	126,9

Critical value of chi^2 = 11,14

A comparison of the correlations appears in Table 4.10 below.

Table 4.10: Coefficients of correlation for each Weinert classification with the overall coefficient of correlation for various plasticity parameters

Weinert's Classification	LL	LLMOD	PI	PIMOD	PL
Acid	-	o	o	o	-
Argillaceous	+	o	-	-	+
Arenaceous	-	o	o	-	o
Basic	o	+	-	o	+
Diamictites	o	o	o	-	o

o indicates no improvement of correlation
+ indicates a better correlation
- indicates a poorer correlation

The group Acid is exactly the same group as granite, where the materials were separated according to horizon. In this analysis too there is little improvement in the coefficient of correlation when the materials are subdivided, and in a fair number of instances the correlation gets worse rather than better. Only two of the groups, argillaceous rocks and basic rocks, show any improvement in correlation over the materials taken all together.

As before, where the confidence limits are reduced, the reduction is small, and again there are a number of cases where the confidence limits are greater for a particular group than they are for the materials taken together.

An analysis was carried out grouping the materials according to their AASHTO classification. It was expected that by grouping the materials in this way, the correlations of the individual groups would not be better than the materials taken together, because the effect of the classification is to group together soils having similar plasticity and particle size properties.

Table 4.11: Chi squared for subdivision of results by AASHTO classification

Parameter	**r**	**z**	**k**	**chi^2**
LL	0,388	0,409	6	143,2
LLMOD	0,459	0,496	6	194,0
PI	0,276	0,283	6	253,2
PIMOD	0,431	0,461	6	345,5
PL	0,294	0,303	6	24,9

Critical value of chi^2 = 14,45

The comparison of the correlations is shown in Table 4.2.1.

Table 4.12: Coefficients of correlation for each AASHTO classification with the overall coefficient of correlation for various plasticity parameters

AASHTO Classification	LL	LLMOD	PI	PIMOD	PL
A-1-a	-	-	-	-	o
A-1-b	-	-	-	-	-
A-2-4	-	-	-	-	-
A-2-6	-	-	-	-	o
A-2-7	o	o	-	o	o
A-4	o	-	-	-	o
A-6	-	o	-	-	+

o indicates no improvement of correlation
+ indicates a better correlation
- indicates a poorer correlation

This indeed was the case. The chi^2 values show that there are differences between the correlation coefficients of individual members of the groups and the groups themselves. Most correlations were worse than the correlation overall, and only in one case was it better. **This suggests that the reason that so few improvements were obtained by grouping soils according to horizon, rock type or Weinert's classification is that grouping them in this way tends to group together soils of similar plasticity and size properties.**

Confidence limits where they do improve are hardly improved at all, and the coefficients of correlation even when significant are generally so small that for practical purposes the optimum moisture content and its confidence limits for a soil from any particular classification are better obtained from the mean and standard deviation of the group than from the regression equations.

4.2.2 Semmelink's Model

Semmelink's (1991) equation was modified by substituting plasticity index in place of Linear Shrinkage, and a multiple linear regression procedure was carried out using the equation

$$OMC = a_0 + a_1(GF)^{0,85} + a_2A + a_3(PI) + a_4A^3.$$

The results are tabulated in Appendix F. As was expected from the preliminary analyses carried out and reported in Chapter 2, the correlation coefficients were very much less than those achieved by Semmelink. The coefficient of correlation overall was comparable in magnitude to the coefficients of correlation achieved using a simple linear regression of the plasticity parameters described in the preceding section, and the confidence limits for the prediction of new values were also of about the same magnitude. Overall, less than 20% of the variation was explained by this regression. As in the case of the simple linear regressions, grouping the materials by horizon, rock type, Weinert's classification and AASHTO classification led to an improvement in correlation in some cases, and a reduction of correlation in others. The results confirm the suspicion voiced in Chapter 2 that there is no justification by way of improved correlation for employing the multiple linear regression procedure for the materials considered in this study. In some cases a coefficient of correlation of zero was achieved, although this was only where the number of observations was small compared with the number of degrees of freedom.

4.3 Models for predicting optimum moisture content based on size parameters

Two measures of particle size were considered. The first is the grading modulus, defined as the sum of the cumulative per cent of material retained on the 2,0 mm, the 0,425 mm and the 0,075 mm sieves, expressed as a ratio. The smaller the grading modulus, the finer is the material that it represents. The second measure is the grading factor, used by Semmelink (1991), and it is defined as

$$GF = \Sigma(\%\ \text{passing sieve size/nominal sieve size (mm)})/100$$

for sieve sizes 75mm, 63mm, 53mm, 37,5mm, 26,5mm, 19mm, 13,2mm, 4,75mm and 2,00mm

The larger the grading modulus, the coarser is the material it represents.

The linear model described by Equation 4.1 was applied to all the materials, using size parameters as the independent variables. The results are shown in Table 4.13 below.

Table 4.13: Results of linear regression analysis on all materials using size parameters.

	Independent variable	
Statistic	**Grading Modulus**	**Grading Factor**
mean x	1,7	0,7
mean OMC	9,3	9,3
Sdv x	0,5	0,1
Sdv OMC	2,3	2,3
a_0	11,06	8,26
a_1	-1,025	1,437
n	5405	5405
r	-0,243	0,108
t_r	18,4	8,01
Conf Lim	±4,28	±4,39

mean x = the mean of the independent variable

mean OMC = the mean optimum moisture content

Sdv x = the standard deviation of the independent variable

Sdv OMC = the standard deviation of the optimum moisture content

a_0, a_1 = the regression coefficients

n = the size of the sample

r is the coefficient of correlation

t_r = the T-statistic for the coefficient of correlation

Conf Lim = the minimum error bound within which predictions of optimum moisture content will lie at the 95% level of confidence. This minimum occurs at the mean value of the independent variable.

For both grading modulus and grading factor, the coefficient of correlation is statistically significant.

X for the difference between Fisher's **z** for the two coefficients of correlation is 7,25, which exceeds the critical value of 1,96 (level of confidence 95%) and the two coefficients of correlation are therefore different. The coefficient of correlation between grading modulus and OMC is of greater magnitude than that of the grading factor, and therefore indicates a stronger correlation. This is confirmed by the larger Student's t shown in Table 4.13 above.

Although both coefficients of correlation are significant, the better coefficient obtained from the grading modulus only explains 6% of the variation. Using the grading modulus, at best the optimum moisture content can be predicted to ±4,3 percentage points at the 95% level of confidence. The mean and standard deviation of optimum moisture content are 9,3% and 2,3% respectively, and the optimum moisture content of any material could be estimated at 9,3% ± 4,6 without any further knowledge of the materials.

The analysis was carried further by subdividing the materials into groups according to horizon, rock type, Weinert's classification, and AASHTO classification. The results appear in Appendix G.

The two hypotheses applied to the plasticity parameters, appearing on page 4.8, were applied. The first test is to determine whether or not the coefficient of correlation of all the results taken together differs from the coefficient of correlation of the individual horizons. The results appear in Table 4.14 below.

Table 4.14: Chi squared for division of particle size results by horizon

Parameter	**r**	**z**	**k**	**chi^2**
Grading Modulus	-0,243	-0,243	12	250,7
Grading Factor	0,108	0,108	12	350,6

Critical value of chi^2 = 21,92

The critical value of chi^2 is 21,92 at the 95% confidence level. Since it is exceeded, the hypothesis that there is a common coefficient of correlation must be rejected. The coefficients of correlation of each horizon can therefore be examined individually. These results appear in Table E.6

and Table E.7. A comparison of the coefficients of correlation is shown in Table 4.15 below.

Table 4.15: Coefficients of correlation for each horizon compared with the overall coefficient of correlation for particle size parameters

Horizon	Grading Modulus	Grading Factor
C-Pd	o	o
Jd	+	+
Nmp	+	+
O-Sn	+	+
Pa	+	+
Pp	-	o
Pv	+	+
Pvo	+	+
Q	o	o
Qb	-	-
TRt	-	-
ZB	+	+

o indicates no improvement of correlation
+ indicates a better correlation
- indicates a poorer correlation

Five of the horizons show either no difference between their coefficients of correlation and the coefficient of correlation of the horizons taken together, or a lower coefficient. Most show slightly narrower limits for the prediction of optimum moisture content, but three horizons, Q, Pvo and TRt exhibit wider limits.

The analysis was extended to materials grouped by rock type, Weinert's Classification and AASHTO classification. As indicated in the following three tables (Table 4.16, 4.17 and 4.18) the coefficients of correlation of group members differ significantly from the correlations of the groups.

Table 4.16: Chi squared for division of particle size results by rock type

Parameter	r	z	k	chi^2
Grading Modulus	-0,243	-0,243	9	159,1
Grading Factor	0,108	0,108	9	227,5

Critical value of chi^2 = 17,53

Table 4.17: Chi squared for division of particle size results by Weinert's classification

Parameter	r	z	k	chi^2
Grading Modulus	-0,243	-0,243	5	116,0
Grading Factor	0,108	0,108	5	214,2

Critical value of chi^2 = 11,14

Table 4.18: Chi squared for division of particle size results by AASHTO classification

Parameter	r	z	k	chi^2
Grading Modulus	-0,243	-0,243	10	105,7
Grading Factor	0,108	0,108	10	64,5

Critical value of chi^2 = 16,01

The comparisons of the individual members with their corresponding groups is given in Tables 4.19, 4.20 and 4.21 below.

Table 4.19: Coefficients of correlation for each rock type compared with the overall coefficient of correlation for particle size parameters

Rock Type	Grading Modulus	Grading Factor
Clay	o	-
Dolerite	+	+
Granite	+	+
Mudstone	-	-
Sand	-	-
Shale	+	+
Sandstone	+	-
Silt	o	o
Tillite	o	-

o indicates no improvement of correlation
+ indicates a better correlation
- indicates a poorer correlation

Table 4.20: Coefficients of correlation for each group of Weinert's classification compared with the overall coefficient of correlation for particle size parameters

Weinert Class	Grading Modulus	Grading Factor
Acid	+	+
Argillaceous	+	+
Arenaceous	o	-
Basic	+	+
Diamictites	o	-

o indicates no improvement of correlation
+ indicates a better correlation
- indicates a poorer correlation

Table 4.21: Coefficients of correlation for each AASHTO class compared with the overall coefficient of correlation for particle size parameters

AASHTO Class	Grading Modulus	Grading Factor
A-1-a	-	-
A-1-b	o	o
A-2-4	-	-
A-2-6	o	-
A-2-7	o	+
A-3	o	o
A-4	-	-
A-6	+	+

o indicates no improvement of correlation
+ indicates a better correlation
- indicates a poorer correlation

The magnitude of the coefficients of correlation is very similar to that of the plasticity parameters, as are the confidence limits for the prediction of optimum moisture content. The coefficients of correlation obtained for the grading modulus generally are slightly greater than those obtained for the grading factor, and additionally more correlation coefficients obtained from the grading modulus are significant than those obtained from the grading factor. Generally, less than 25% of the variation is explained by size parameters. Where there is an improvement in the confidence limits for the prediction of optimum moisture content, it is small.

4.4 Summary

A variety of models was applied to the data, which was subdivided by means of a variety of classifications. The amount of variation explained by these models was a small proportion of the total variation. Although many subgroups of materials showed an improved coefficient of correlation, this improvement was generally slight. Some subgroups showed no improvement, whilst others exhibited coefficients of correlation which were significantly less than the entire groups of which they were a part. The confidence limits for the prediction of optimum moisture content were large, both in comparison with the mean values of optimum moisture content, and the limits required for practical use to be made of the predictions.

Chapter 5

THE DATA FOR THE SECOND SUB-PROBLEM

The data for the second sub-problem consist of the most effective of the factors influencing the relationship between soil properties used for classification and identification, and optimum moisture content. The most effective factors are those that predict optimum moisture content within the narrowest confidence limits for prediction.

Optimum moisture content can be predicted for all soils by taking the mean for all soils. The confidence limits for the prediction are then 1,96 times the standard deviation. If the soil can be classified, then means and standard deviations can be obtained for each of the groups into which the soils can be classified. Optimum moisture content and corresponding confidence limits for prediction can also be obtained from the linear regression of optimum moisture content on each of the various soil properties, as discussed in the preceding chapters. The regression procedure can also be applied to groups obtained from classification of the soil.

The mean optimum moisture content of all the soils studied is 9,3, with a standard deviation of 2,3, which yields confidence limits of 4,51 at the 95% level of confidence for the prediction of optimum moisture content. Expressed another way, it can be expected that any soil of subgrade or subbase quality occurring in the area under study will have an optimum moisture content in the range 4,8% to 13,8% in nineteen cases out of twenty.

If the optimum moisture content is predicted from various soil properties, then the confidence limits for the prediction of optimum moisture content are reduced as shown in Table 5.1 below.

Table 5.1: Soil properties and confidence limits for predicting optimum moisture content.

Soil Property	**Conf Lim**
Liquid Limit	4.23
Liquid Limit Modulus	4.08
Plasticity Index	4.31
Plastic Limit	4.39
Plasticity Modulus	4.04
LL,PI,GF and %passing 0,425mm sieve	4.13
Grading Modulus	4.28
Grading Factor	4.39

If the soils are subdivided according to their classification by horizon, rock type, Weinert's Classification or AASHTO Classification, then in many cases the confidence limits are reduced further, as shown in the following tables.

Table 5.2: Confidence limits for predicting optimum moisture content for soils classified by horizon.

Horizon	Conf Lim
C-Pd	3.49
Jd	3.82
Nmp	3.11
O-Sn	3.43
Pa	4.12
Pp	3.81
Pv	3.87
Pvo	7.51
Q	4.83
Qb	3.36
TRt	5.18
ZB	2.88

Table 5.3: Confidence limits for predicting optimum moisture content for soils classified by rock type.

Rock type	Conf Lim
cl	7.78
Dol	3.82
Gr	3.04
Ms	4.72
s	3.50
Sh	4.76
Ss	3.71
st	10.35
T	3.49

Table 5.4: Confidence limits for predicting optimum moisture content for soils classified by Weinert's Classification.

Weinert Class	Conf Lim
A	3.04
ag	5.60
an	3.66
B	3.82
D	3.49

Table 5.5: Confidence limits for predicting optimum moisture content for soils classified by AASHTO Classification.

AASHTO Class	**Conf Lim**
A-1-a	3.50
A-1-b	3.10
A-2-4	3.63
A-2-5	2.21*
A-2-6	3.99
A-2-7	10.14
A-3	4.10
A-4	4.55
A-5	5.94*
A-6	5.60

*Estimated from 3 observations only. Included for completeness only. The small number of observations renders the results unreliable.

Linear regression of optimum moisture content on soil properties can be applied to each of the classes. The resulting confidence limits appear in the tables and figures below.

Table 5.6: Confidence limits for the prediction of optimum moisture content using linear regression of optimum moisture content on soil properties, soils classified by horizon.

	Property or method used to predict optimum moisture content							
Horizon	**GF**	**GM**	**LL**	**LM**	**PI**	**PM**	**PL**	**Semm**
C-Pd	3.54	3.50	3.25	3.32	3.40	3.41	3.38	3.34
Jd	3.67	3.55	3.62	3.29	3.82	3.54	3.51	3.50
Nmp	2.77	2.69	2.98	2.69	3.05	3.09	2.90	2.69
O-Sn	3.24	3.16	3.36	3.30	3.30	3.52	3.17	3.33
Pa	3.67	3.52	3.89	3.40	4.04	3.91	3.65	3.64
Pp	3.85	3.84	3.65	3.72	3.85	3.54	3.84	3.74
Pv	3.80	3.67	3.37	3.25	3.63	3.62	3.26	3.28
Pvo	6.56	6.55	6.02	5.74	7.38	6.08	6.46	6.31
Q	5.09	4.88						
Qb	3.37	3.37	2.43	2.46	2.48	2.52	2.48	2.41
TRt	5.22	5.23	4.34	5.10	5.16	3.81	5.17	5.16
ZB	2.63	2.57	2.80	2.57	2.79	2.90	2.57	2.50

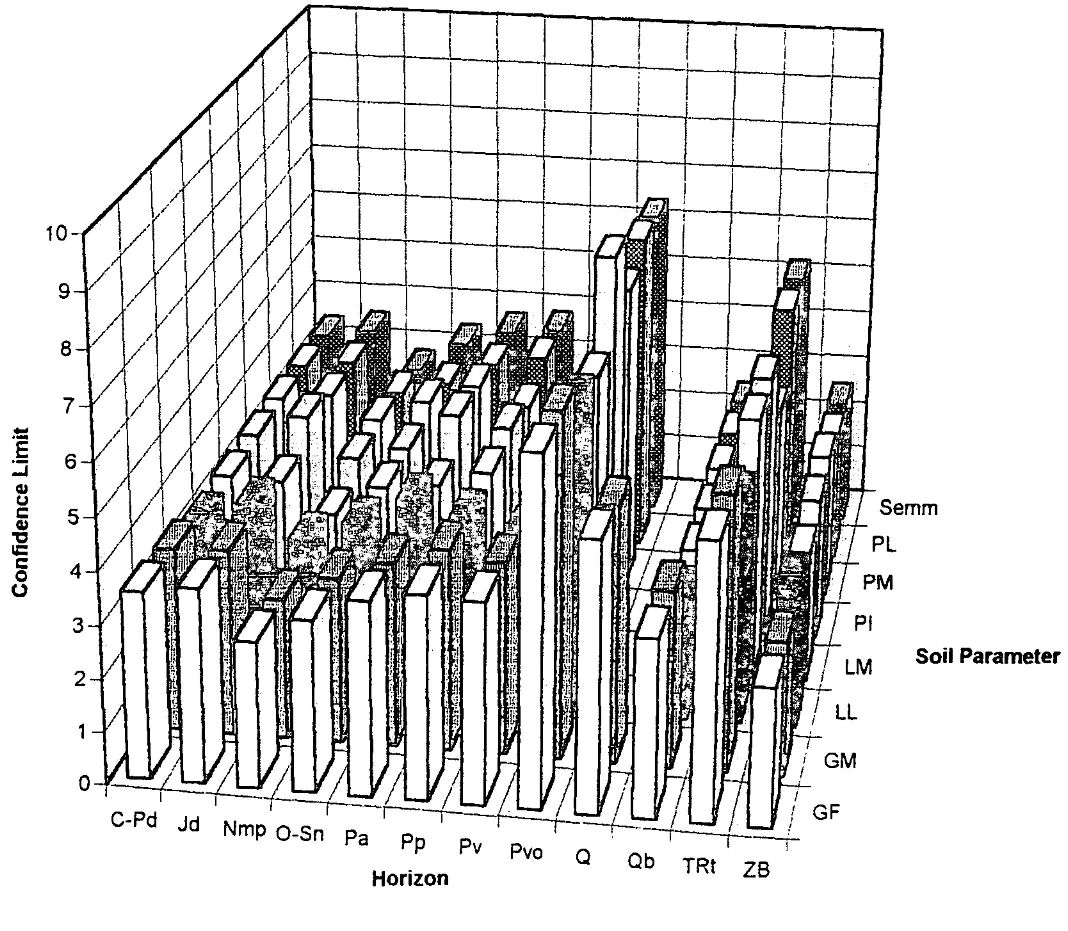


Figure 5.1: 95% Confidence limits for the prediction of optimum moisture content using linear regression of optimum moisture content on soil properties, soils classified by horizon.

Table 5.7: 95% Confidence limits for the prediction of optimum moisture content using linear regression of optimum moisture content on soil properties, soils classified by rock type.

	Property or method used to predict optimum moisture content							
Rock type	**GF**	**GM**	**LL**	**LM**	**PI**	**PM**	**PL**	**Semm**
cl	8.14	8.17	6.29	7.16	8.02	4.94	8.03	
Dol	3.67	3.55	3.62	3.29	3.82	3.54	3.51	3.50
Gr	2.73	2.66	2.92	2.66	2.96	3.03	2.79	2.64
Ms	4.77	4.78	3.85	4.65	4.67	3.92	4.73	4.38
s	3.51	3.51	2.50	2.48	2.54	2.57	2.51	2.46
Sh	4.50	4.50	4.29	4.24	4.71	4.28	4.44	4.43
Ss	3.67	3.50	3.58	3.47	3.62	3.61	3.47	3.52
st	11.18	11.21	8.03	10.72	11.22	7.29	11.17	
T	3.54	3.50	3.25	3.32	3.40	3.41	3.38	3.34

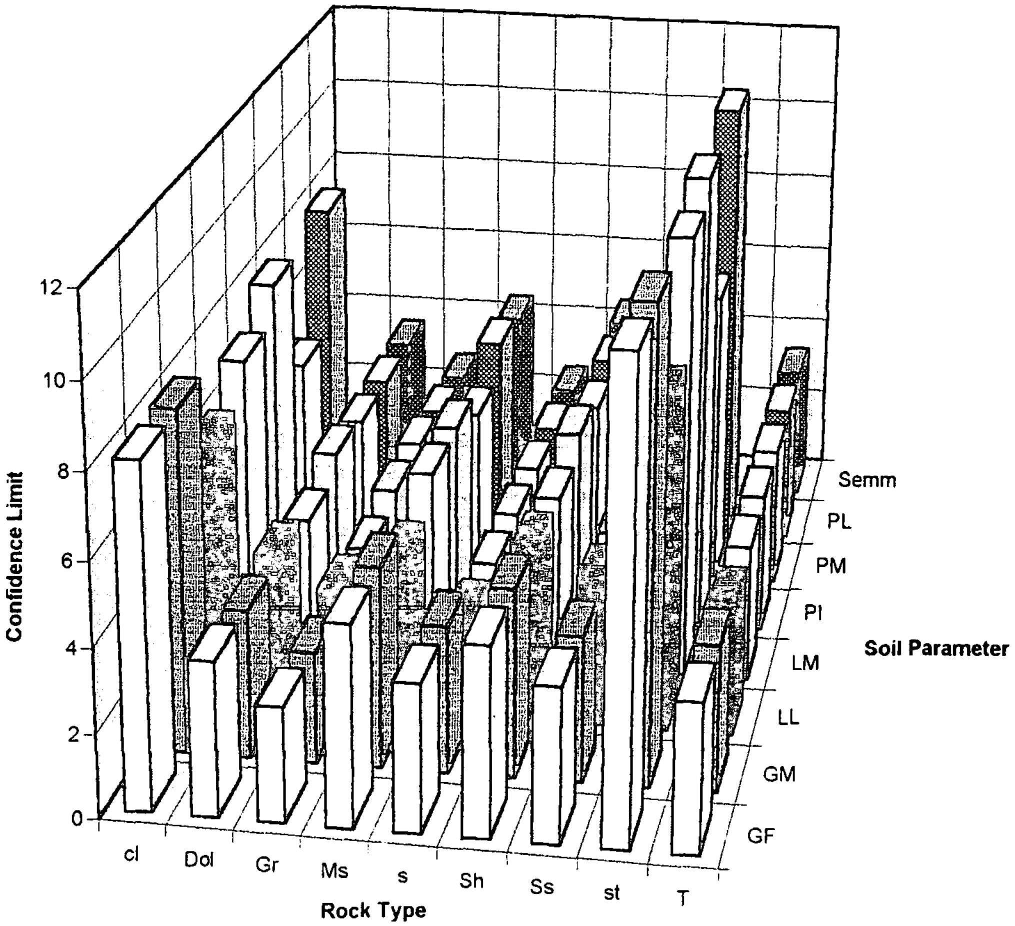


Figure 5.2: 95% Confidence limits for the prediction of optimum moisture content using linear regression of optimum moisture content on soil properties, soils classified by rock type.

Table 5.8: 95% Confidence limits for the prediction of optimum moisture content using linear regression of optimum moisture content on soil properties, soils classified by Weinert's Classification.

	Property or method used to predict optimum moisture content							
Weinert Class	GF	GM	LL	LM	PI	PM	PL	Semm
A	2.73	2.66	2.92	2.66	2.96	3.03	2.79	2.64
ag	5.34	5.27	4.75	4.90	5.52	4.76	5.26	5.26
an	3.62	3.52	3.54	3.37	3.49	3.57	3.33	3.45
B	3.67	3.55	3.62	3.29	3.82	3.54	3.51	3.50
D	3.54	3.50	3.25	3.32	3.40	3.41	3.38	3.34

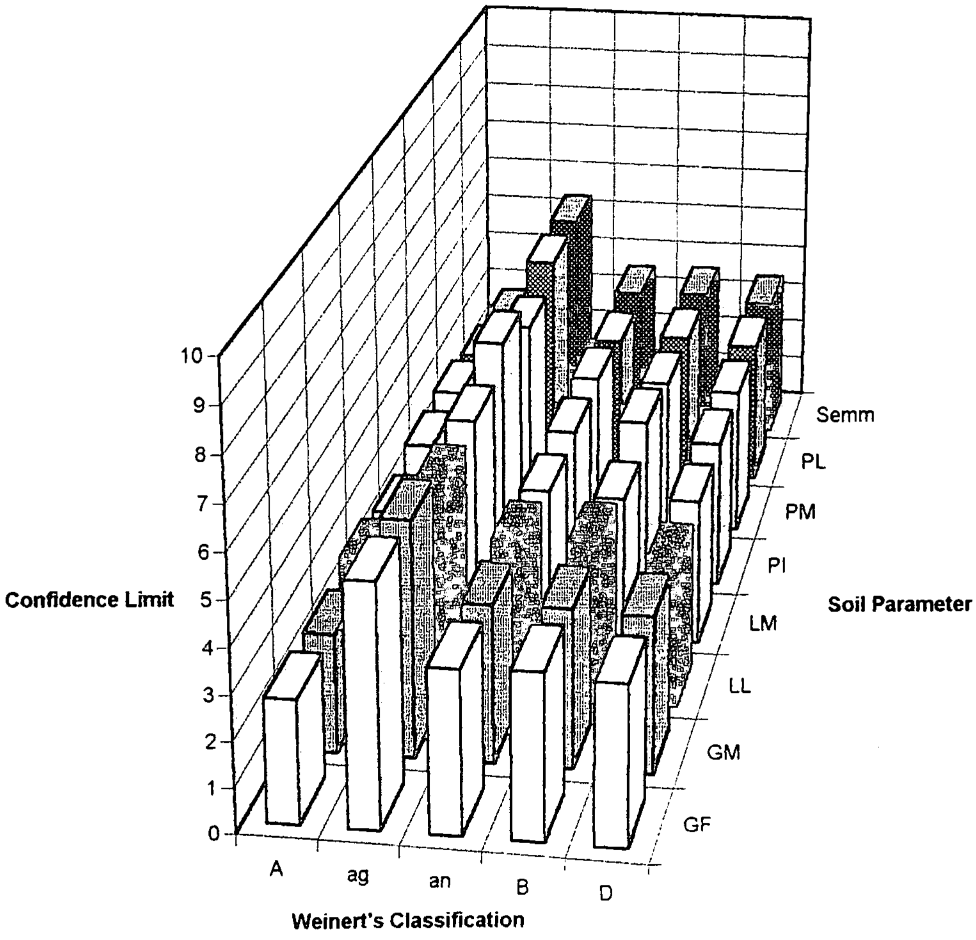


Figure 5.3: 95% Confidence limits for the prediction of optimum moisture content using linear regression of optimum moisture content on soil properties, soils classified by Weinert's Classification.

Table 5.9: 95% Confidence limits for the prediction of optimum moisture content using linear regression of optimum moisture content on soil properties, soils classified by the AASHTO Classification.

	Property or method used to predict optimum moisture content							
AASHTO Class	**GF**	**GM**	**LL**	**LM**	**PI**	**PM**	**PL**	**Semm**
A-1-a	3.48	3.50	3.62	3.70	3.59	3.59	3.62	3.67
A-1-b	3.09	3.05	3.14	3.13	3.12	3.11	3.15	3.15
A-2-4	3.63	3.60	3.69	3.59	3.66	3.55	3.66	3.56
A-2-6	3.94	3.87	3.88	3.75	4.00	3.86	3.82	3.82
A-2-7	9.78	10.29	10.43	10.47	10.67	10.53	9.71	9.67
A-3	4.12	4.07						
A-4	4.57	4.61	4.32	4.58	4.63	4.63	4.31	4.56
A-6	5.45	5.22	4.88	4.77	5.68	5.50	5.01	5.35

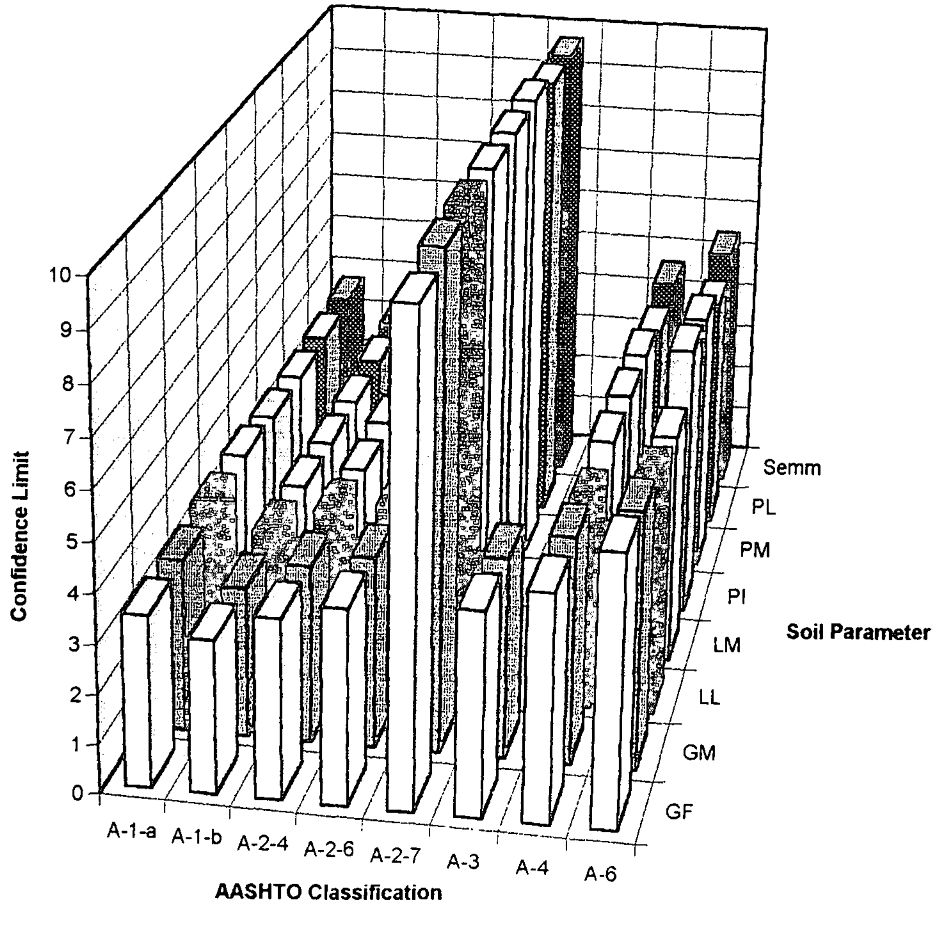


Figure 5.4: 95% Confidence limits for the prediction of optimum moisture content using linear regression of optimum moisture content on soil properties, soils classified by the AASHTO Classification.

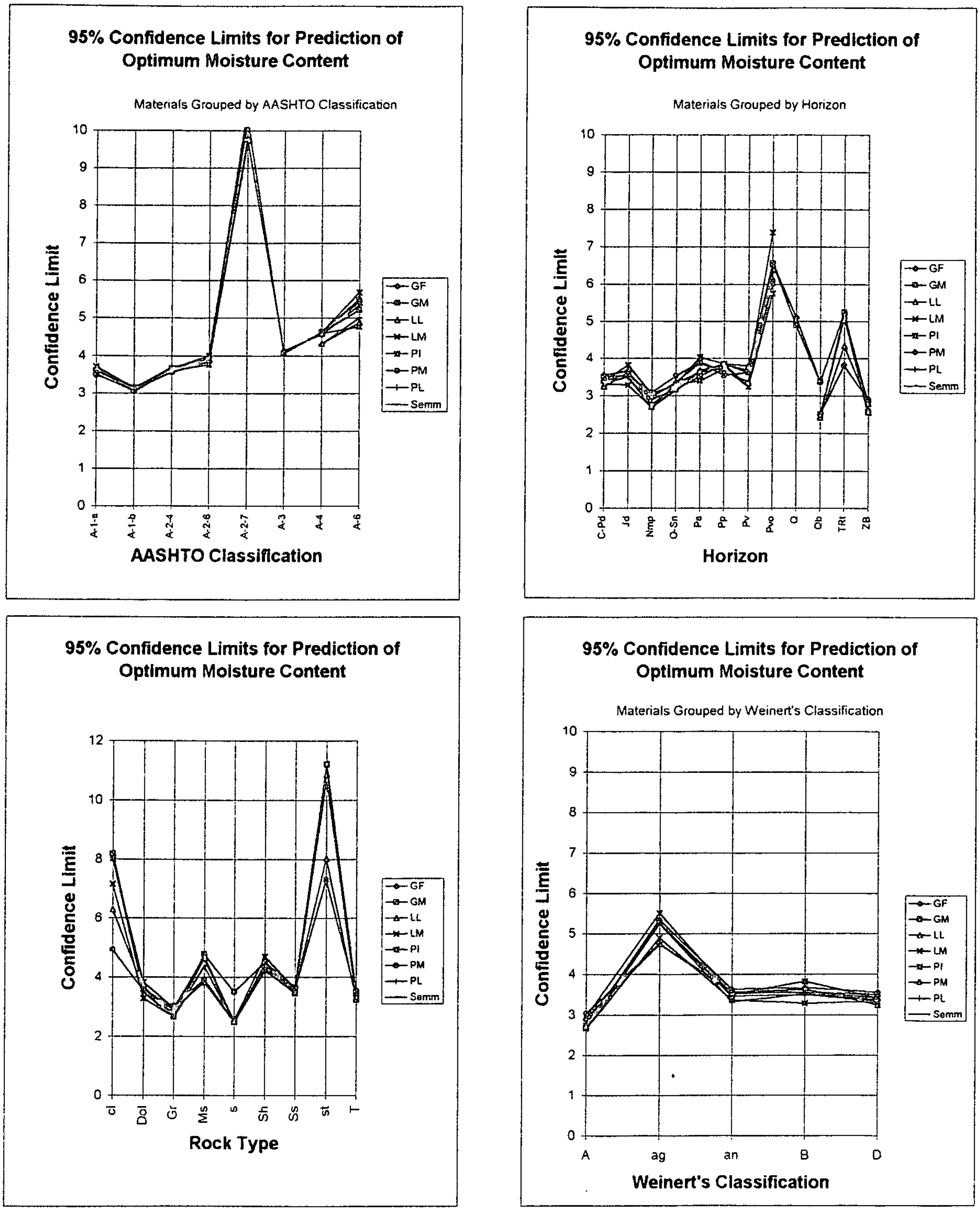


Figure 5.5: Summary of Confidence limits for the prediction of optimum moisture content using linear regression of optimum moisture content on soil properties.

5.1 The most effective factors to predict optimum moisture content

The confidence limits for the prediction of optimum moisture content by linear regression on soil properties are less than the confidence limits obtained from the standard deviation of the soils as a whole, in all cases. Of the soil properties, the plasticity modulus and the liquid limit modulus are the most effective in predicting optimum moisture content, the confidence limits being 4,04 and 4,08 respectively. The improvement, however, is very modest compared with the overall value of 4,51. Subdividing the soils in various ways has mixed results. Soils that are argillaceous in nature, represented by the groups clay, mudstone, silt and shale when classified by rock type, or argillaceous when classified using Weinert's Classification, show larger confidence intervals than the overall confidence limits. This is also true of the poorer subgrade materials represented by the AASHTO Classification grades A-2-7, A-4 and A-6. Single size non-plastic Recent sands (horizon Q) also have large confidence limits.

An anomaly arises when the argillaceous materials are related to the geological classifications. The Volksrust Shale Formation (Pvo) shows larger than average confidence limits of 7,51, whereas the Pietermaritzburg Shale Formation (Pp) shows smaller confidence limits (3,81), although all the materials investigated were shales or mudstones. Tarkastad Formation (TRt) soils show large confidence limits (5,18), with 36% of the materials being argillaceous, whereas Adelaide Formation soils, which were 84% argillaceous, showed smaller confidence limits of 4,12. These limits can be compared with 5,60 for argillaceous materials, and 7,78, 4,72 and 4,76 for clay, mudstone and shale respectively. Grouping the soils by means of their geological horizon is therefore more effective than grouping the soils according to their rock type or by Weinert's Classification, since it is able to discriminate between similar rock types. This statement should be qualified in that it can only be true where there is no change of facies, as is the case for the materials studied here as specified in the delimitations of the study. The reason for the improved effectiveness is that, in this case, the geological horizons consist of similar materials that also have similar geological histories, and therefore properties that cannot be identified from the plastic and size properties alone. In this case, the Volksrust Shale Formation and Tarkastad Formation horizon contain calcium rich minerals (Geological Survey 1989), and both show some maximum dry densities that are anomalously high for shale and argillaceous rocks.

The results are also consistent with the AASHTO classification, in that the groups consisting of better subgrade and subbase materials which have narrow specifications show confidence limits that are smaller than those of the poorer groups which have looser specifications.

Applying linear regression to the results of soils grouped according to horizon leads to modest improvements of between 7% and 28% to the confidence limits for the prediction of optimum moisture content. Generally, the liquid limit modulus is the predictor which gives the smallest confidence limits, which lie in the range 2,57 (for ZB) to 5,74 (for Pvo). Even more modest improvements are gained from applying linear regression to soils grouped using the AASHTO Classification, and there is no single soil property that is consistently better than any other. The best confidence limits obtained lie in the range 3,48 to 9,67. The modest improvement in the confidence limits obtained by applying linear regression is attributed to the classification processes grouping together soils which have similar plastic and size properties. This is especially the case with the AASHTO Classification which is designed specifically to do this.

The above results thus lead to the conclusion that the most effective factor overall for predicting the optimum moisture content of the range of soils investigated in this study is the liquid limit modulus, and that it is most effective when used with soils that have been classified by geological horizon. If the geological horizon is not available, then the most effective classification to use is the AASHTO classification. However, for individual soils, very slightly better results may in some circumstances be from other factors, which may be obtained by reference to the tables in this chapter.

Chapter 6

FORMULATION OF A TEST METHOD

Compaction tests require the determination of at least five points on the moisture density curve. TMH1 (1986) recommends that the the moisture content of the first point should be at approximately optimum moisture content, which can be estimated by adding water to the soil until, in the opinion of the operator, it is at optimum moisture content. Some advice is given on how to judge optimum moisture content. A second determination is suggested at a moisture content one percent higher or lower than the first. The moisture content for the third point is determined from plotting the density and moisture content of the first two points. The third point is plotted, and from the curve drawn using the three points, the fourth and fifth determinations are made such that there are at least two points differing by one percent on either side of optimum, and ideally there should also be one point on optimum moisture content. The ideal test should therefore be carried out at moisture contents ranging from around two percent dry of optimum to two percent wet of optimum. In practice this range is generally somewhat larger, and the higher the optimum moisture content the greater is the range.

The aim of predicting the optimum moisture content is to allow the operator to compact the specimen at the optimum moisture content (or sufficiently close to it for there to be no significant difference between the determined density and maximum density) and thus to eliminate four of the five determinations. In some circumstances, where the maximum density has to be determined without doubt, it might be necessary to determine two other points, which, following the recommendations of TMH1 (1986), should preferably be within half a percent of optimum moisture content.

6.1 Test procedure

The test procedure would therefore be:

1. Estimate the optimum moisture content from one of the methods given in the previous chapters.

2. Compact a specimen at this moisture content. The dry density of the specimen is the maximum dry density.

3. If the density to be reported has to be demonstrated to be the maximum density, then two further points on the moisture density curve must be determined, such that of the three points, one is at optimum, one is about half of one percent dry of optimum, and one is about half of one percent wet of optimum. The second point can be selected either on the wet or the dry side of the first; and the third can be determined from the plot of the first two points.

The first two steps of the procedure constitute the test proposed by Hammond (1980). Provided that the initial estimate is sufficiently accurate, this method could be expected to yield results comparable in accuracy to the standard test.

The requirements of the standard test method indicate that it would be necessary to estimate the optimum moisture content to within one half of one percent of optimum in order to achieve results which are as reliable and accurate as those of the standard test. This applies whether only one point or three points are determined.

Chapter 5 shows that of the factors investigated in this study, the liquid limit modulus yields the most accurate prediction of optimum moisture content, and that this prediction is improved by taking into account the geological horizon of the soil being tested. The equation and its parameters used for prediction is given in Table D.1. Of the horizons analyzed, the horizon yielding the narrowest confidence limits is Qb. In this case, the optimum moisture content can be predicted to ±2,46 percent. In this best case, the accuracy with which optimum moisture content needs to be predicted is five times greater than can be achieved in practice. Furthermore, the accuracy of prediction is only valid at the average optimum moisture content of the soils, and increases for all other optimum moisture contents. The range of values within which the optimum moisture content can be predicted is of the same order of magnitude as the range of moisture contents of the points of the standard test. This leads to the conclusion that, for the range of soils investigated in this study, it is not possible to predict optimum moisture content from plasticity and size parameters sufficiently accurately to formulate a test method that can yield test results comparable in reliability and accuracy to the results yielded by the standard test, and require less effort than the standard test. It must be concluded that information about the optimum moisture content obtained from plasticity and size parameters is about the same as that which can be obtained by an experienced operator "feeling" the soil.

Chapter 7

EVALUATION OF TEST METHODS BASED ON ESTIMATING OPTIMUM MOISTURE CONTENT

Plasticity and size parameters are usually determined as a matter of routine whenever a compaction test is carried out. Correlations exist between optimum moisture content, maximum dry density and other properties and these parameters (see, for example, Carter and Bentley 1991) and it is therefore tempting to use the relationships to predict values rather than go through the expensive process of testing. It was hypothesized (the Second Hypothesis, Chapter 1) that it is possible to formulate a test method for the determination of maximum dry density that will be shorter than the standard method of test while producing results of comparable accuracy and consistency. This hypothesis has been shown to be false.

The reason for the failure of the hypothesis is that the plasticity and size parameters by themselves give insufficient information about optimum moisture content. The best predictor, liquid limit modulus, has an overall coefficient of correlation of 0,459. The level of significance indicated its t is so high that it is not tabulated in Biometrika (Biometrika 1976,Table 9), but it is in excess of 99,999 percent. However, although the correlation is highly significant, it only explains 21 percent of the variation, leaving 79 percent unexplained (by the liquid limit modulus). It is this unexplained variation that is responsible for the uncertainty in predicting optimum moisture content.

The other parameters used for predicting optimum moisture content, although having highly significant coefficients of correlation with optimum moisture content, also can explain only a small proportion (less than 20 percent) of the variation. This is also the case even when the soils are arranged in groups having similar properties. For example, from Table C.2 it can be seen that the largest coefficient of correlation achieved between liquid limit modulus and optimum moisture content is 0,661, which leaves 56 percent of the variation of optimum moisture content to be accounted for by something other than the liquid limit modulus. Another example is given by the multiple linear regression analysis carried out on soils classified according to the AASHTO Classification. In this instance, where the PI, liquid limit and the size of the material are taken into account, and the soil is classified according to its measured properties, it might be expected that the coefficients of correlation would be high. However, the largest coefficient of correlation achieved was 0,426, which accounts for 18% of the variation. It seems that no matter which size and plasticity parameters are used, in whatever combination, or how they may be grouped, the amount of unexplained variation remains between 60 and 80 percent.

It is possible that the unexplained variation might be due to variation in the tests caused by having different operators. To investigate this correlations were calculated for soils selected from particular projects, to measure correlation of soils tested in the same time period and geographical location. Such a selection of soils would have been tested by a limited number of operators in only a few laboratories. The results are shown in Table 7.1 below.

Table 7.1: Correlation of OMC with Liquid Limit Modulus for selected jobs.

Job No	Horizon	Rock Type	N.Obs	Mean LM	Mean OMC	Sdv LM	Sdv OMC
271	Nmp	Gr	147	9.2	7.7	2.3	1.0
078	Nmp	Gr	71	8.5	7.5	2.3	0.9
058	ZB	Gr	114	7.1	7.6	2.4	0.9
172	ZB	Gr	87	13.8	8.4	4.7	1.5
222	Jd	Dol	136	5.2	8.3	1.9	1.1
306	Jd	Dol	130	4.9	8.8	2.3	1.0
311	Jd	Dol	94	6.3	9.8	3.3	1.5
197	TRt	Ss	97	14.4	10.9	3.1	1.2
197	TRt	Ms	80	9.2	12.4	3.2	2.1
061	Pvo	Sh	92	10.9	12.3	6.2	4.0
063	Pa	Sh	73	15.0	10.1	8.1	2.5
272	Qb	s	85	20.8	10.2	2.8	1.1

Job No	a_0	a_1	r	t_r	Conf Lim
271	5.43	0.251	0.572	8.39	1.68
078	6.72	0.093	0.233	1.99	1.78
058	7.26	0.049	0.129	1.38	1.81
172	5.40	0.221	0.708	9.25	2.08
222	6.91	0.260	0.459	5.98	1.90
306	8.39	0.087	0.193	2.23	2.05
311	9.25	0.094	0.201	1.97	3.04
197	8.92	0.135	0.344	3.57	2.31
197	11.10	0.142	0.221	2.00	4.06
061	8.18	0.376	0.578	6.71	6.66
063	6.06	0.273	0.875	15.26	2.47
272	6.72	0.166	0.408	4.07	2.09

Regression Equation: $OMC = a_0 + a_1 LM$

The results show that even where the materials are specific to a particular job, there is no guarantee that the confidence limits for the prediction of optimum moisture content are going to be narrower than for the materials representative of the entire population. Although some confidence limits show an improvement, others show a worsening, and overall no improvement can be shown to occur. The coefficients of correlation are better in some cases and worse in others. The reliability of the coefficients of correlation of some of the samples are less than those of the materials as a whole. The amount of variation explained by the regression remains much the same, although one job, 063, shows 77% of the variation to be explained by the liquid limit modulus.

Because the plasticity and size parameters by themselves do not give sufficient information to be able to predict optimum moisture content with sufficient accuracy to give values comparable with the standard test procedures, it is not to feasible to predict accurately other parameters which depend on optimum moisture content, such as maximum dry density and California Bearing Ratio. This explains, for example, the difficulty experienced by Stephens (1988) in predicting CBR from plasticity parameters.

It also points to the danger of relying on visual classification of soil to estimate optimum moisture content and maximum dry density. It is the practice on some sites, once a number of compaction tests have been carried out, to maintain a reference set of samples of different soils, and then to relate maximum dry density of a soil by comparing its appearance with the standard set. It has been shown in this study that even when soils appear to be the same, have similar plasticity and size parameters and have the same classification, that the variation in optimum moisture content and hence maximum dry density is sufficient to make such comparisons invalid for the purpose of determining relative density.

Chapter 8

DISCUSSION

The intent of this investigation at its inception was to determine relationships between plasticity and particle size and optimum moisture content that would allow the determination of optimum moisture content so that maximum dry density could be determined by compacting a single specimen, or at most only three specimens, instead of the normal five, thus achieving the economically useful effect of substantially reducing the amount of laboratory testing required during road construction. This direction was not taken arbitrarily but was taken on the basis partly of the encouraging results reported by Hammond (1980) and Hammond and Gyimah (1984), as well as those of other researchers who reported good correlations. It was hypothesized that by using a large number of reliable measurements that correlations previously reported could be refined. This study differed from those previous investigations in that it was based on a large body of results obtained from homogeneous and controlled test results carried out on a variety of materials, and that it examined the variance of the results and the confidence with which predictions could be made. It was found that the variance in the measured parameters would not allow predictions of optimum moisture content to be made sufficiently accurately for the declared purpose, and that this was due to the plasticity and size parameters having only a limited influence on optimum moisture content. This leads to the more important conclusion that any accurate prediction of a property of an individual soil that depends on compaction frome plasticity or particle size values is not feasible, and is responsible for the generally poor performance of methods of estimating optimum moisture content, maximum dry density and CBR.

8.1 Other factors affecting optimum moisture content

Only the plasticity and particle size attributes of soils were considered because the purpose of this study is to employ only the results of tests carried out routinely with the moisture density test to predict optimum moisture content. The intention is to reduce the amount of testing that has to be carried out, and so anything that would require additional testing effort was ruled out. However, it is apparent from the results already presented that plasticity and particle size parameters are able to explain only a portion of the variance of optimum moisture content and maximum dry density, so that it is appropriate that some of the factors which were not considered in the study should be discussed here.

8.1.1 Shape and particle size distribution

The two major properties of soils not investigated in this study that are considered likely to affect optimum moisture content and maximum dry density are shape and particle size distribution. These have been examined extensively elsewhere (Yong and Warkentin 1975, Soil Mechanics for Road Engineers 1952). Semmelink (1991) uses a "shape factor" (SF) test and a "shaken bulk density" (SBD) test which measure the effect of particle shape and texture of a material, in addition to plasticity and particle size parameters, to predict maximum dry density and optimum moisture content. However, he finds that the improvements obtained by taking the SF and SBD into account are slight.

8.1.2 Variability of soil structure before compaction

It was noticed that even soils with similar plasticity and size properties, and tested under similar conditions, showed considerable variance in their optimum moisture content and maximum dry density. This was the case even with clayey single sized sands of the Berea Formation. If the soils are similar, then the dissimilarity of optimum moisture content may be due to variation in the test method. There appear to be two factors that would be out of the control of the operator, namely the change of grading during compaction, and the structure of the soil as it is deposited in the mould prior to compaction. In the case of the Volksrust Shale Formation and the Pietermaritzburg Shale Formation, the large confidence interval for the prediction of optimum moisture content of the Volksrust Shale Formation compared to that of the Pietermaritzburg Shale Formation may be due to the presence of calcareous material in the Volksrust Shale Formation which may inhibit breakdown of particles during compaction by varying degrees. Semmelink (Semmelink 1991) regards the total grading of the material after compaction to be the most important factor influencing the compactability of the material. It is suspected that the structure of the soil before it is compacted, that is the orientation of the particles relative to one another, will also affect the compactability of the soil because in the confines of the mould the compaction method provides no method for the particles to be reorientated. In the case of compaction by vibration of cohesionless soils the particles are free to rotate to a considerable extent, and soils compacted under these conditions generally achieve a higher density than the same soils compacted by means of a hammer.

8.2 Other applications

8.2.1 Estimating optimum moisture content

Although it is not possible to predict optimum moisture content for individual soils sufficiently accurately to substitute for a compaction test, it is possible to predict *average* optimum moisture content using the equations given in Appendix D. The 95% confidence limits for the prediction of average optimum are shown by the inner dotted lines of the figures shown in Appendix D. Since all the major types of material used in the province were examined, and since samples were drawn in such a way that they were representative of the province, this may prove useful for the evaluation of materials during the preliminary and exploratory phase of road building projects. The equations may also prove useful in validating and checking test results for consistency and reliability.

8.2.2 Estimating maximum dry density

Average maximum dry density may be obtained from the predicted average moisture content and five percent air voids line, and may be used for the same purposes given for average optimum moisture content listed in the immediately preceding paragraph.

8.3 Methodology

This study was possible only because the opportunity existed to consult a large archive of primary data. The validity of the data used rested on the fact that the testing on which it was based was carried out under strict control, yet its applicability was general because it was carried out under normal working conditions, and the conclusions reached can therefore be applied to work carried out under strict control under normal working conditions. This contrasts with other investigations employing limited testing carried out under specialized laboratory conditions. The data used was comprehensive and representative of all the major soil and geological types, as well as being distributed evenly over a large geographical area. The negative result obtained from the study may thus be regarded as valid rather than inconclusive, which would have been the case had it been based on a much smaller, less comprehensive body of information, such as those used in investigations described in the literature review.

8.4 Conclusions

1. It is not feasible, using only plasticity and size parameters as determined in the routine tests accompanying the compaction test, to predict the optimum moisture content of local natural subgrade and subbase materials sufficiently accurately to justify reducing the amount of testing required to determine optimum moisture content.

2. It is not feasible using only these parameters to determine any property dependent on optimum moisture content, such as maximum dry density and CBR.

3. The equations presented in this study allow the prediction of average optimum moisture content, and hence maximum dry density, sufficiently accurately for estimation purposes during the preliminary phases of a road building project, and for the evaluation and monitoring of test results.

4. The study confirms the existence of correlations between plasticity and particle size parameters and optimum moisture content, but shows that the correlations explain only a small part of the variance in these correlations.

5. The stratigraphic origin of the soils significantly influences the relationships between plasticity parameters

and particle size parameters and optimum moisture content, and may be used to improve predictions of optimum moisture content.

6. The parent rock type, expressed as lithological type or as classified by Weinert (1980), may also be used to improve the prediction of optimum moisture content.

7. The soils classified as better construction materials by the AASHTO classification tend to have optimum moisture contents that are nearly independent of the plasticity parameters, while the poorer construction materials are more influenced by their plasticity.

8. There is no basis for assigning maximum dry density to a soil by referring to the appearance of standard exemplars, and this practice could prove to be misleading.

8.5 Suggestions for further research

The present study has been restricted to natural road building materials, which of course have been selected for their good quality as construction materials. It would be interesting to see if a similar result would be obtained for low grade materials such as silts and clays. Unfortunately the practical benefits of such a study would be limited because of the necessarily minor usage of these materials in construction.

The influence of soil structure prior to compaction on compactability, and the mechanisms by which soil particles are reorientated during compaction would also be of interest. These are both influenced by the shape of the particles size distribution curve, the shape of the particles and the crushing of particles by the hammer during testing. Undoubtedly at least some of the variance in optimum moisture content and maximum dry density not explained by the factors examined in this study could be accounted for by these aspects.

The present work illustrates the large amount of useful primary data that is available for research. The cost of the experimental work on which the results are based runs into several millions of rands and thousands of hours of effort. The archives from which it was drawn contain much other information, which would be useful if analysed and presented in a comprehensive but compact form.

Appendix A

REFERENCES

Akroyd, T.N.W. 1957. Laboratory testing in soil engineering. Soil Mechanics Limited, London.

Al-Khafaji, A.N. 1979. A simple approach to the estimation of soil compaction parameters. Quarterly Journal of Engineering Geology, London, Vol. 20, pp 15-30.

AASHTO. 1982. Standard specification for transportation materials and methods of testing and sampling. American Association of State Highway and Transportation Officials.

Biometrika. 1976. Biometrika Tables for Statisticians. Volume 1. Edited by E.S.Pearson and H.O.Hartley. Biometrika Trust, London.

Brink, A.B.A. 1979. Engineering Geology of Southern Africa. Volume 1. Building Publications, Pretoria.

Brink, A.B.A. 1983. Engineering Geology of Southern Africa. Volume 3. Building Publications, Pretoria.

Brink, A.B.A. 1985. Engineering Geology of Southern Africa. Volume 4. Building Publications, Pretoria.

BS 1377:Part 4. 1990. British Standard Methods of test for Soils for civil engineering purposes. Part 4. Compaction-related tests. British Standards Institution.

Carter, M. and S.P. Bentley. 1991. Correlations of soil properties. Pentech Press, London.

D.O.E. Transport and Road Research Laboratory (U.K.). 1952. Soil mechanics for road engineers. H.M.S.O., London.

Geological Survey. 1984. Geological Map of the Republics of South Africa, Transkei, Bophutatswana, Venda and Ciskei and the Kingdoms of Lesotho and Swaziland, 1:1 000 000. Geol. Surv. S. Afr.

Geological Survey. 1988. Geological Sheet 2930 (Durban) 1:250 000. Geol. Surv. S. Afr.

Geological Survey. 1989. Explanation of the 1:1 000 000 Geological Map, Fourth Edition, 1984: The Geology of the Republics of South Africa, Transkei, Bophutatswana, Venda and Ciskei and the Kingdoms of Lesotho and Swaziland (Compiled by D.J.L. Visser). Geol. Surv. S. Afr.

Hammond, A.A. 1980. Evolution of one-point method for determining the laboratory maximum dry density. International Conference on Compaction. Ecole Nationale des Ponts et Chaussees and Laboratoire Centrale des Ponts et Chaussees, Paris, Volume 1, pp 47-50.

Hammond, A.A. and S.A. Gyimah. 1984. A statistical appraisal of a one point method for determining the laboratory maximum dry density. Proceedings of the Eighth

Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Harare.

Morin, W.J. and P.C. Todor. 1977. Laterites and lateritic soils and other problem soils of the tropics. United States Agency for International Development, A10/csd 3682.

Rowlands, G.O. 1984. The Casagrande A and U-lines in soil classification. Proceedings of the Eighth Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Harare.

Semmelink, C.J. 1991. Factors influencing the compactability and bearing capacity of untreated roadbuilding materials. Proceedings of the Tenth Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Maseru.

South African Committee for Stratigraphy (SACS). 1980. Stratigraphy of South Africa. Part 1 (Comp. L. E. Kent). Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda. Handb. geol. Surv. S. Afr., 8.

Stephens, D. J. 1988. The Variation of the California Bearing Ratio with Standard Classification and Shear strength Parameters for a Selection of Natal Soils. M.Sc. Thesis, University of Durban-Westville, Durban.

TMH1. 1986. Standard methods of testing road construction materials. National Institute for Traffic and Road Research, CSIR, Pretoria.

Weinert, H.H. 1980. The natural road construction materials of Southern Africa. H & R Academica, Pretoria.

Yong, R.N. & B.P. Warkentin. 1975. Soil properties and behaviour. Elsevier, Amsterdam.

Appendix B

Abbreviations

Abbreviations used in the text

Abbreviations have been used in some tables, figures and equations in place of full names in order to make them clearer to follow. Standard abbreviations have been used wherever these exist.

Abbreviations used for geological formations

Jd	Jurassic intrusives
O-Sn	Natal Group
Nmp	Namibian intrusives and metamorphics
Qb	Berea Formation sands
Pv	Vryheid Formation
Pa	Adelaide Formation
Pvo	Volksrust Shale Formation
ZB	Archaean Granites
TRt	Tarkastad Formation
Pp	Pietermaritzburg Shale Formation
C-Pd	Dwyka Formation
Q	Recent sands

Abbreviations used for soil properties

PI	Plasticity Index

PL	Plastic Limit
LL	Liquid Limit
LS	Linear Shrinkage
OMC	Optimum Moisture Content
LLMOD	Liquid Limit Modulus
LM	Liquid Limit Modulus (Used on axes of graphs)
PIMOD	Plasticity Index Modulus
PM	Plasticity Index Modulus (Used on axes of graphs)
GM	Grading Modulus
GF	Grading Factor
Semm	This abbreviation was used on some graphs to indicate that the dependent variable was obtained using the multiple linear regression equation given in Appendix F.

Abbreviations used for rock types

Abbreviations having a lower case initial letter indicate loose materials, while those having an upper case initial letter indicate solid or indurated materials.

cl	clay
Dol	Dolerite
Gr	Granite
Ms	Mudstone
s	sand
Sh	Shale
Ss	Sandstone
st	silt
T	Tillite

Abbreviations used for Weinert's classification

A	Acidic
ag	argillaceous
an	arenaceous
B	Basic
D	Diamictites

Appendix C

Typical worksheet for data collection

DATA FROM NPA MATERIALS CONTROL SHEETS DATE 4/10/90 PAGE 232

Book 215 Area 121 MR387 Nr Compensation.

No:	53,0		4605			4606		
BOOK/LAYER/PAGE	37,5 26,5	CS CFS	40/556/1	100				
Descr	19,0 13,2	MFS FFS	Br Dec Dol	99 98			100 97	
MDD	4,75 2,0	SC GM	2118	91 54	2.19	2232	82 50	2.29
OMC	425 75	PI LL	8.0	19 8	4 22	9.8	15 5	6 28
607			608			609		
	100							
	99 85			100			100 99	
2103	56 30	2.57	2171	92 60	2.09	2155	86 54	2.18
9.6	10 3	5 29	6.8	21 9	4 27	8.2	19 9	3 29
610			611			612		
	100			100 99			100 96	
2133	91 60	2.09	2080	78 45	2.20	2137	85 50	2.16
11.7	21 9	3 30	9.0	16 6	4 26	9.8	23 10	2 27
613			614			615		
215/705/1								
4 Dec Ss	100			100			100	
2018	99 98	1.23	2053	99 98	1.21	2028	99 98	1.28
9.6	57 23	4 18	9.5	56 24	6 23	9.7	52 21	7 24
616			617			618		
	100 94						100 93	
	94 94			100 98			91 86	
2006	93 92	1.03	2050	96 95	1.22	2129	80 77	1.55
9.8	72 32	10 27	9.5	59 25	8 23	6.8	51 18	7 20
619			620			621		
/2						Pk dec Ss		
	100 98			100			100	
1989	95 92	1.13	2035	97 95	1.15	2050	99 97	1.12
9.7	65 29	8 21	9.5	59 31	12 29	10.1	63 27	9 24
622			623			4624		
	100 98							
2040	97 96	1.13	2031	100	1.01	2006	100 99	1.14
10.0	63 29	12 28	9.9	73 26	6 23	9.1	64 23	7 24

Appendix D

Results of Regression Analyses

Abbreviations

The following abbreviations are used in this appendix.

OMC = Optimum Moisture Content

LL = Liquid Limit

LM = Liquid Limit Modulus

PI = Plasticity Index

PM = Plasticity Index Modulus

PL = Plastic Limit

ALL = All results

Sdv = Standard Deviation

a_0, a_1 = regression coefficients

r = coefficient of correlation

t_r = Student's t for r

Conf Lim = Minimum 95% confidence limits for prediction of OMC

Table D.1: Regression analysis OMC vs liquid limit by horizon

Horizon	N.Obs	Mean LL	Mean OMC	Sdv LL	Sdv OMC
ALL	4362	26.8	9.4	5.4	2.3
Jd	1247	28.8	9.0	5.3	2.0
O-Sn	484	23.5	9.0	4.6	1.9
Nmp	518	25.8	8.0	4.1	1.6
Qb	147	21.6	10.3	3.9	1.3
Pv	470	26.3	9.7	4.9	2.0
Pa	291	28.1	10.5	5.0	2.2
Pvo	272	29.3	11.2	6.2	3.9
ZB	262	26.2	8.1	4.7	1.5
TRt	255	25.8	11.2	5.6	2.7
Pp	239	28.9	11.0	4.4	1.9
C-Pd	177	24.2	9.3	4.2	1.8

Horizon	a_0	a_1	r	t_r	Conf Lim
ALL	4.90	0.169	0.388	27.77	4.23
Jd	5.11	0.135	0.361	13.67	3.62
O-Sn	4.90	0.176	0.428	10.41	3.36
Nmp	4.94	0.118	0.302	7.18	2.98
Qb	7.98	0.106	0.322	4.09	2.43
Pv	4.11	0.210	0.520	13.16	3.37
Pa	4.97	0.198	0.448	8.53	3.89
Pvo	0.07	0.382	0.616	12.84	6.02
ZB	5.61	0.095	0.302	5.11	2.80
TRt	4.29	0.267	0.566	10.93	4.34
Pp	7.12	0.133	0.304	4.92	3.65
C-Pd	5.19	0.168	0.398	5.74	3.25

Regression Equation: $OMC = a_0 + a_1 LL$

Table D.2: Regression analysis OMC vs liquid limit modulus by horizon

Horizon	N.Obs	Mean LM	Mean OMC	Sdv LM	Sdv OMC
ALL	4362	10.6	9.4	5.8	2.3
Jd	1247	7.3	9.0	4.0	2.0
O-Sn	484	13.0	9.0	5.0	1.9
Nmp	518	9.8	8.0	3.5	1.6
Qb	147	20.3	10.3	4.1	1.3
Pv	470	13.3	9.7	6.2	2.0
Pa	291	14.4	10.5	7.8	2.2
Pvo	272	9.6	11.2	6.3	3.9
ZB	262	10.1	8.1	5.0	1.5
TRt	255	12.0	11.2	4.8	2.7
Pp	239	9.6	11.0	4.2	1.9
C-Pd	177	10.8	9.3	4.4	1.8

Horizon	a_0	a_1	r	t_r	Conf Lim
ALL	7.45	0.185	0.459	34.12	4.08
Jd	7.08	0.261	0.531	22.13	3.29
O-Sn	6.77	0.176	0.463	11.48	3.30
Nmp	5.69	0.233	0.513	13.59	2.69
Qb	8.46	0.089	0.287	3.61	2.46
Pv	7.20	0.184	0.566	14.84	3.25
Pa	8.00	0.176	0.625	13.60	3.40
Pvo	7.32	0.407	0.661	14.47	5.74
ZB	6.63	0.145	0.486	8.97	2.57
TRt	9.56	0.134	0.243	3.99	5.10
Pp	9.92	0.108	0.232	3.67	3.72
C-Pd	7.75	0.142	0.350	4.95	3.32

Regression Equation: $OMC = a_0 + a_1 LM$

Table D.3: Regression analysis OMC vs plasticity index by horizon

Horizon	N.Obs	Mean PI	Mean OMC	Sdv PI	Sdv OMC
ALL	4810	7.8	9.3	4.3	2.3
Jd	1280	9.3	9.0	4.2	2.0
O-Sn	656	5.2	8.8	4.0	1.8
Nmp	575	5.7	7.9	3.2	1.6
Qb	256	3.7	9.7	3.5	1.5
Pv	499	8.0	9.6	4.0	2.0
Pa	326	10.4	10.5	4.7	2.1
Pvo	273	10.5	11.2	3.3	3.9
ZB	269	7.0	8.1	3.4	1.5
TRt	259	7.7	11.2	3.1	2.6
Pp	240	10.1	10.9	3.1	1.9
C-Pd	177	8.3	9.3	2.8	1.8

Horizon	a_0	a_1	r	t_r	Conf Lim
ALL	8.20	0.147	0.276	19.90	4.31
Jd	8.46	0.056	0.120	4.33	3.82
O-Sn	8.09	0.143	0.322	8.70	3.30
Nmp	7.25	0.122	0.242	5.97	3.05
Qb	8.90	0.216	0.515	9.58	2.48
Pv	8.16	0.181	0.361	8.64	3.63
Pa	9.39	0.104	0.234	4.33	4.04
Pvo	8.16	0.293	0.253	4.30	7.38
ZB	7.21	0.124	0.285	4.86	2.79
TRt	10.02	0.147	0.170	2.76	5.16
Pp	11.23	-0.029	-0.046	0.72	3.85
C-Pd	7.77	0.181	0.283	3.90	3.40

Regression Equation: $OMC = a_0 + a_1 PI$

Table D.4: Regression analysis OMC vs plastic limit by horizon

Horizon	**N.Obs**	**Mean PL**	**Mean OMC**	**Sdv PL**	**Sdv OMC**
ALL	4362	18.2	9.4	3.7	2.3
Jd	1247	19.2	9.0	3.5	2.0
O-Sn	484	16.4	9.0	3.5	1.9
Nmp	518	19.4	8.0	3.1	1.6
Qb	147	15.2	10.3	3.2	1.3
Pv	470	17.8	9.7	3.1	2.0
Pa	291	16.5	10.5	3.2	2.2
Pvo	272	18.7	11.2	4.9	3.9
ZB	262	19.0	8.1	3.3	1.5
TRt	255	18.0	11.2	4.0	2.7
Pp	239	18.8	11.0	4.1	1.9
C-Pd	177	15.9	9.3	3.2	1.8

Horizon	a_0	a_1	**r**	t_r	**Conf Lim**
ALL	6.08	0.184	0.294	20.29	4.39
Jd	4.51	0.232	0.407	15.72	3.54
O-Sn	6.20	0.173	0.321	7.44	3.52
Nmp	6.47	0.077	0.151	3.48	3.09
Qb	9.12	0.076	0.187	2.29	2.52
Pv	5.09	0.257	0.397	9.37	3.62
Pa	5.44	0.308	0.441	8.36	3.91
Pvo	2.36	0.474	0.606	12.52	6.08
ZB	6.83	0.067	0.149	2.43	2.90
TRt	2.88	0.462	0.689	15.13	3.81
Pp	7.58	0.180	0.384	6.40	3.54
C-Pd	6.84	0.152	0.276	3.79	3.41

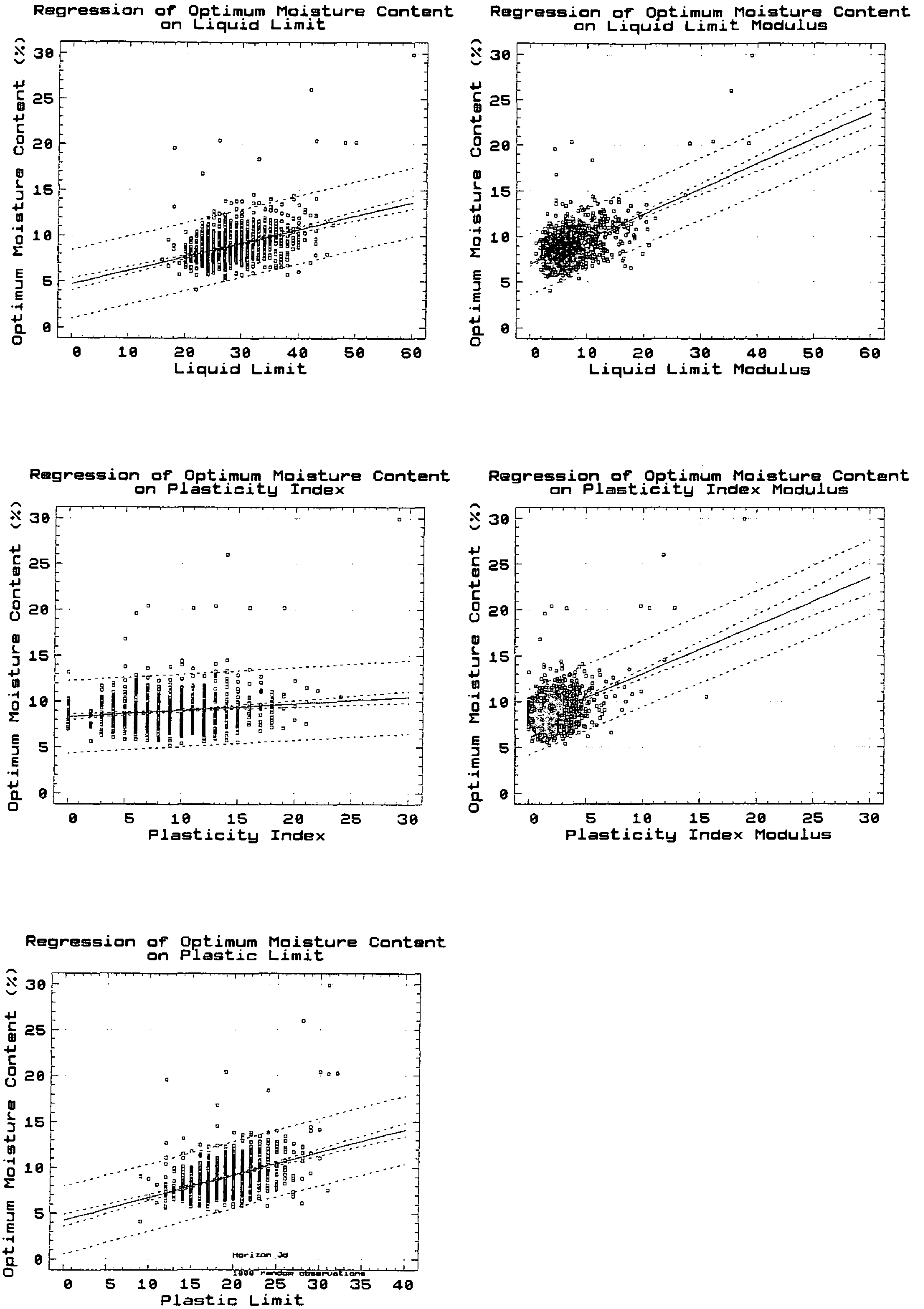
Regression Equation: $OMC = a_0 + a_1 PL$

Table D.5: Regression analysis OMC vs Plasticity modulus by horizon

Horizon	**N.Obs**	**Mean PM**	**Mean OMC**	**Sdv PM**	**Sdv OMC**
ALL	4810	3.1	9.3	2.5	2.3
Jd	1280	2.3	9.0	1.7	2.0
O-Sn	656	2.9	8.8	2.5	1.8
Nmp	575	2.2	7.9	1.6	1.6
Qb	256	3.4	9.7	3.2	1.5
Pv	499	4.0	9.6	2.9	2.0
Pa	326	5.4	10.5	4.2	2.1
Pvo	273	3.5	11.2	2.4	3.9
ZB	269	2.8	8.1	2.1	1.5
TRt	259	3.4	11.2	1.6	2.6
Pp	240	3.3	10.9	1.8	1.9
C-Pd	177	3.7	9.3	2.0	1.8

Horizon	a_0	a_1	**r**	t_r	**Conf Lim**
ALL	8.13	0.393	0.431	33.14	4.04
Jd	7.86	0.481	0.409	16.01	3.51
O-Sn	7.98	0.295	0.416	11.71	3.17
Nmp	7.11	0.376	0.386	10.02	2.90
Qb	8.90	0.232	0.515	9.57	2.48
Pv	8.09	0.379	0.548	14.62	3.26
Pa	9.17	0.240	0.481	9.88	3.65
Pvo	8.31	0.848	0.532	10.34	6.46
ZB	7.16	0.327	0.470	8.71	2.57
TRt	10.21	0.276	0.162	2.63	5.17
Pp	10.60	0.101	0.092	1.42	3.84
C-Pd	8.25	0.275	0.301	4.18	3.38

Regression Equation: $OMC = a_0 + a_1 PM$



A random sample of 1000 observations out of a total 1247 was used for this figure.

Figure D.1: Regression analysis for horizon Jd

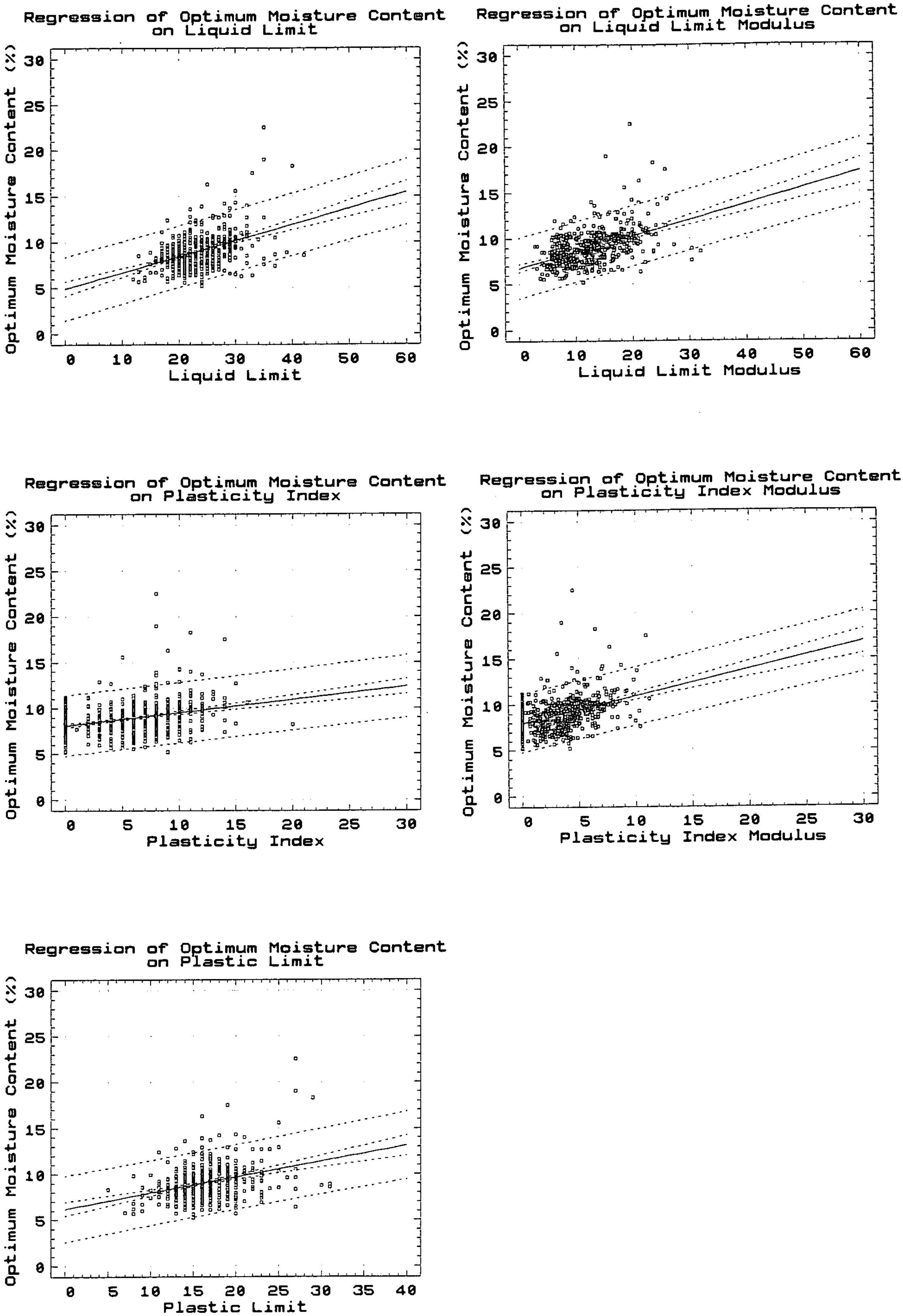


Figure D.2: Regression analysis for horizon O-Sn

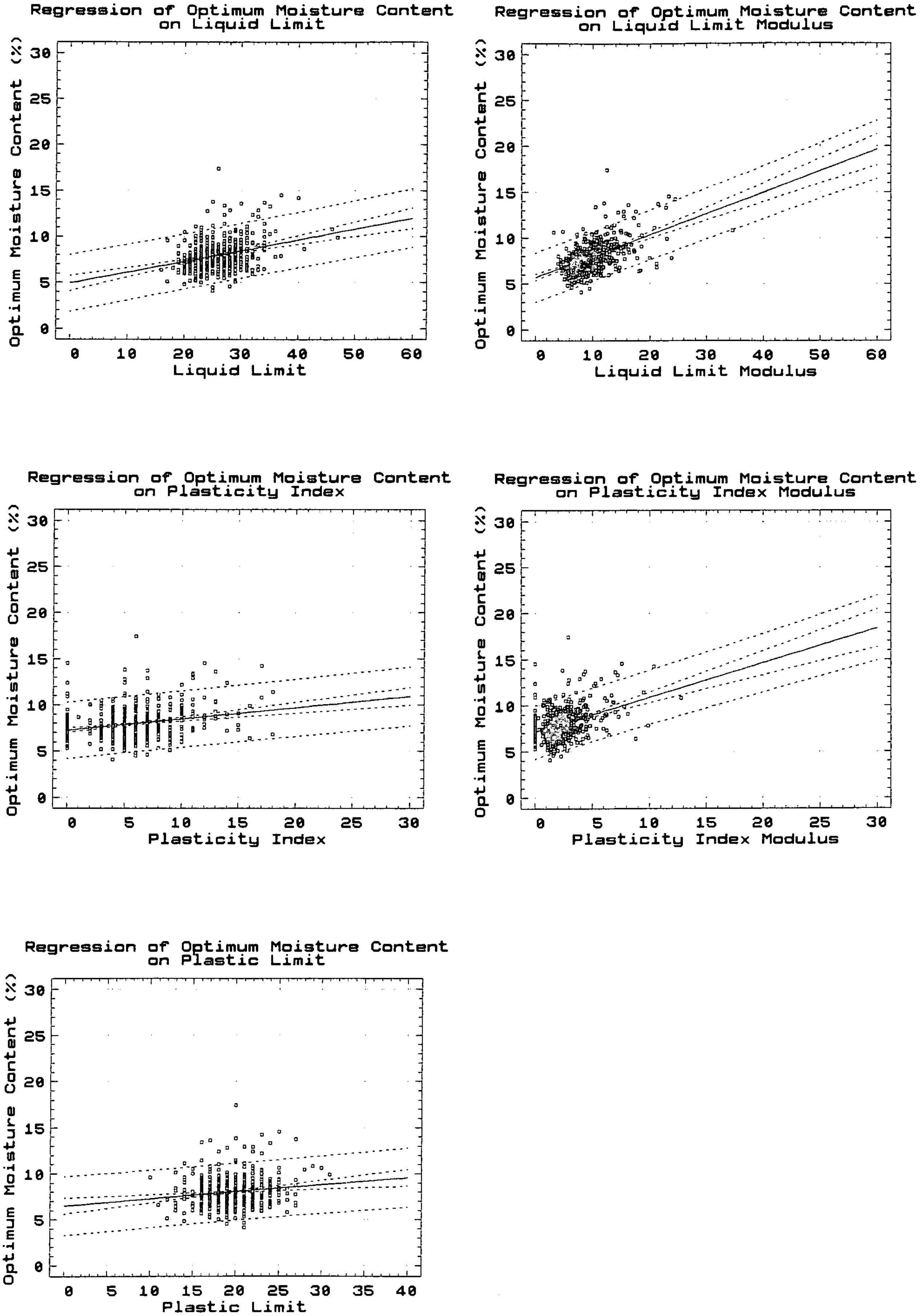


Figure D.3: Regression analysis for horizon Nmp

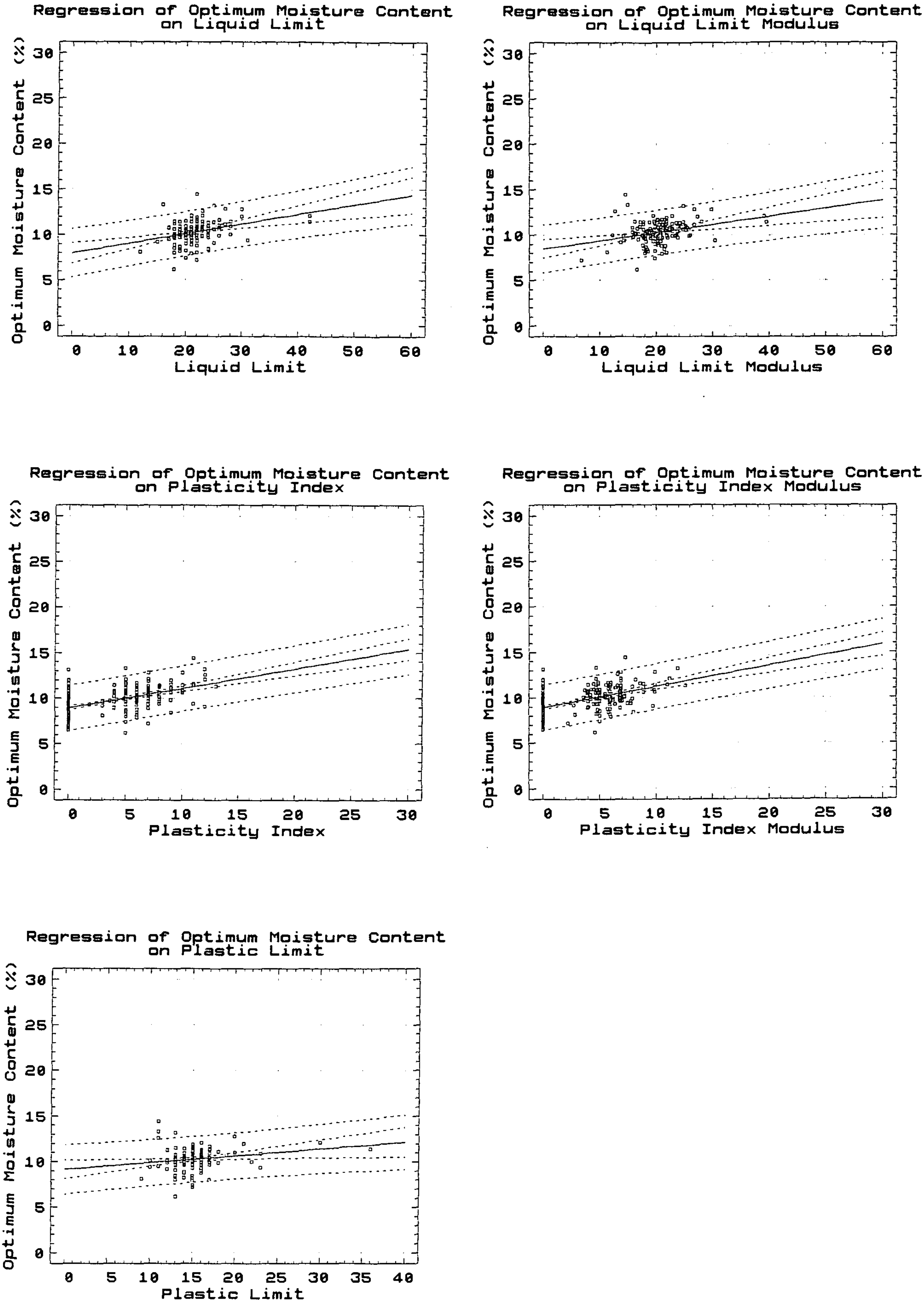


Figure D.4: Regression analysis for horizon Qb

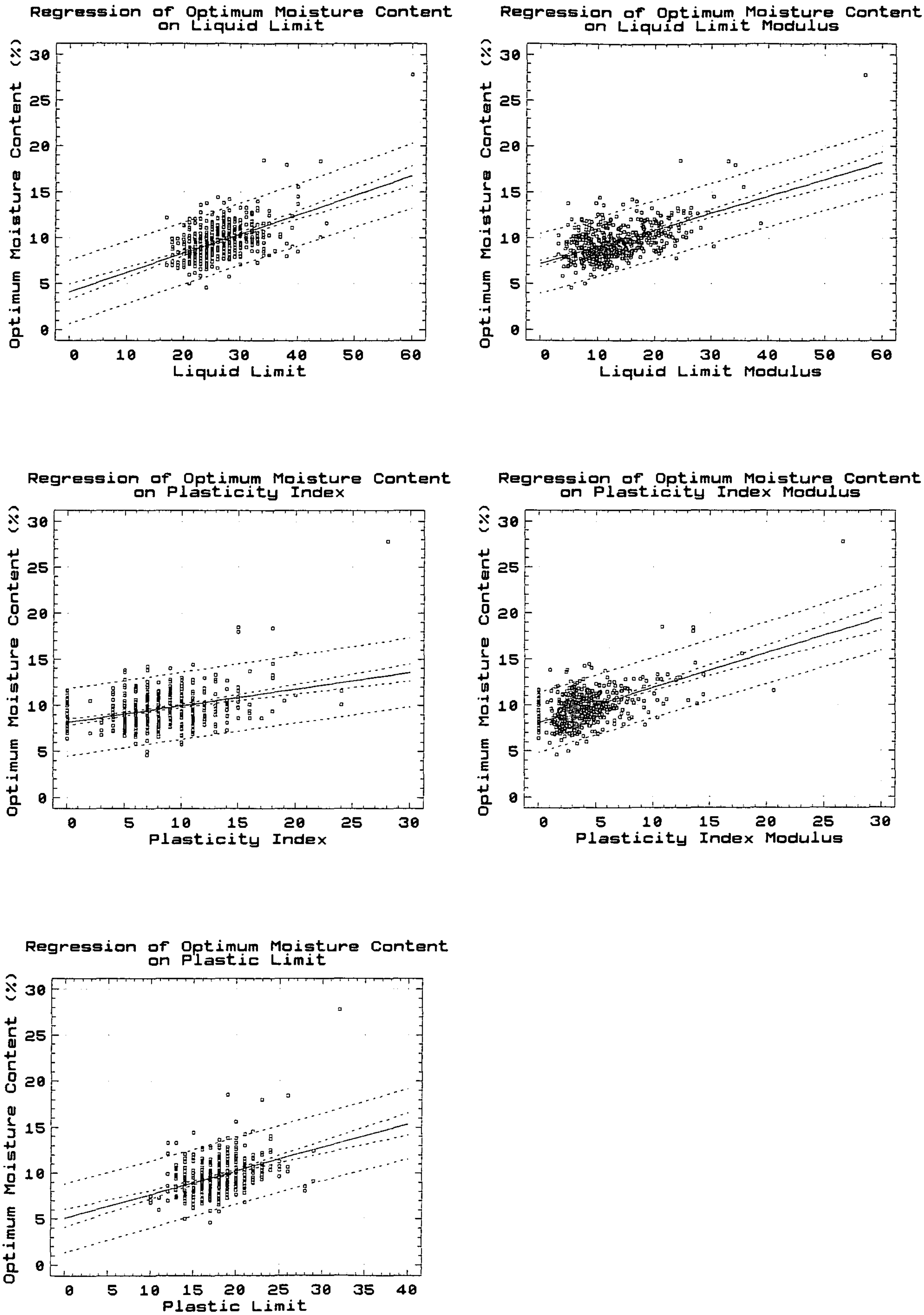


Figure D.5: Regression analysis for horizon Pv

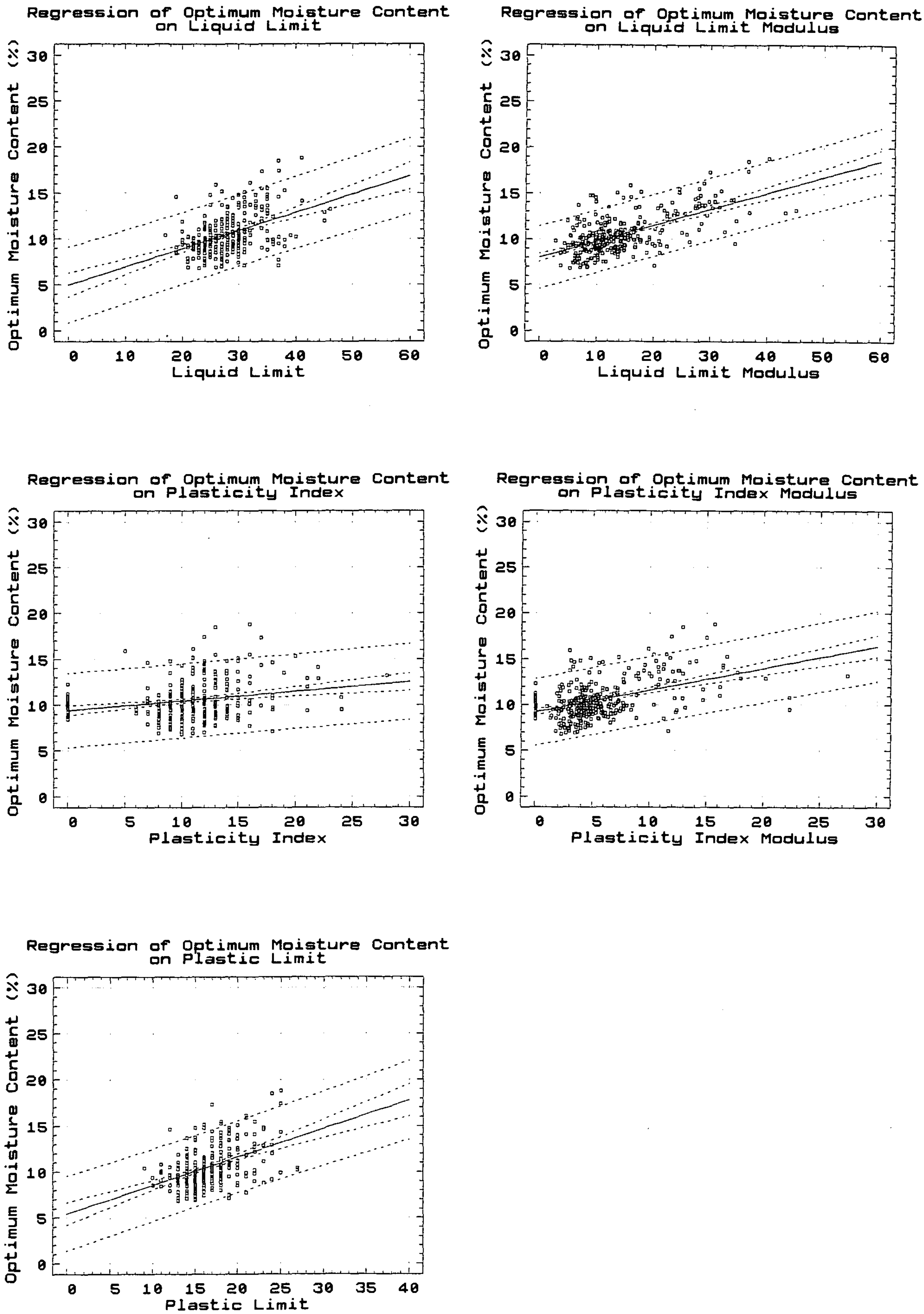


Figure D.6: Regression analysis for horizon Pa

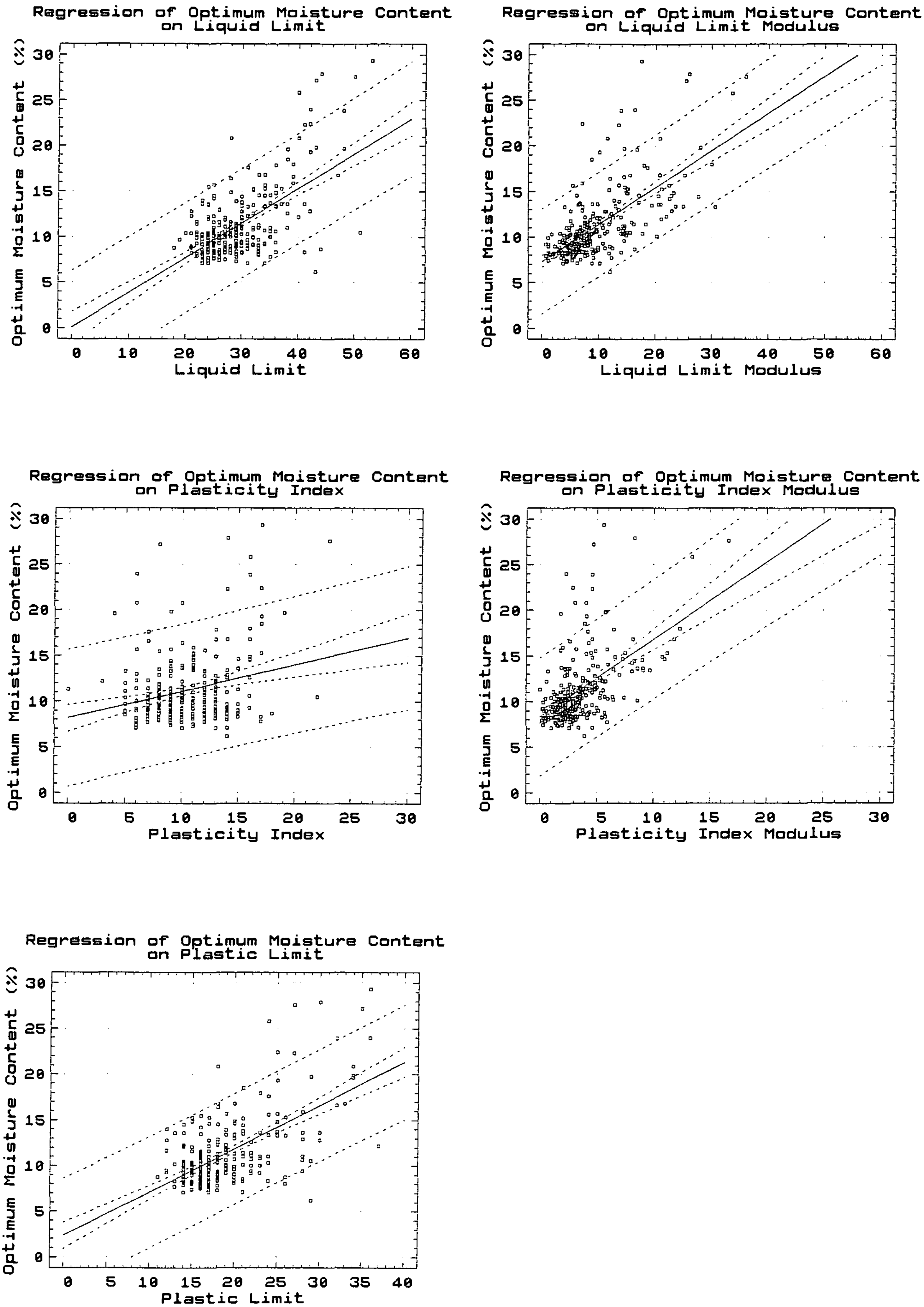


Figure D.7: Regression analysis for horizon Pvo

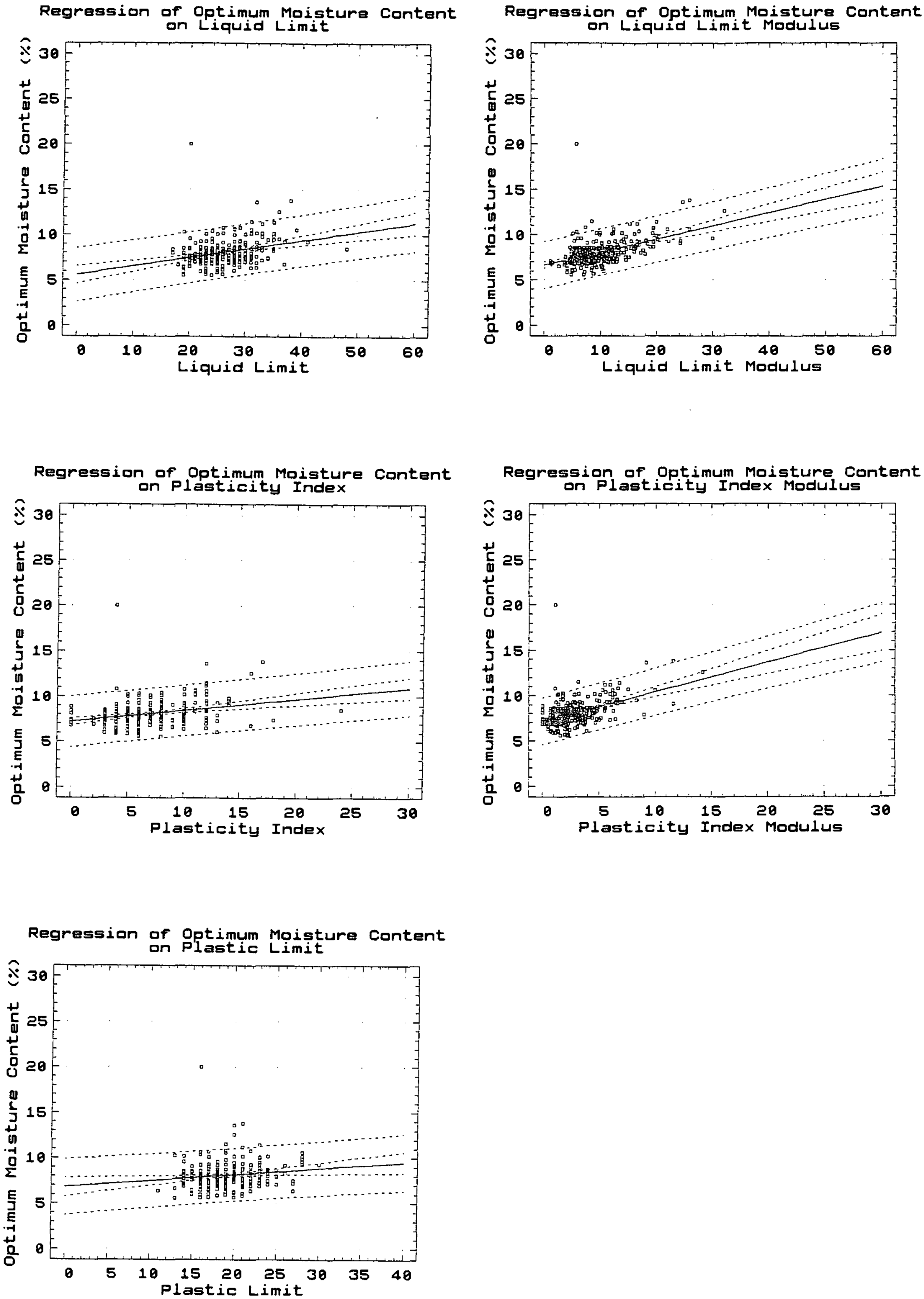


Figure D.8: Regression analysis for horizon ZB

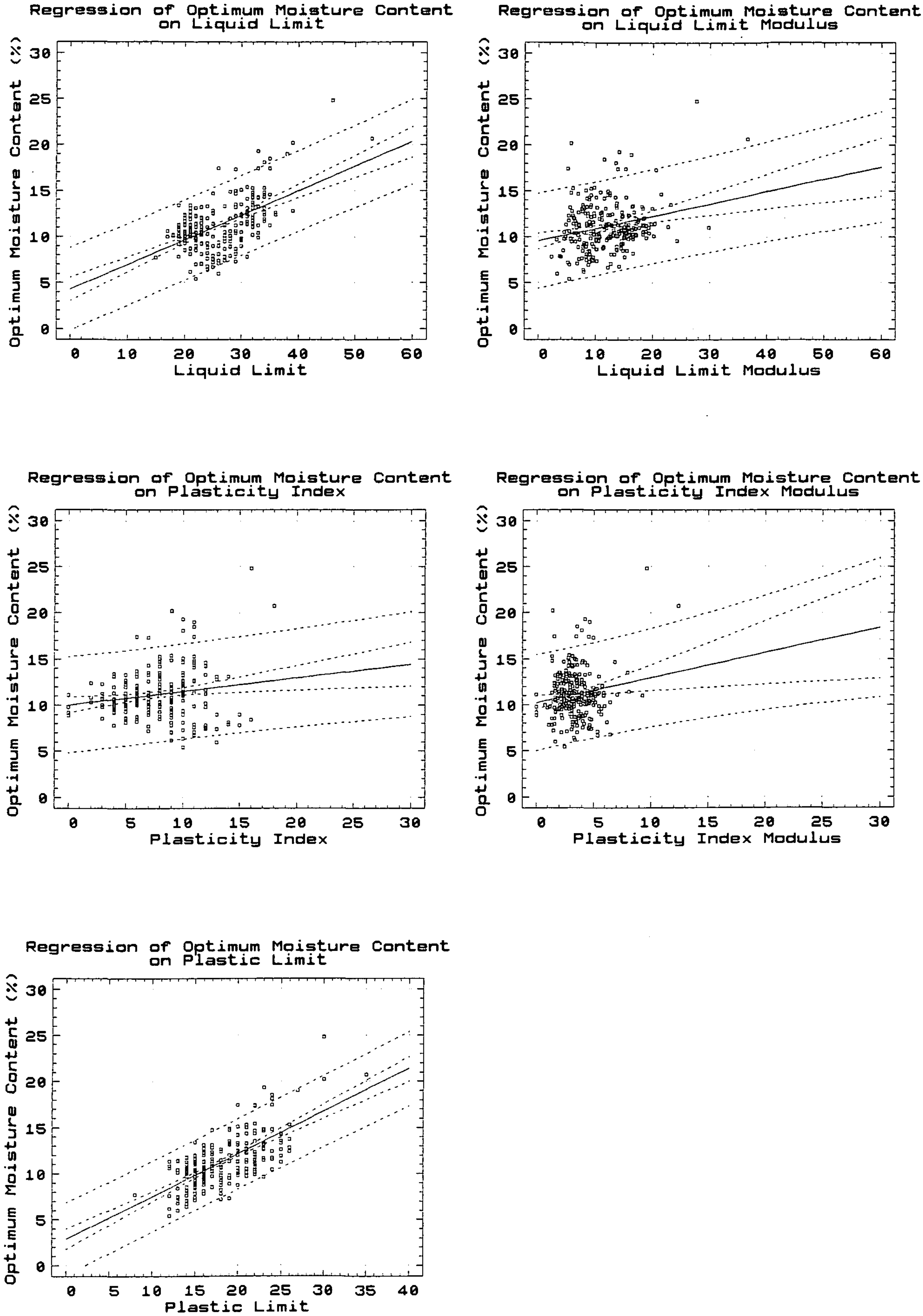


Figure D.9: Regression analysis for horizon TRt

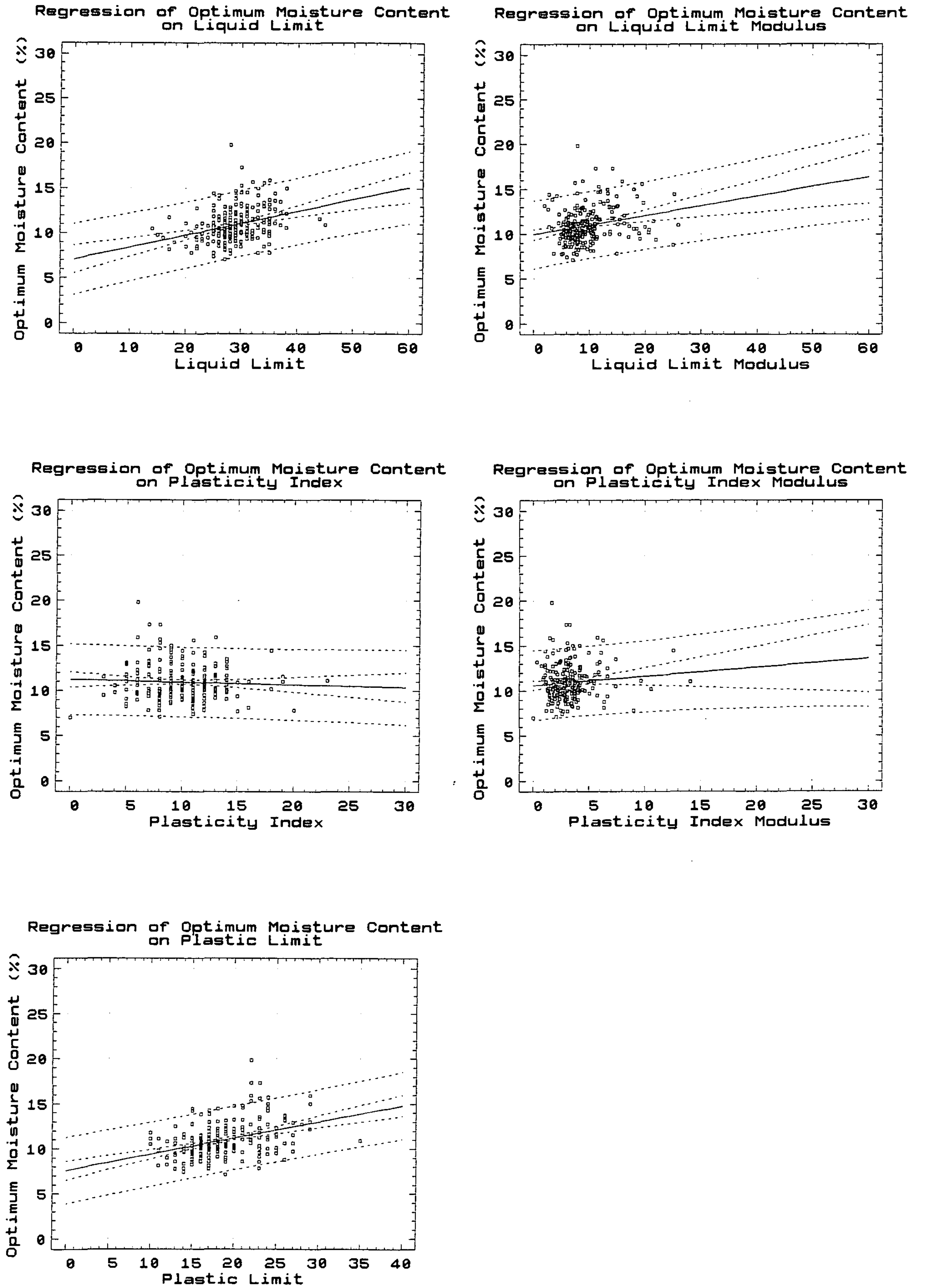


Figure D.10: Regression analysis for horizon Pp

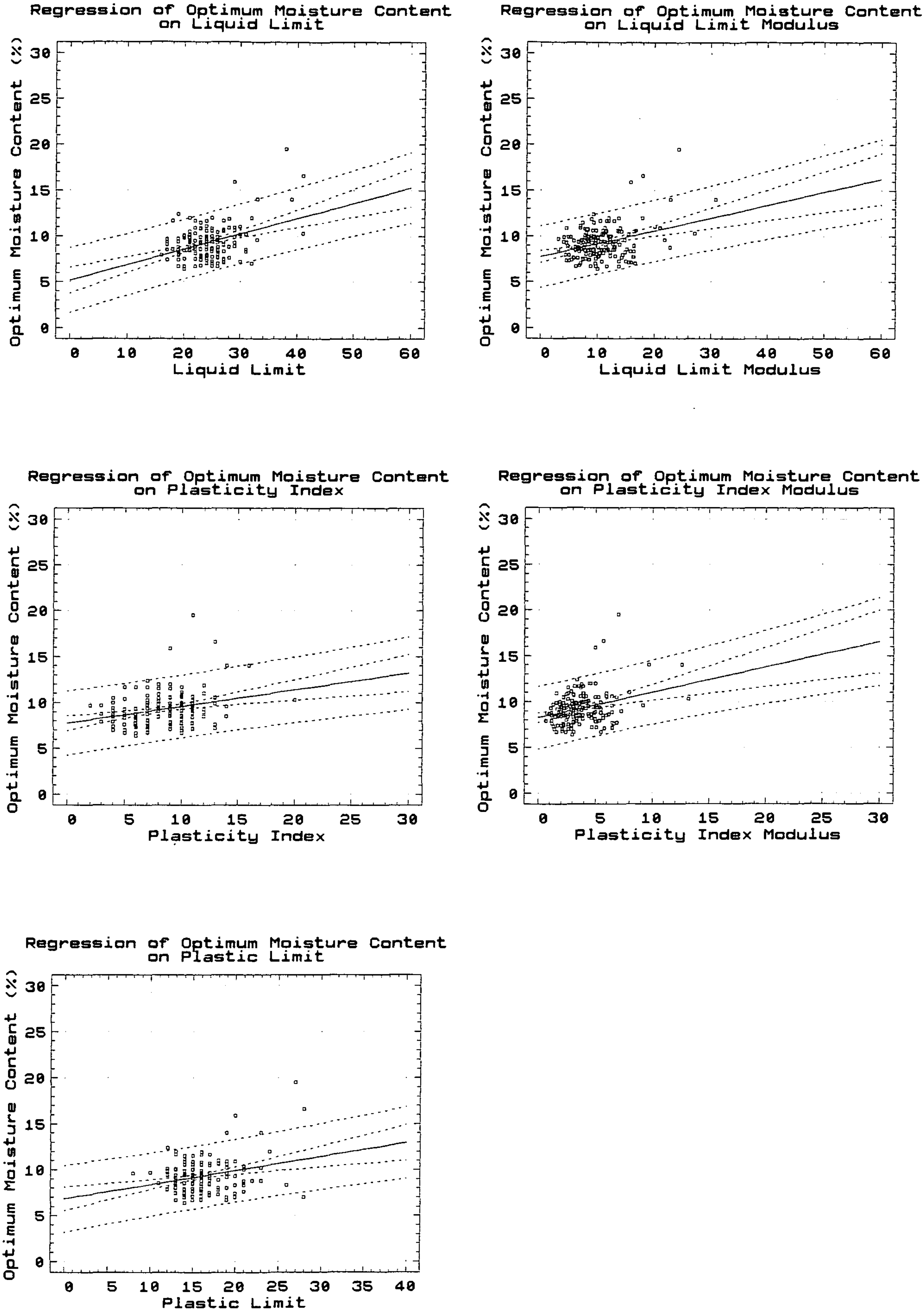


Figure D.11: Regression analysis for horizon C-Pd

Table D.6: Regression analysis OMC vs liquid limit by rock type

Rock Type	N.Obs	Mean LL	Mean OMC	Sdv LL	Sdv OMC
ALL	4362	26.8	9.4	5.4	2.3
Sandstone	1013	24.0	9.5	4.4	2.0
Sand	149	21.6	10.2	3.9	1.3
Silt	33	32.4	15.2	7.4	5.3
Shale	699	28.8	10.5	4.8	2.4
Mudstone	213	29.1	11.4	4.8	2.4
Clay	51	32.6	13.2	8.1	4.0
Granite	780	25.9	8.0	4.3	1.6
Dolerite	1247	28.8	9.0	5.3	2.0
Tillite	177	24.2	9.3	4.2	1.8

Rock Type	a_0	a_1	r	t_r	Conf Lim
ALL	4.90	0.169	0.388	27.77	4.23
Sandstone	5.39	0.170	0.378	12.99	3.58
Sand	8.04	0.102	0.303	3.85	2.50
Silt	-0.97	0.500	0.702	5.49	8.03
Shale	4.01	0.224	0.444	13.09	4.29
Mudstone	2.68	0.299	0.597	10.82	3.85
Clay	2.68	0.322	0.653	6.03	6.29
Granite	5.19	0.109	0.301	8.82	2.92
Dolerite	5.11	0.135	0.361	13.67	3.62
Tillite	5.19	0.168	0.398	5.74	3.25

Regression Equation: $OMC = a_0 + a_1 LL$

Table D.7: Regression analysis OMC vs liquid limit modulus by rock type

Rock Type	N.Obs	Mean LM	Mean OMC	Sdv LM	Sdv OMC
ALL	4362	10.6	9.4	5.8	2.3
Sandstone	1013	13.4	9.5	5.0	2.0
Sand	149	20.2	10.2	4.2	1.3
Silt	33	20.6	15.2	6.5	5.3
Shale	699	9.7	10.5	5.4	2.4
Mudstone	213	11.3	11.4	5.4	2.4
Clay	51	25.1	13.2	8.8	4.0
Granite	780	9.9	8.0	4.1	1.6
Dolerite	1247	7.3	9.0	4.0	2.0
Tillite	177	10.8	9.3	4.4	1.8

Rock Type	a_0	a_1	r	t_r	Conf Lim
ALL	7.45	0.185	0.459	34.12	4.08
Sandstone	7.14	0.173	0.441	15.60	3.47
Sand	8.22	0.100	0.322	4.12	2.48
Silt	10.04	0.253	0.309	1.81	10.72
Shale	8.45	0.208	0.463	13.79	4.24
Mudstone	10.12	0.113	0.251	3.77	4.65
Clay	7.43	0.229	0.505	4.10	7.16
Granite	6.14	0.189	0.493	15.80	2.66
Dolerite	7.08	0.261	0.531	22.13	3.29
Tillite	7.75	0.142	0.350	4.95	3.32

Regression Equation: $OMC = a_0 + a_1 LLM$

Table D.8: Regression analysis OMC vs plasticity index by rock type

Rock Type	N.Obs	Mean PI	Mean OMC	Sdv PI	Sdv OMC
ALL	4810	7.8	9.3	4.3	2.3
Sandstone	1247	5.8	9.3	3.7	1.9
Sand	258	3.7	9.7	3.5	1.5
Silt	33	11.5	15.2	4.8	5.3
Shale	703	10.7	10.4	3.1	2.4
Mudstone	216	9.8	11.4	2.7	2.4
Clay	52	15.1	13.1	5.1	4.0
Granite	844	6.1	8	3.3	1.6
Dolerite	1280	9.3	9	4.2	2.0
Tillite	177	8.3	9.3	2.8	1.8

Rock Type	a_0	a_1	r	t_r	Conf Lim
ALL	8.2	0.147	0.276	19.9	4.31
Sandstone	8.59	0.121	0.239	8.68	3.62
Sand	8.92	0.205	0.489	8.97	2.54
Silt	16.47	-0.107	-0.098	0.55	11.22
Shale	9.02	0.133	0.169	4.55	4.71
Mudstone	9.55	0.186	0.211	3.16	4.67
Clay	10.61	0.168	0.216	1.57	8.02
Granite	7.25	0.122	0.258	7.74	2.96
Dolerite	8.46	0.056	0.120	4.33	3.82
Tillite	7.77	0.181	0.283	3.90	3.40

Regression Equation: $OMC = a_0 + a_1 PI$

Table D.9: Regression analysis OMC vs plastic limit by rock type

Rock Type	N.Obs	Mean PL	Mean OMC	Sdv PL	Sdv OMC
ALL	4362	18.2	9.4	3.7	2.3
Sandstone	1013	16.8	9.5	3.4	2.0
Sand	149	15.2	10.2	3.2	1.3
Silt	33	20.9	15.2	7.5	5.3
Shale	699	18.0	10.5	3.7	2.4
Mudstone	213	19.2	11.4	4.1	2.4
Clay	51	17.2	13.2	5.3	4.0
Granite	780	19.3	8.0	3.2	1.6
Dolerite	1247	19.2	9.0	3.5	2.0
Tillite	177	15.9	9.3	3.2	1.8

Rock Type	a_0	a_1	r	t_r	Conf Lim
ALL	6.08	0.184	0.294	20.29	4.39
Sandstone	5.93	0.210	0.358	12.19	3.61
Sand	9.01	0.081	0.195	2.41	2.57
Silt	3.92	0.540	0.763	6.57	7.29
Shale	5.17	0.293	0.447	13.2	4.28
Mudstone	4.92	0.337	0.577	10.26	3.92
Clay	2.71	0.609	0.804	9.46	4.94
Granite	6.63	0.072	0.147	4.15	3.03
Dolerite	4.51	0.232	0.407	15.72	3.54
Tillite	6.84	0.152	0.276	3.79	3.41

Regression Equation: $OMC = a_0 + a_1 PL$

Table D.10: Regression analysis OMC vs Plasticity modulus by rock type

Rock Type	N.Obs	Mean PM	Mean OMC	Sdv PM	Sdv OMC
ALL	4810	3.1	9.3	2.5	2.3
Sandstone	1247	3.2	9.3	2.4	1.9
Sand	258	3.4	9.7	3.2	1.5
Silt	33	7.6	15.2	4.1	5.3
Shale	703	3.6	10.4	2.3	2.4
Mudstone	216	3.9	11.4	2.2	2.4
Clay	52	11.8	13.1	5.5	4.0
Granite	844	2.4	8.0	1.8	1.6
Dolerite	1280	2.3	9.0	1.7	2.0
Tillite	177	3.7	9.3	2	1.8

Rock Type	a_0	a_1	r	t_r	Conf Lim
ALL	8.13	0.393	0.431	33.14	4.04
Sandstone	8.36	0.286	0.363	13.76	3.47
Sand	8.89	0.230	0.505	9.37	2.51
Silt	16.52	-0.169	-0.132	0.74	11.17
Shale	9.04	0.387	0.374	10.66	4.44
Mudstone	10.74	0.162	0.149	2.21	4.73
Clay	11.35	0.151	0.208	1.51	8.03
Granite	7.14	0.352	0.412	13.13	2.79
Dolerite	7.86	0.481	0.409	16.01	3.51
Tillite	8.25	0.275	0.301	4.18	3.38

Regression Equation: $OMC = a_0 + a_1 PM$

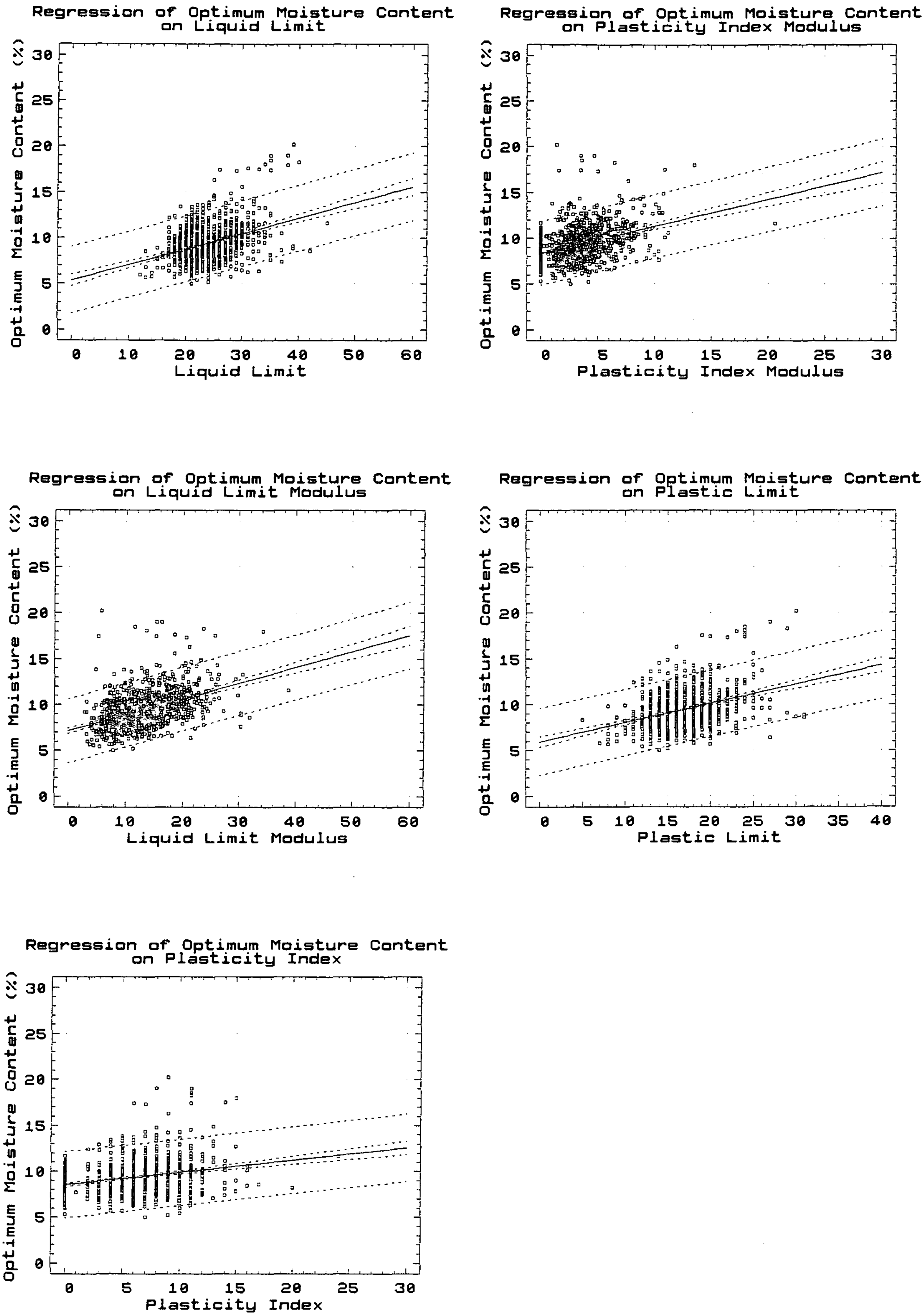


Figure D.12: Regression analysis for Sandstone

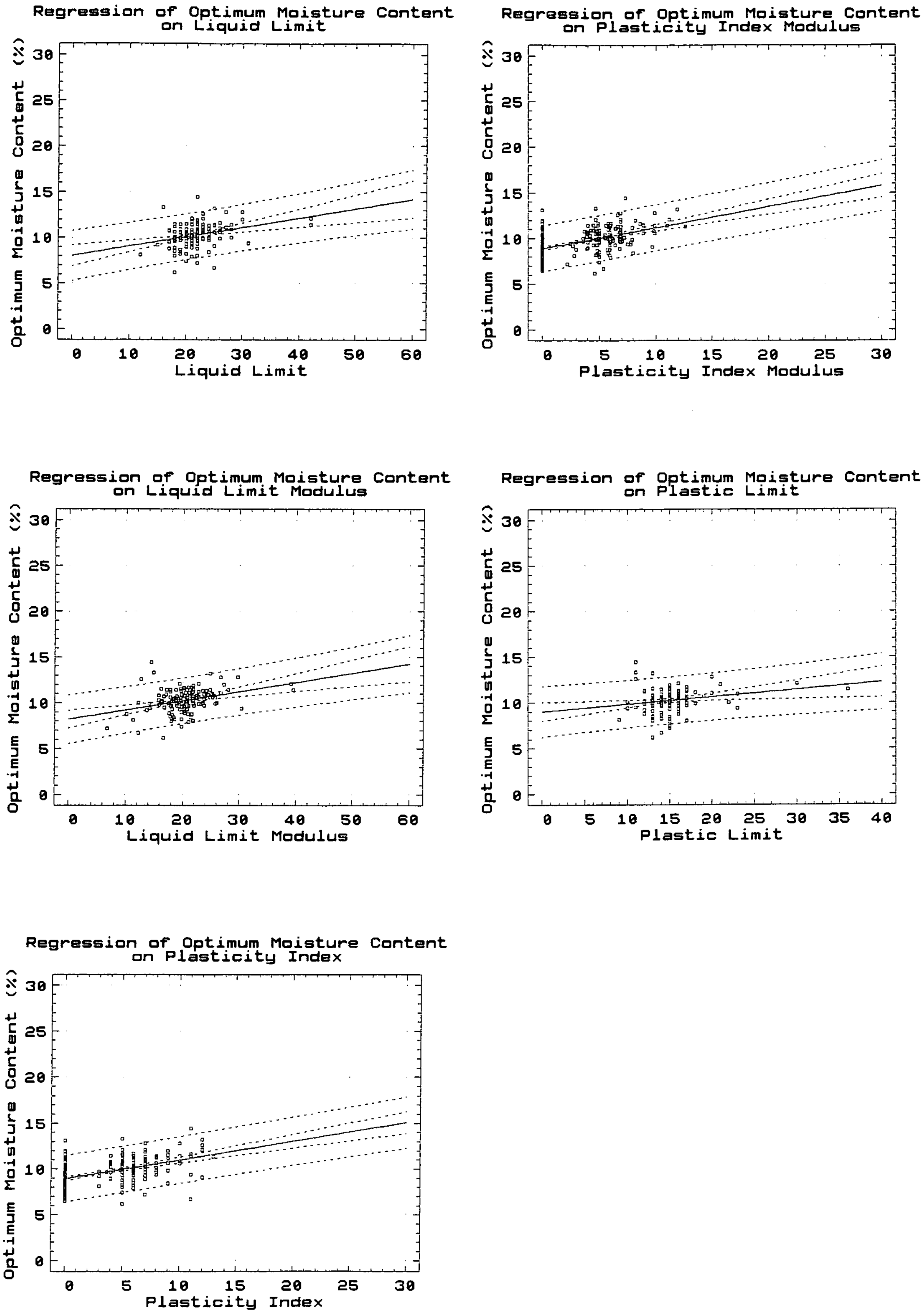


Figure D.13: Regression analysis for Sand

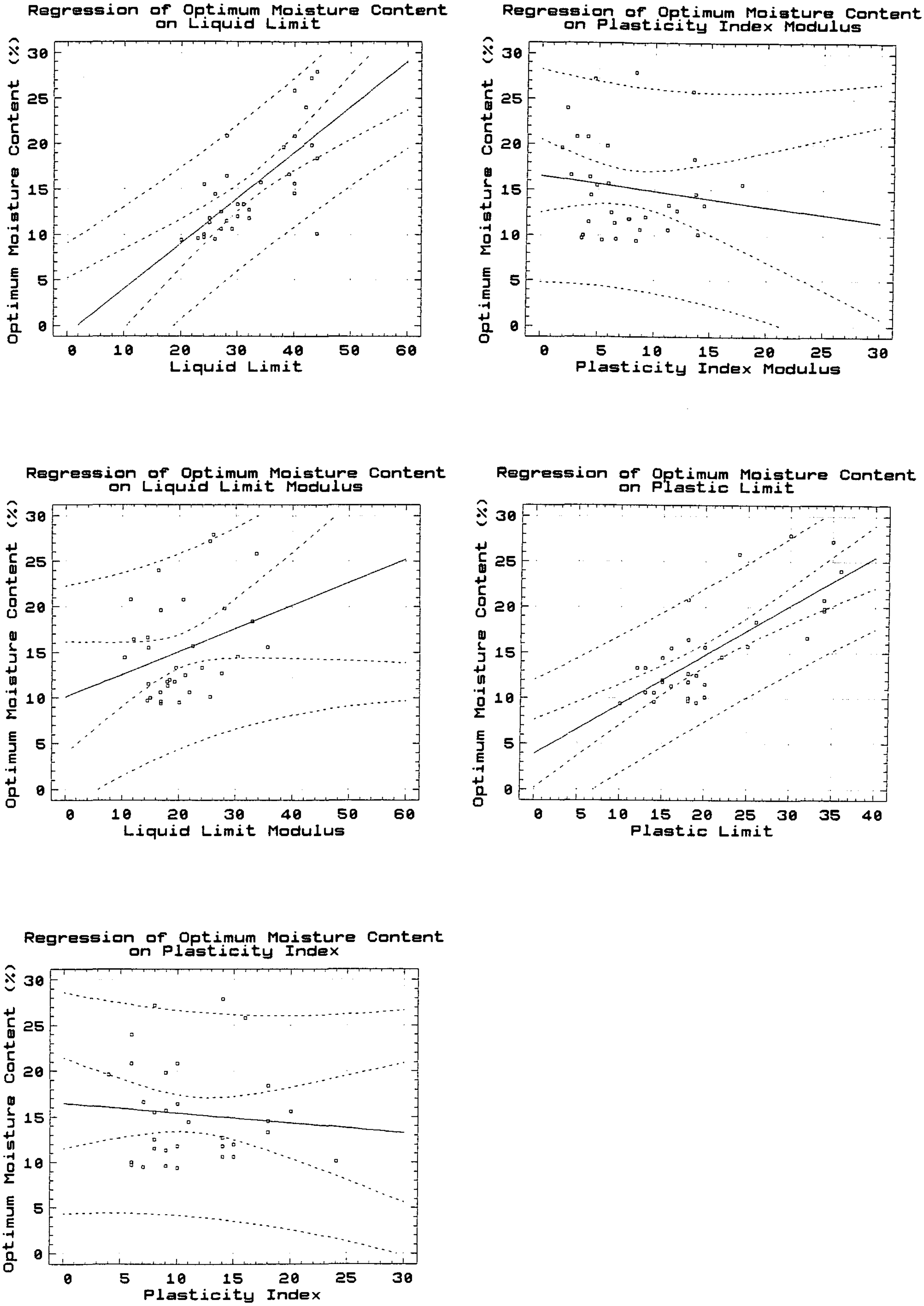


Figure D.14: Regression analysis for horizon Silt

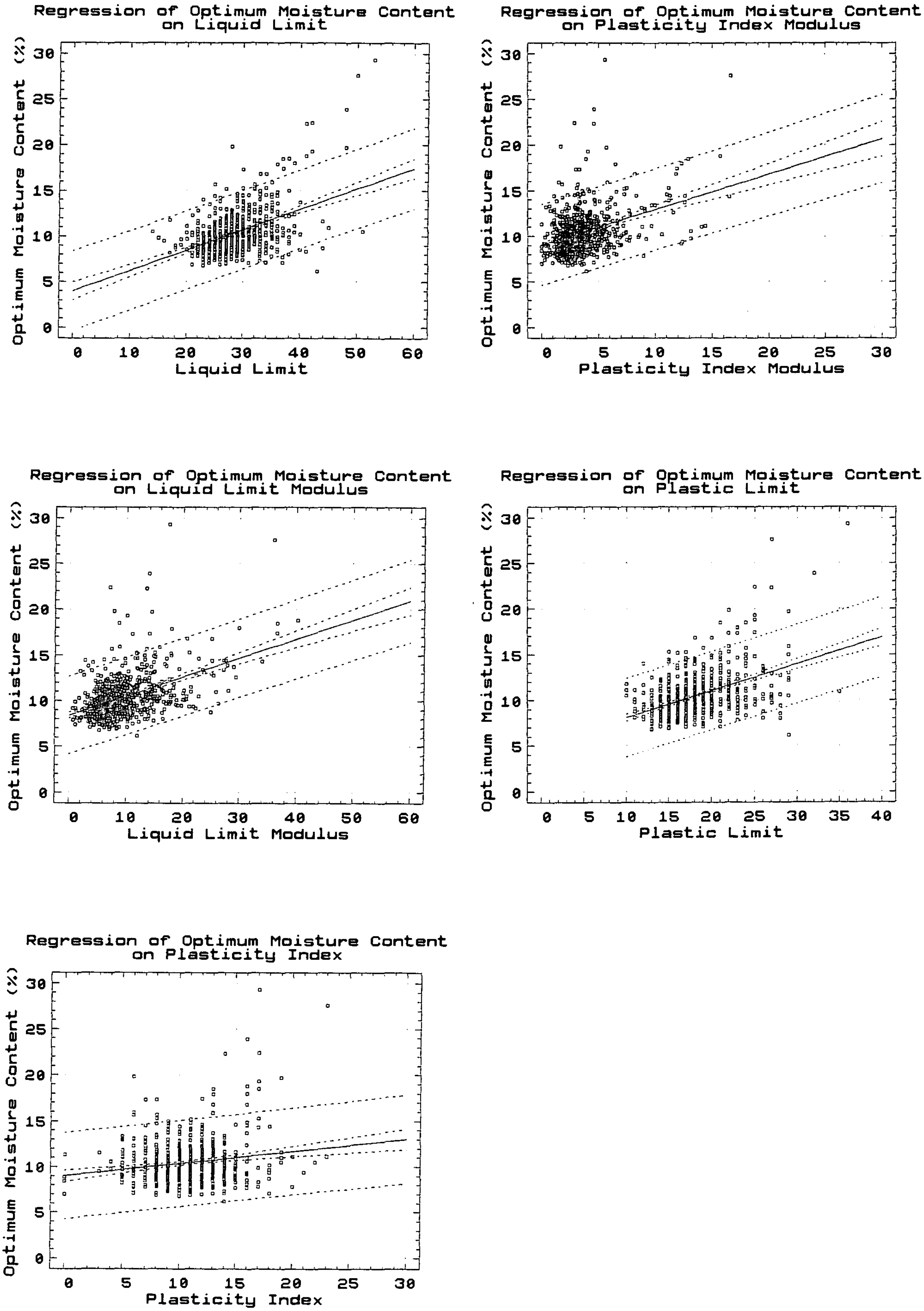


Figure D.15: Regression analysis for horizon Shale

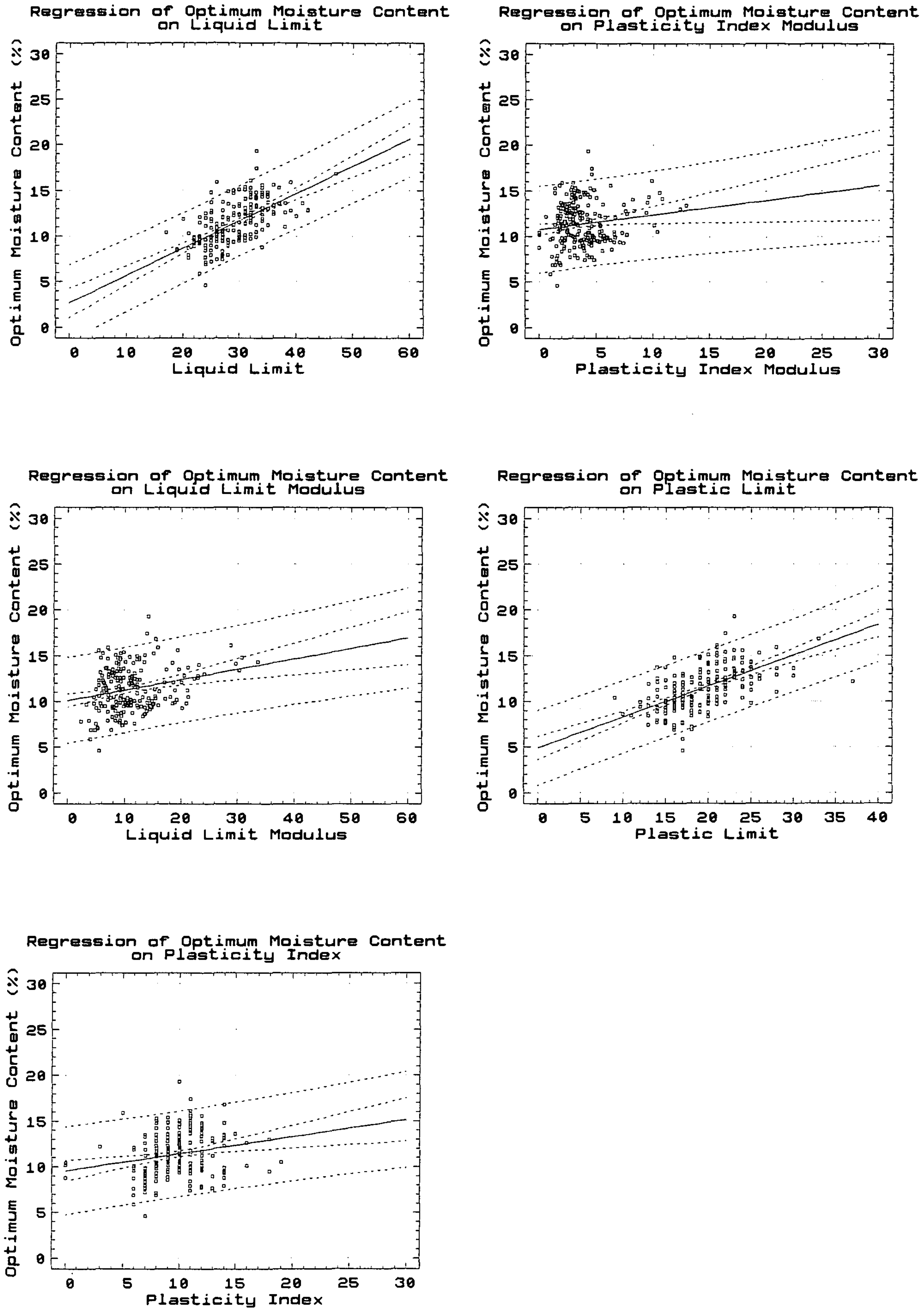


Figure D.16: Regression analysis for Mudstone

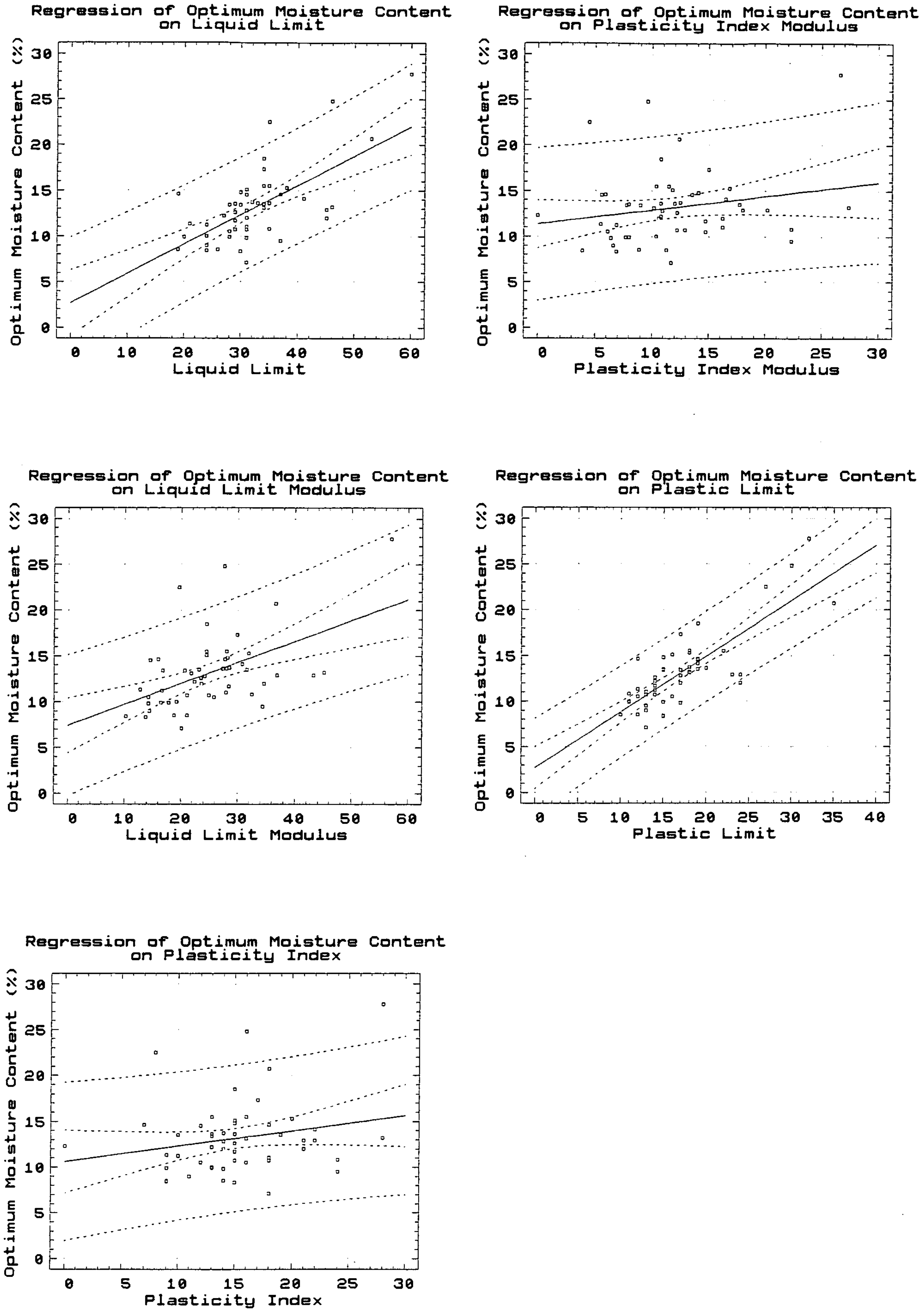


Figure D.17: Regression analysis for Clay

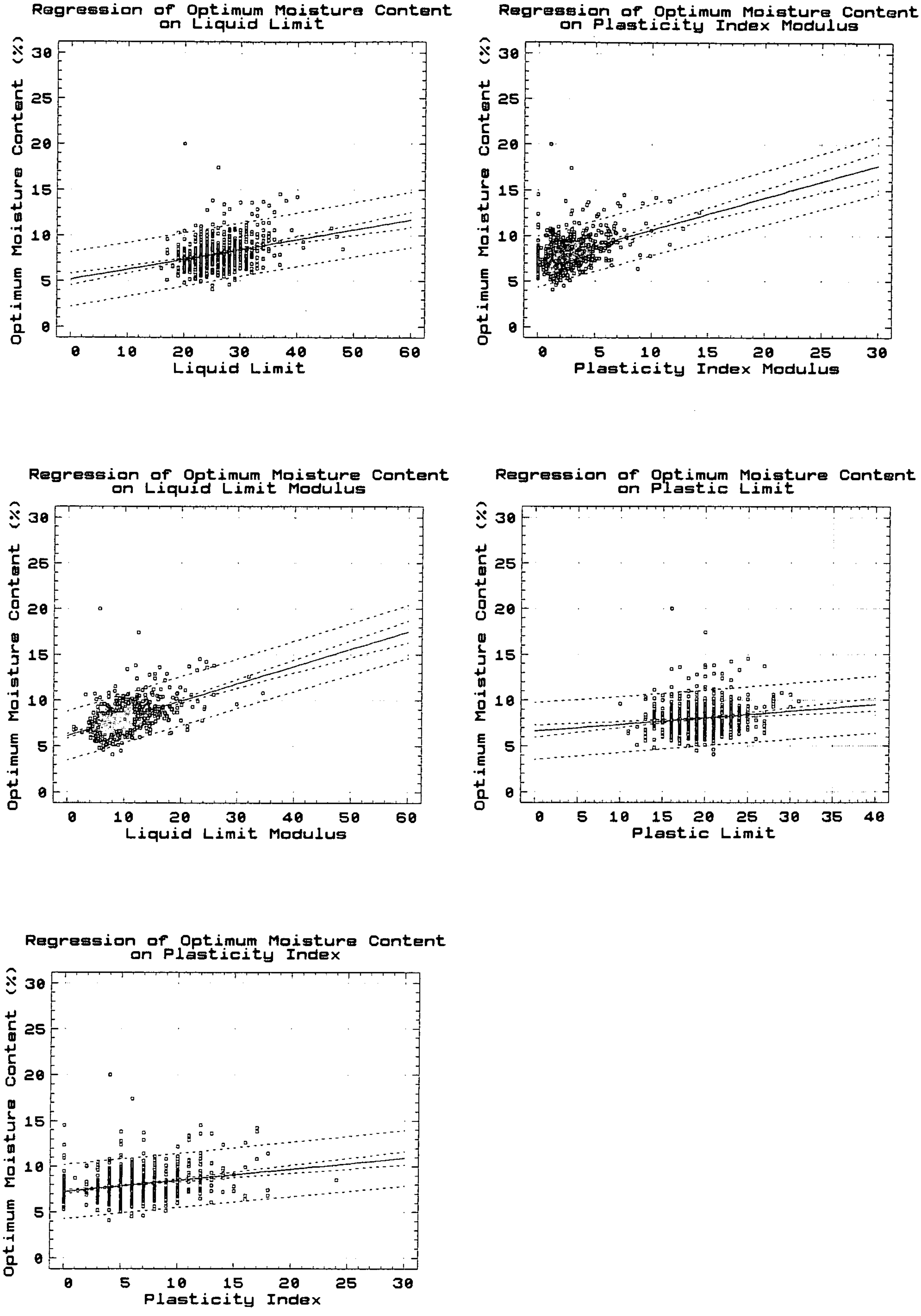
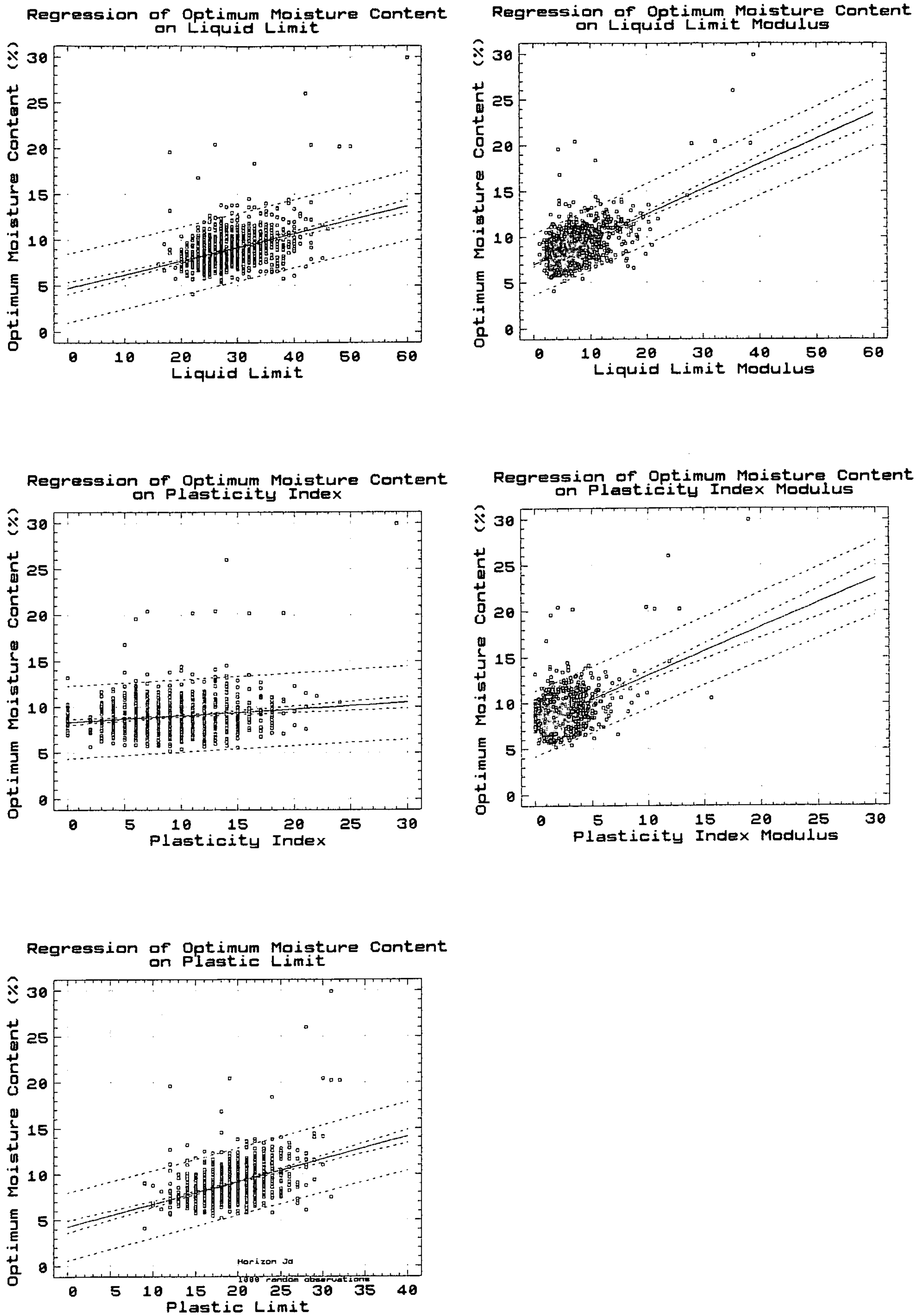


Figure D.18: Regression analysis for Granite



A random sample of 1000 observations out of a total 1247 was used for this figure.

Figure D.19: Regression analysis for Dolerite

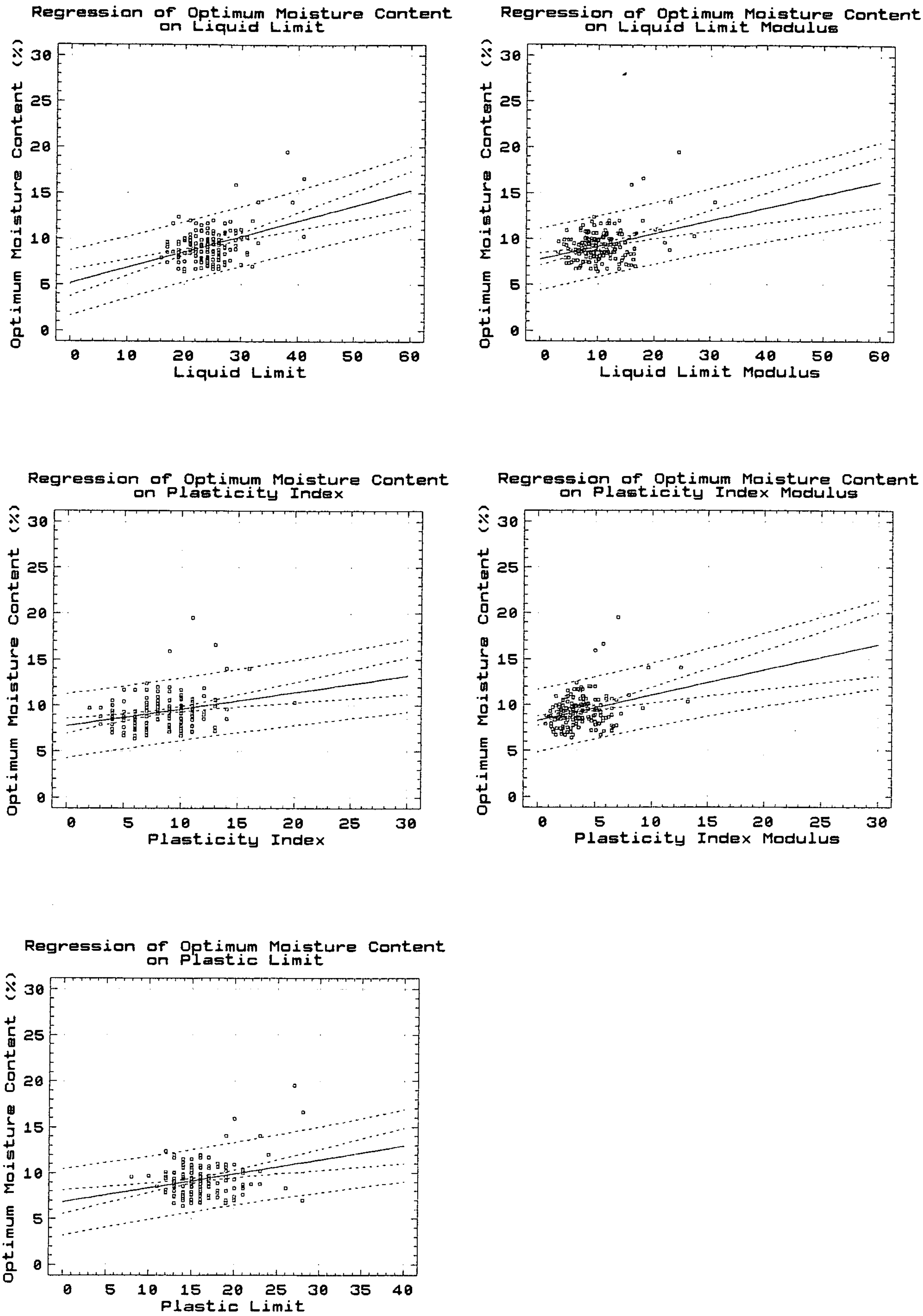


Figure D.20: Regression analysis for Tillite

Table D.11: Regression analysis OMC vs liquid limit by Weinert's Classification

Weinert's Classification	N.Obs	Mean LL	Mean OMC	Sdv LL	Sdv OMC
ALL	4362	26.8	9.4	5.4	2.3
Acidic	780	25.9	8.0	4.3	1.6
Basic	1247	28.8	9.0	5.3	2.0
Arenaceous	1162	23.7	9.6	4.4	1.9
Argillaceous	996	29.2	11.0	5.3	2.9
Diamictites	177	24.2	9.3	4.2	1.8

Weinert's Classification	a_0	a_1	r	t_r	Conf Lim
ALL	4.90	0.169	0.388	27.77	4.23
Acidic	5.19	0.109	0.301	8.82	2.92
Basic	5.11	0.135	0.361	13.67	3.62
Arenaceous	6.09	0.146	0.337	12.18	3.54
Argillaceous	2.37	0.294	0.539	20.17	4.75
Diamictites	5.19	0.168	0.398	5.74	3.25

Regression Equation: $OMC = a_0 + a_1 LL$

Table D.12: Regression analysis OMC vs liquid limit modulus by Weinert's Classification

Weinert's Classification	N.Obs	Mean LM	Mean OMC	Sdv LM	Sdv OMC
ALL	4362	10.6	9.4	5.8	2.3
Acidic	780	9.9	8.0	4.1	1.6
Basic	1247	7.3	9.0	4.0	2.0
Arenaceous	1162	14.3	9.6	5.4	1.9
Argillaceous	996	11.2	11.0	6.8	2.9
Diamictites	177	10.8	9.3	4.4	1.8

Weinert's Classification	a_0	a_1	r	t_r	Conf Lim
ALL	7.45	0.185	0.459	34.12	4.08
Acidic	6.14	0.189	0.493	15.80	2.66
Basic	7.08	0.261	0.531	22.13	3.29
Arenaceous	7.31	0.157	0.445	16.91	3.37
Argillaceous	8.63	0.208	0.495	17.96	4.90
Diamictites	7.75	0.142	0.350	4.95	3.32

Regression Equation: $OMC = a_0 + a_1 LLM$

Table D.13: Regression analysis OMC vs plasticity index by Weinert's Classification

Weinert's Classification	N.Obs	Mean PI	Mean OMC	Sdv PI	Sdv OMC
ALL	4810	7.8	9.3	4.3	2.3
Acidic	844	6.1	8.0	3.3	1.6
Basic	1280	9.3	9.0	4.2	2.0
Arenaceous	1505	5.5	9.4	3.8	1.8
Argillaceous	1004	10.8	10.9	3.4	2.9
Diamictites	177	8.3	9.3	2.8	1.8

Weinert's Classification	a_0	a_1	r	t_r	Conf Lim
ALL	8.20	0.147	0.276	19.90	4.31
Acidic	7.25	0.122	0.258	7.74	2.96
Basic	8.46	0.056	0.120	4.33	3.82
Arenaceous	8.70	0.120	0.247	9.89	3.49
Argillaceous	9.24	0.158	0.190	6.11	5.52
Diamictites	7.77	0.181	0.283	3.90	3.40

Regression Equation: $OMC = a_0 + a_1 PI$

Table D.14: Regression analysis OMC vs plastic limit by Weinert's Classification

Weinert's Classification	N.Obs	Mean PL	Mean OMC	Sdv PL	Sdv OMC
ALL	4362	18.2	9.4	3.7	2.3
Acidic	780	19.3	8.0	3.2	1.6
Basic	1247	19.2	9.0	3.5	2.0
Arenaceous	1162	16.6	9.6	3.4	1.9
Argillaceous	996	18.3	11.0	4.1	2.9
Diamictites	177	15.9	9.3	3.2	1.8

Weinert's Classification	a_0	a_1	r	t_r	Conf Lim
ALL	6.08	0.184	0.294	20.29	4.39
Acidic	6.63	0.072	0.147	4.15	3.03
Basic	4.51	0.232	0.407	15.72	3.54
Arenaceous	6.61	0.178	0.313	11.24	3.57
Argillaceous	4.14	0.372	0.536	20.03	4.76
Diamictites	6.84	0.152	0.276	3.79	3.41

Regression Equation: $OMC = a_0 + a_1 PL$

Table D.15: Regression analysis OMC vs Plasticity modulus by Weinert's Classification

Weinert's Classification	**N.Obs**	**Mean PM**	**Mean OMC**	**Sdv PM**	**Sdv OMC**
ALL	4810	3.1	9.3	2.5	2.3
Acidic	844	2.4	8.0	1.8	1.6
Basic	1280	2.3	9.0	1.7	2.0
Arenaceous	1505	3.3	9.4	2.6	1.8
Argillaceous	1004	4.2	10.9	3.3	2.9
Diamictites	177	3.7	9.3	2.0	1.8

Weinert's Classification	a_0	a_1	**r**	t_r	**Conf Lim**
ALL	8.13	0.393	0.431	33.14	4.04
Acidic	7.14	0.352	0.412	13.13	2.79
Basic	7.86	0.481	0.409	16.01	3.51
Arenaceous	8.47	0.272	0.381	15.96	3.33
Argillaceous	9.62	0.312	0.355	12.04	5.26
Diamictites	8.25	0.275	0.301	4.18	3.38

Regression Equation: $OMC = a_0 + a_1 PM$

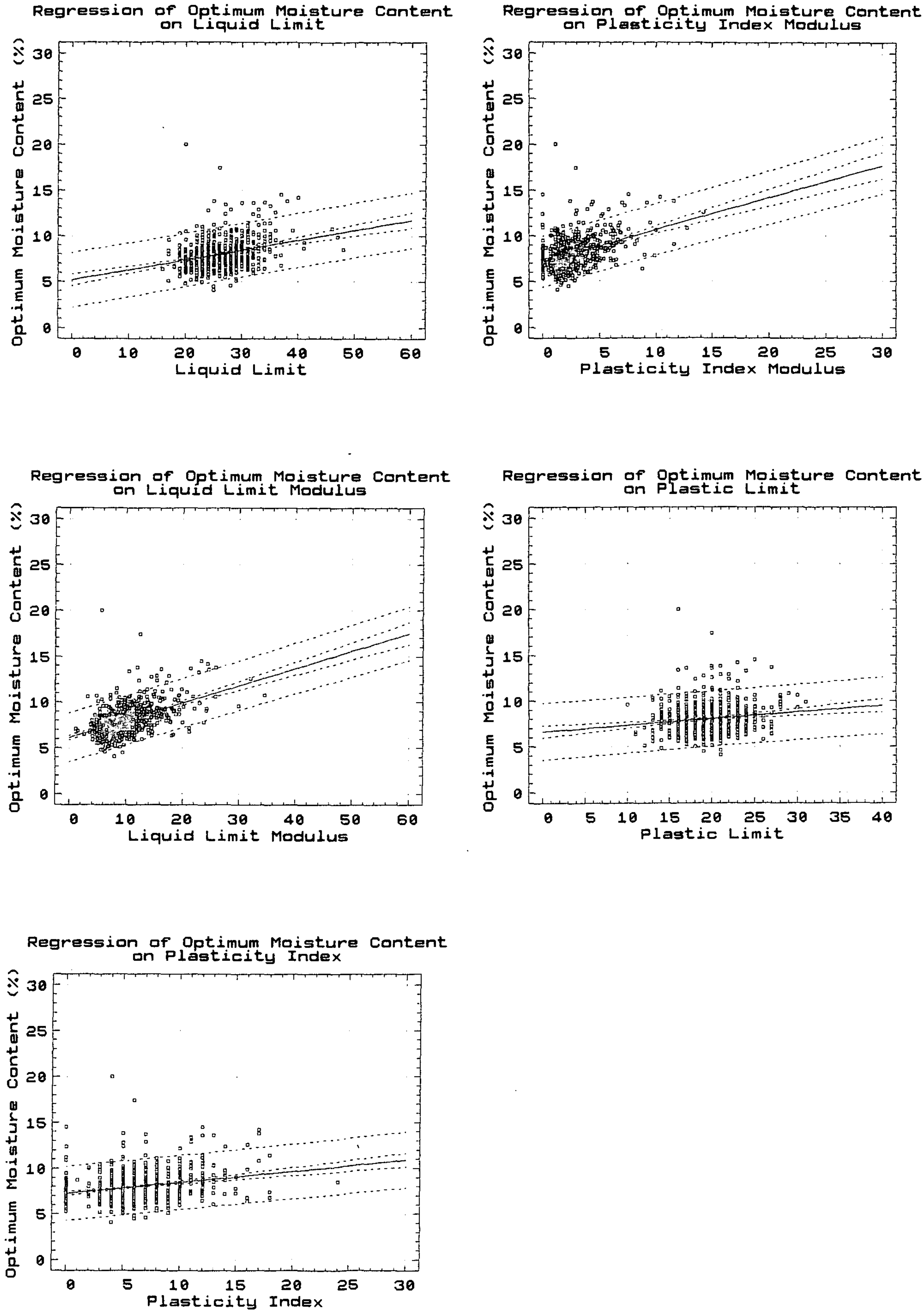
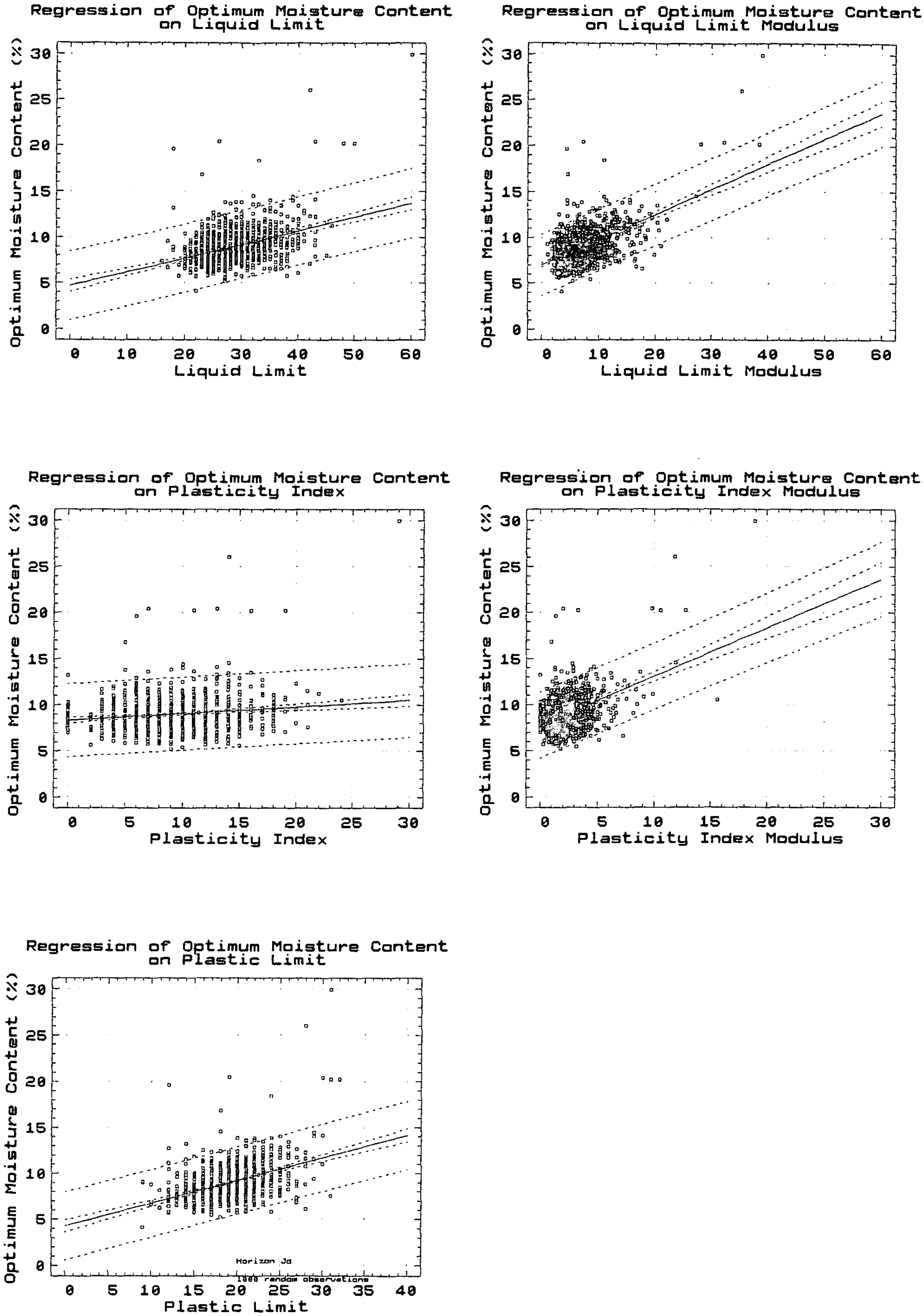


Figure D.21: Regression analysis for Acidic Rocks



A random sample of 1000 observations out of a total 1247 was used for this figure.

Figure D.22: Regression analysis for Basic Rocks

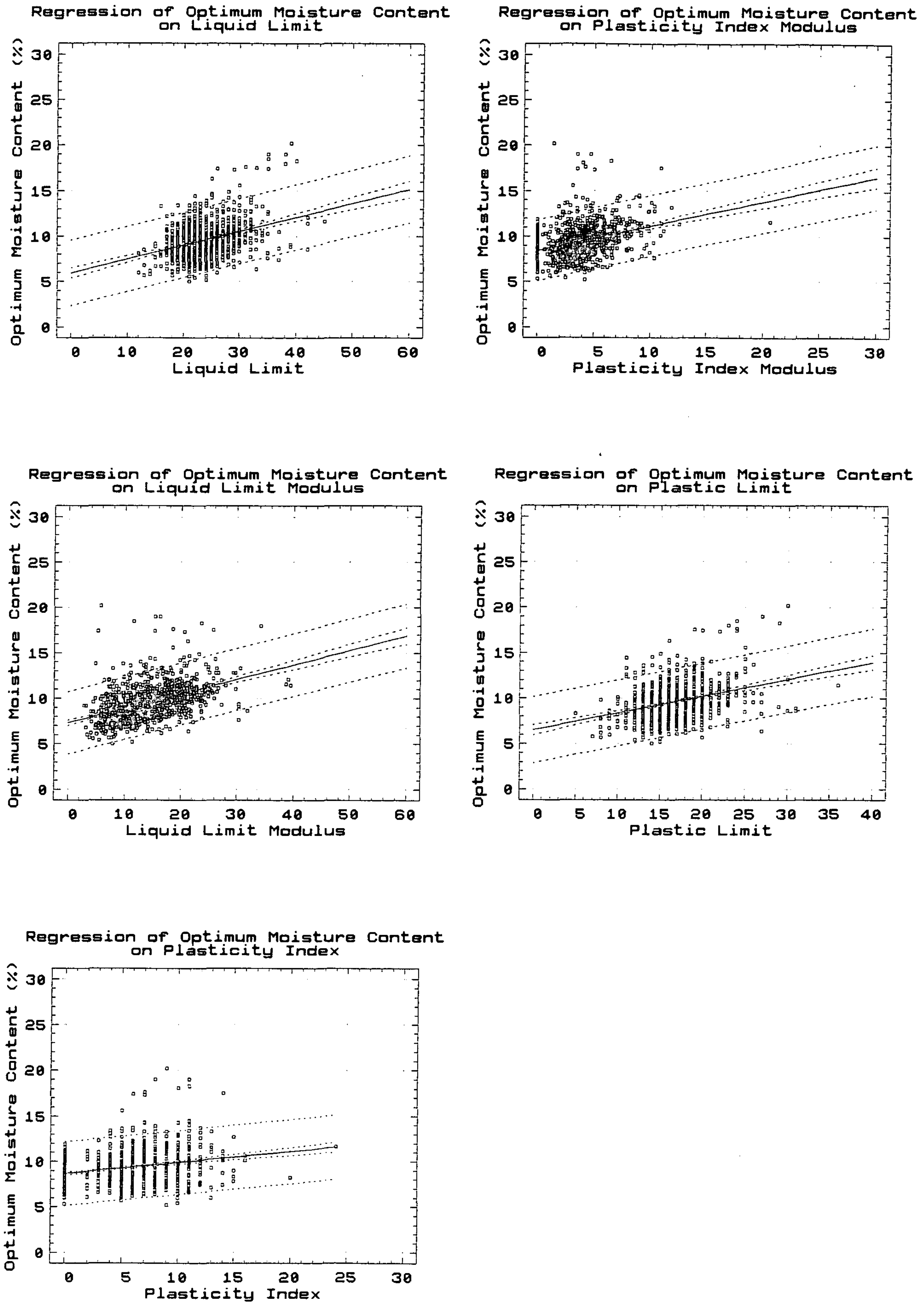


Figure D.23: Regression analysis for Arenaceous Rocks

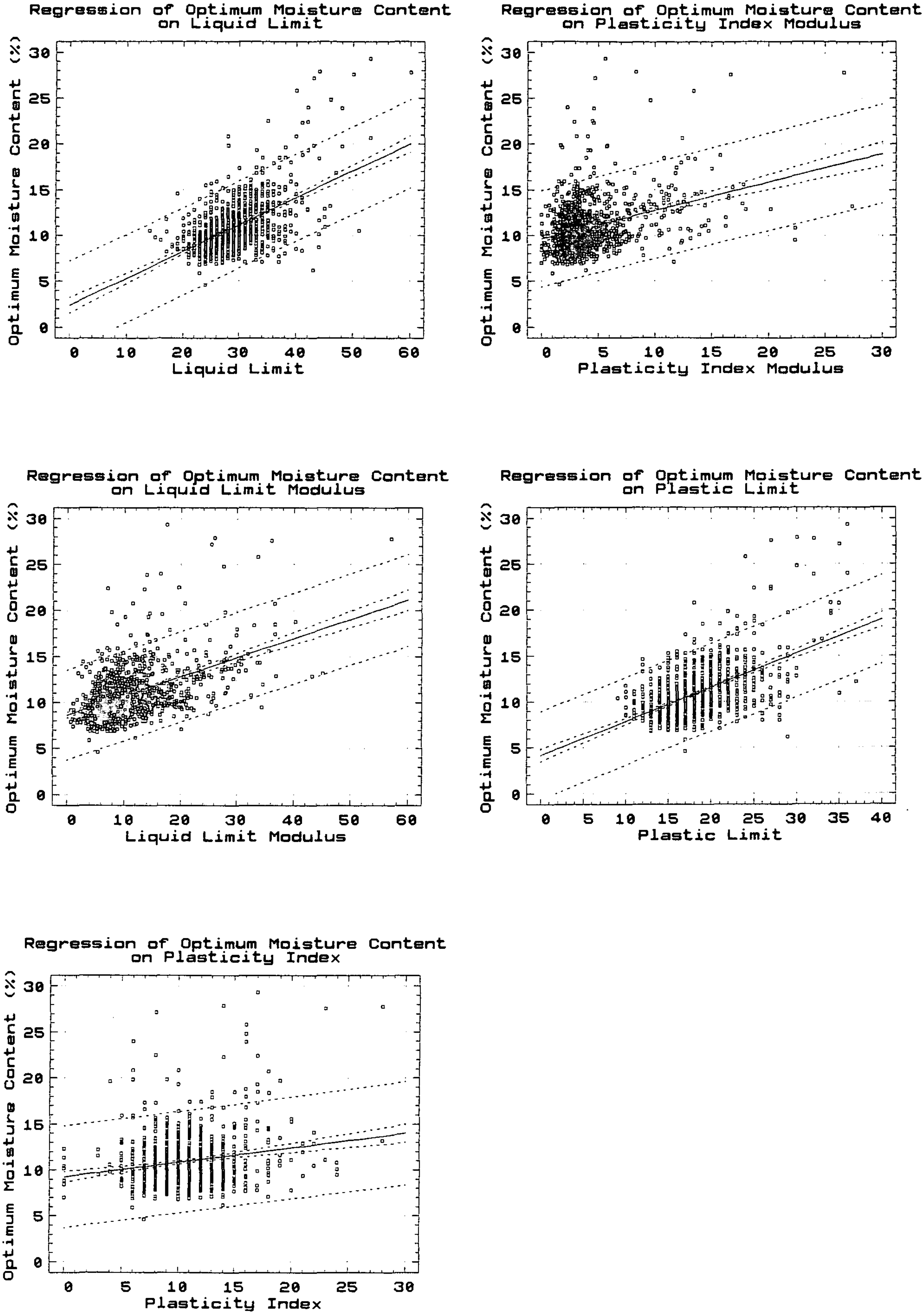
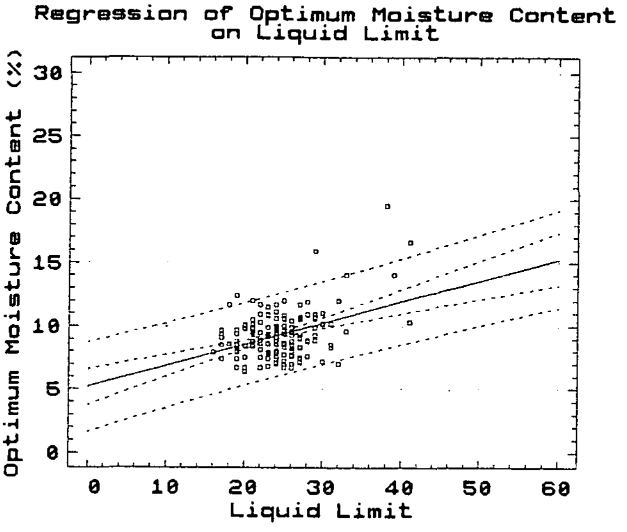
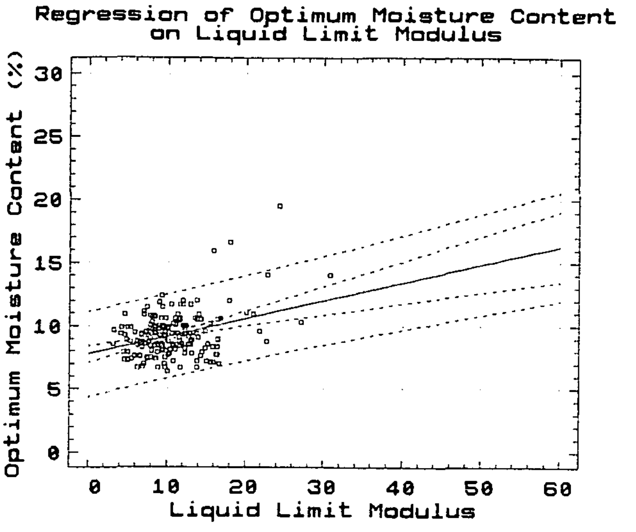
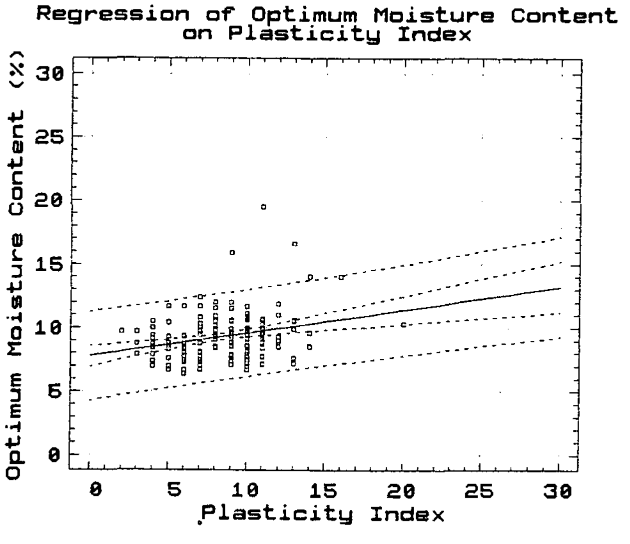
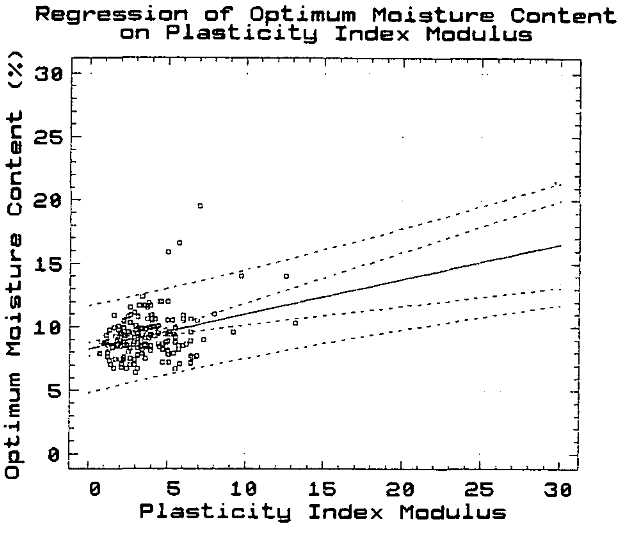


Figure D.24: Regression analysis for Argillaceous Rocks









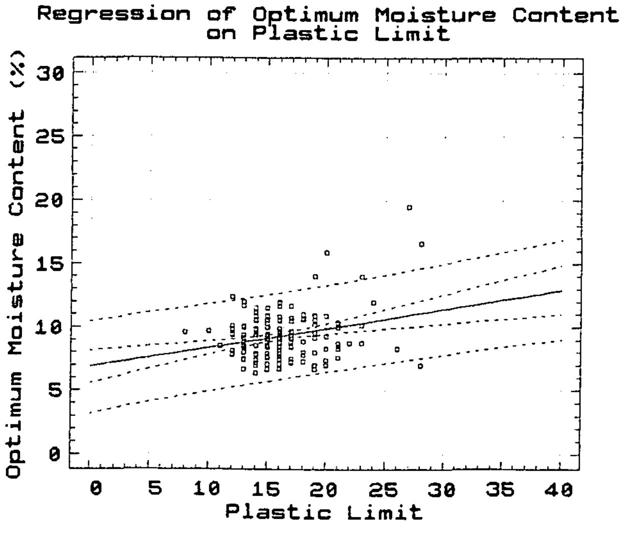


Figure D.25: Regression analysis for Diamictites

Table D.16: Regression analysis OMC vs liquid limit by AASHTO Classification

AASHTO Classification	N.Obs	Mean LL	Mean OMC	Sdv LL	Sdv OMC
ALL	4362	26.8	9.4	5.4	2.3
A-1-a	238	23.8	8.4	2.8	1.9
A-1-b	692	23.6	8.3	3.4	1.6
A-2-4	2023	25.3	9.3	4.2	1.9
A-2-5	3	44.0	10.4	1.4	1.1
A-2-6	1008	30.9	9.6	3.9	2.0
A-2-7	44	44.0	12.5	3.4	5.2
A-4	175	25.3	10.9	4.7	2.3
A-5	3	42.7	23.7	0.5	3.0
A-6	152	31.9	12.1	3.9	2.9

AASHTO Classification	a_0	a_1	r	t_r	Conf Lim
ALL	4.90	0.169	0.388	27.77	4.23
A-1-a	4.90	0.145	0.220	3.46	3.62
A-1-b	5.82	0.105	0.215	5.78	3.14
A-2-4	6.96	0.094	0.205	9.39	3.69
A-2-5	33.10	-0.517	-0.649	0.85	21.79
A-2-6	5.61	0.129	0.250	8.17	3.88
A-2-7	-5.12	0.400	0.262	1.76	10.43
A-4	6.08	0.191	0.382	5.43	4.32
A-5	45.00	-0.500	-0.078	0.08	76.77
A-6	-0.08	0.382	0.518	7.41	4.88

Regression Equation: $OMC = a_0 + a_1 LL$

Table D.17: Regression analysis OMC vs liquid limit modulus by AASHTO Classification

AASHTO Classification	N.Obs	Mean LM	Mean OMC	Sdv LM	Sdv OMC
ALL	4362	10.6	9.4	5.8	2.3
A-1-A	238	4.3	8.4	1.5	1.9
A-1-B	692	8.2	8.3	2.1	1.6
A-2-4	2023	11.1	9.3	5.0	1.9
A-2-5	3	21.9	10.4	12.9	1.1
A-2-6	1008	9.1	9.6	4.2	2.0
A-2-7	44	12.6	12.5	7.4	5.2
A-4	175	17.8	10.9	4.2	2.3
A-5	3	23.2	23.7	5.0	3.0
A-6	152	22.9	12.1	5.4	2.9

AASHTO Classification	a_0	a_1	r	t_r	Conf Lim
ALL	7.45	0.185	0.459	34.12	4.08
A-1-A	8.04	0.073	0.060	0.92	3.70
A-1-B	6.82	0.179	0.228	6.16	3.13
A-2-4	8.05	0.116	0.304	14.34	3.59
A-2-5	8.80	0.072	0.822	1.44	16.29
A-2-6	8.07	0.168	0.350	11.85	3.75
A-2-7	10.30	0.175	0.250	1.67	10.47
A-4	8.97	0.109	0.197	2.64	4.58
A-5	27.75	-0.176	-0.288	0.30	73.75
A-6	5.40	0.292	0.549	8.04	4.77

Regression Equation: $OMC = a_0 + a_1 LLM$

Table D.18: Regression analysis OMC vs plasticity index by AASHTO Classification

AASHTO Classification	N.Obs	Mean PI	Mean OMC	Sdv PI	Sdv OMC
ALL	4810	7.8	9.3	4.3	2.3
A-1-a	288	3.9	8.3	2.1	1.8
A-1-b	852	3.9	8.3	2.1	1.6
A-2-4	2252	6.9	9.3	2.9	1.9
A-2-5	3	8.7	10.4	1.9	1.1
A-2-6	1008	12.8	9.6	2.0	2.0
A-2-7	44	16.8	12.5	3.2	5.2
A-4	178	7.4	10.9	2.2	2.3
A-5	3	7.7	23.7	1.2	3.0
A-6	152	13.9	12.1	2.8	2.9

AASHTO Classification	a_0	a_1	r	t_r	Conf Lim
ALL	8.20	0.147	0.276	19.90	4.31
A-1-a	8.10	0.055	0.063	1.07	3.59
A-1-b	8.21	0.020	0.026	0.77	3.12
A-2-4	8.96	0.046	0.072	3.44	3.66
A-2-5	13.73	-0.388	-0.649	0.85	21.79
A-2-6	9.97	-0.028	-0.027	0.86	4.00
A-2-7	16.91	-0.261	-0.162	1.06	10.67
A-4	10.71	0.029	0.027	0.35	4.63
A-5	31.11	-0.971	-0.400	0.44	70.58
A-6	10.81	0.093	0.090	1.11	5.68

Regression Equation: $OMC = a_0 + a_1 PI$

Table D.19: Regression analysis OMC vs plastic limit by AASHTO Classification

AASHTO Classification	**N.Obs**	**Mean PL**	**Mean OMC**	**Sdv PL**	**Sdv OMC**
ALL	4362	18.2	9.4	3.7	2.3
A-1-a	238	19.1	8.4	2.7	1.9
A-1-b	692	18.9	8.3	3.3	1.6
A-2-4	2023	17.6	9.3	3.5	1.9
A-2-5	3	35.3	10.4	0.5	1.1
A-2-6	1008	18.1	9.6	3.4	2.0
A-2-7	44	27.2	12.5	3.2	5.2
A-4	175	17.8	10.9	4.4	2.3
A-5	3	35.0	23.7	0.8	3.0
A-6	152	18.0	12.1	3.7	2.9

AASHTO Classification	a_0	a_1	**r**	t_r	**Conf Lim**
ALL	6.08	0.184	0.294	20.29	4.39
A-1-a	5.43	0.153	0.218	3.43	3.62
A-1-b	6.41	0.100	0.201	5.40	3.15
A-2-4	7.08	0.128	0.236	10.94	3.66
A-2-5	-44.40	1.550	0.649	0.85	21.79
A-2-6	6.40	0.177	0.300	9.97	3.82
A-2-7	-6.75	0.708	0.439	3.17	9.71
A-4	7.30	0.203	0.384	5.47	4.31
A-5	-49.83	2.100	0.566	0.69	63.49
A-6	5.42	0.371	0.478	6.66	5.01

Regression Equation: $OMC = a_0 + a_1 PL$

Table D.20: Regression analysis OMC vs Plasticity modulus by AASHTO Classification

AASHTO Classification	N.Obs	Mean PM	Mean OMC	Sdv PM	Sdv OMC
ALL	4810	3.1	9.3	2.5	2.3
A-1-a	288	0.7	8.3	0.5	1.8
A-1-b	852	1.4	8.3	0.8	1.6
A-2-4	2252	2.9	9.3	1.7	1.9
A-2-5	3	3.8	10.4	1.5	1.1
A-2-6	1008	3.8	9.6	1.8	2.0
A-2-7	44	4.6	12.5	2.2	5.2
A-4	178	5.3	10.9	1.9	2.3
A-5	3	4.3	23.7	1.5	3.0
A-6	152	10.0	12.1	3.1	2.9

AASHTO Classification	a_0	a_1	r	t_r	Conf Lim
ALL	8.13	0.393	0.431	33.14	4.04
A-1-a	8.14	0.237	0.061	1.03	3.59
A-1-b	8.09	0.144	0.076	2.21	3.11
A-2-4	8.49	0.270	0.251	12.31	3.55
A-2-5	7.65	0.713	0.940	2.76	9.75
A-2-6	8.51	0.288	0.260	8.55	3.86
A-2-7	10.07	0.532	0.228	1.52	10.53
A-4	10.99	-0.014	-0.011	0.14	4.63
A-5	27.13	-0.804	-0.388	0.42	70.96
A-6	9.63	0.246	0.265	3.36	5.50

Regression Equation: $OMC = a_0 + a_1 PM$

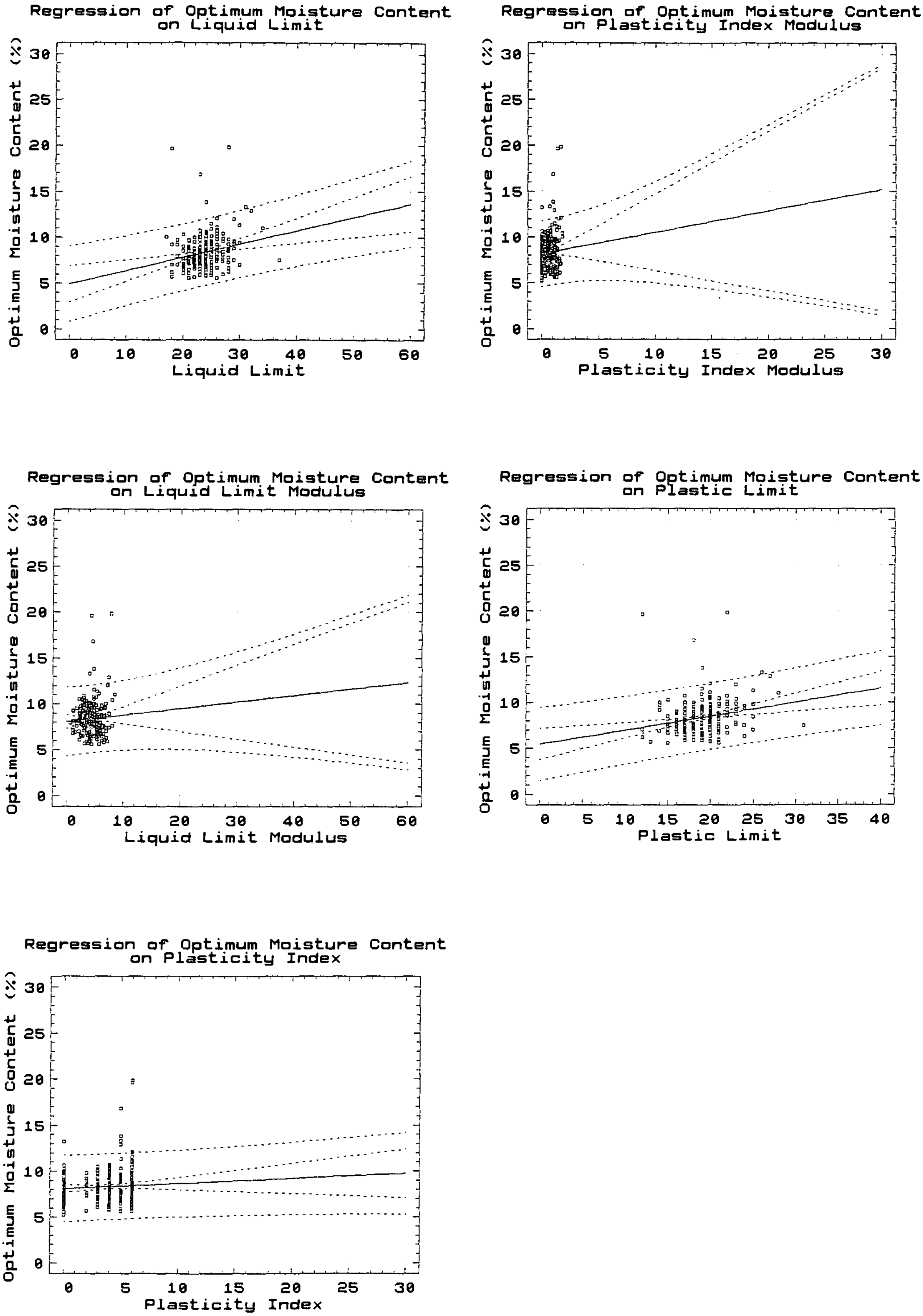


Figure D.26: Regression analysis for AASHTO Class A-1-a

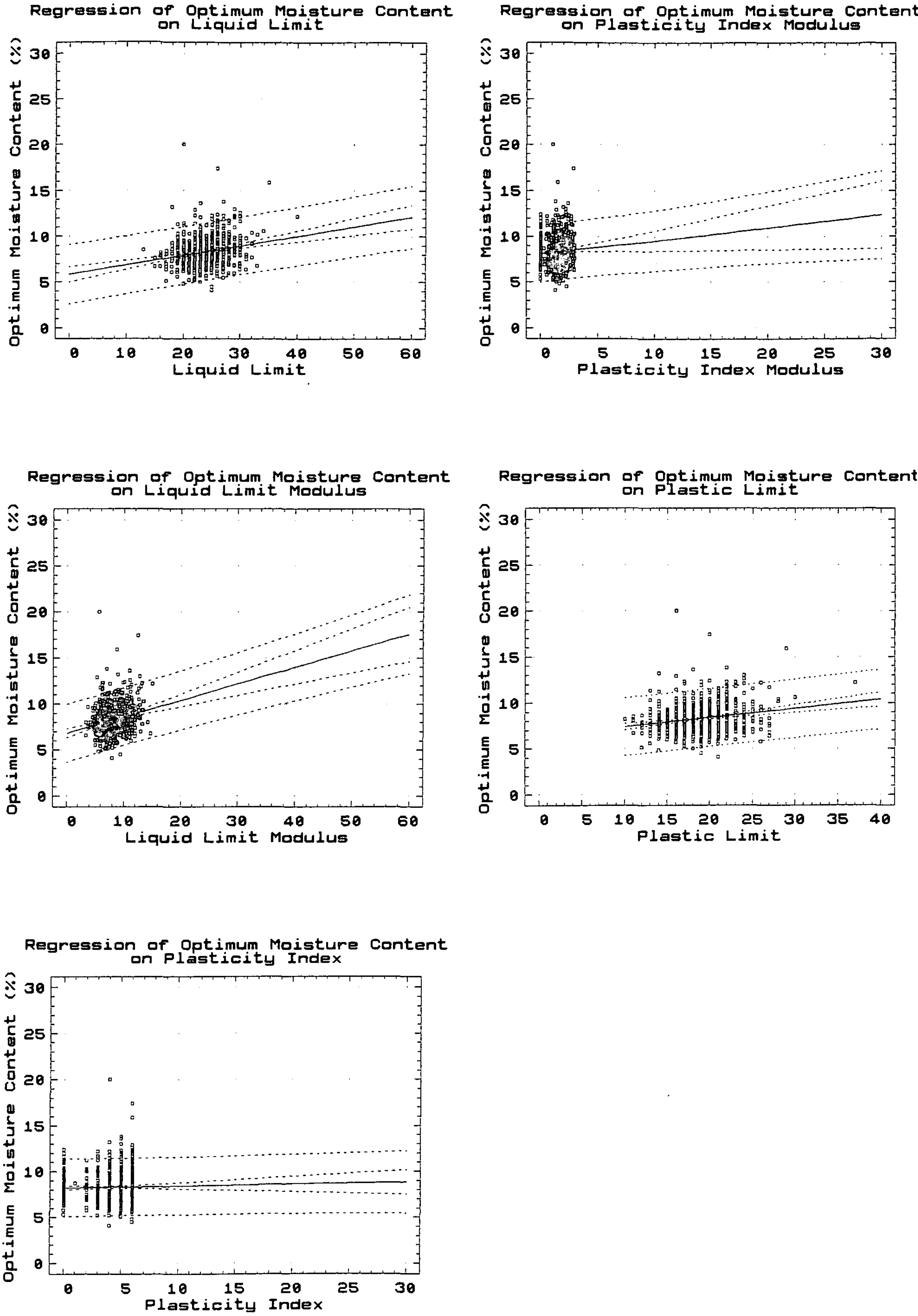


Figure D.27: Regression analysis for AASHTO Class A-1-b

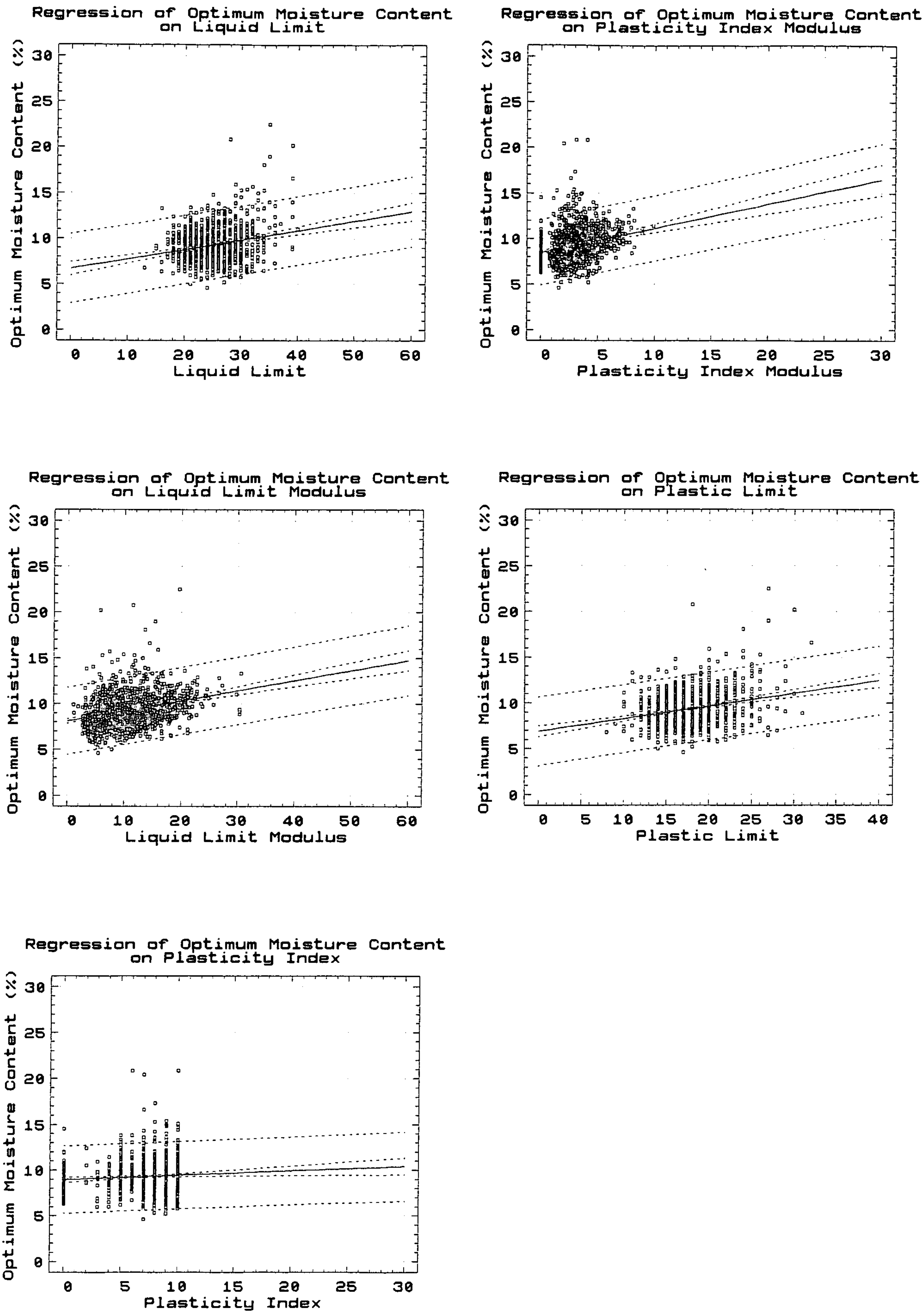


Figure D.28: Regression analysis for AASHTO Class A-2-4

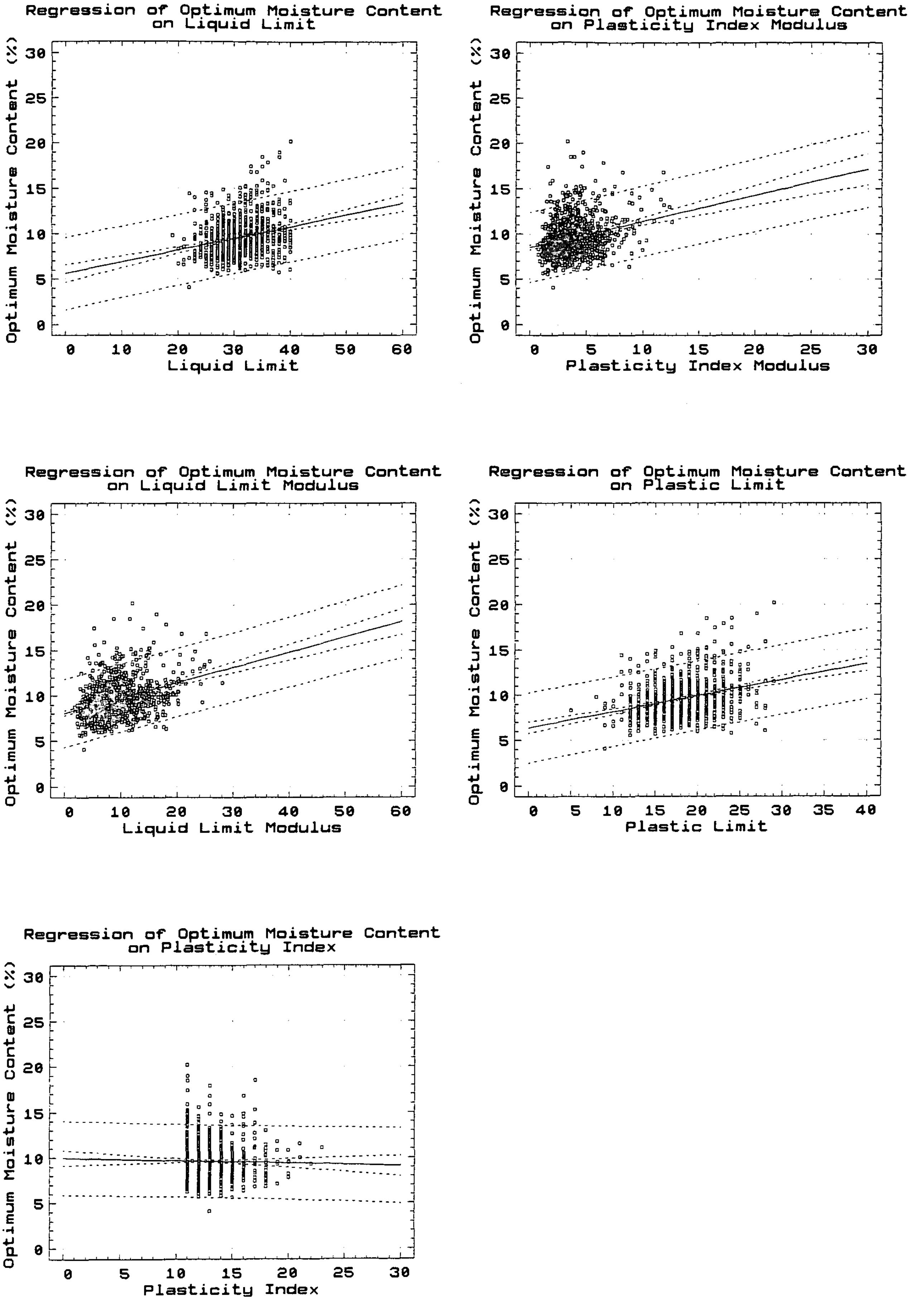


Figure D.29: Regression analysis for AASHTO Class A-2-6

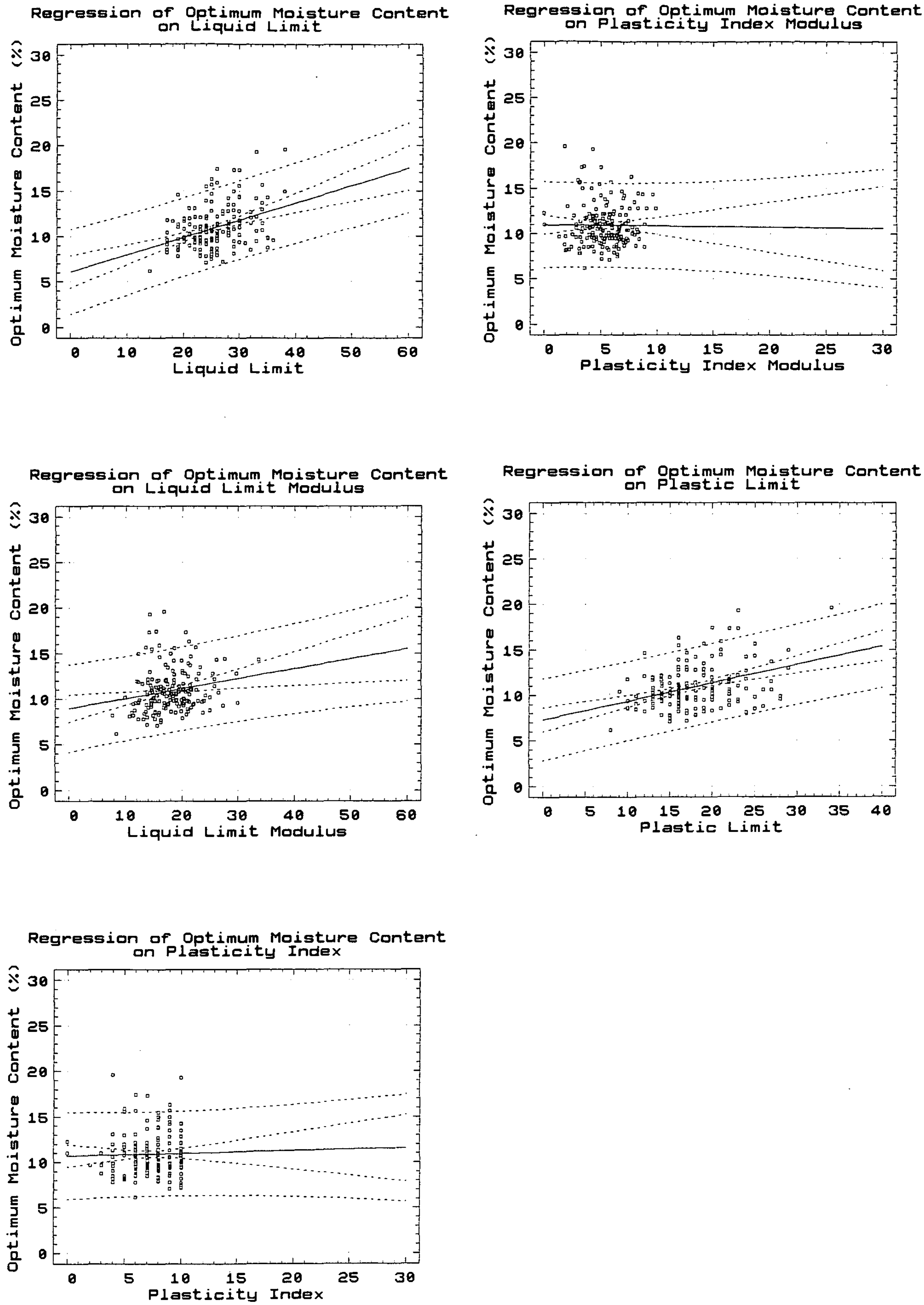


Figure D.30: Regression analysis for AASHTO Class A-4

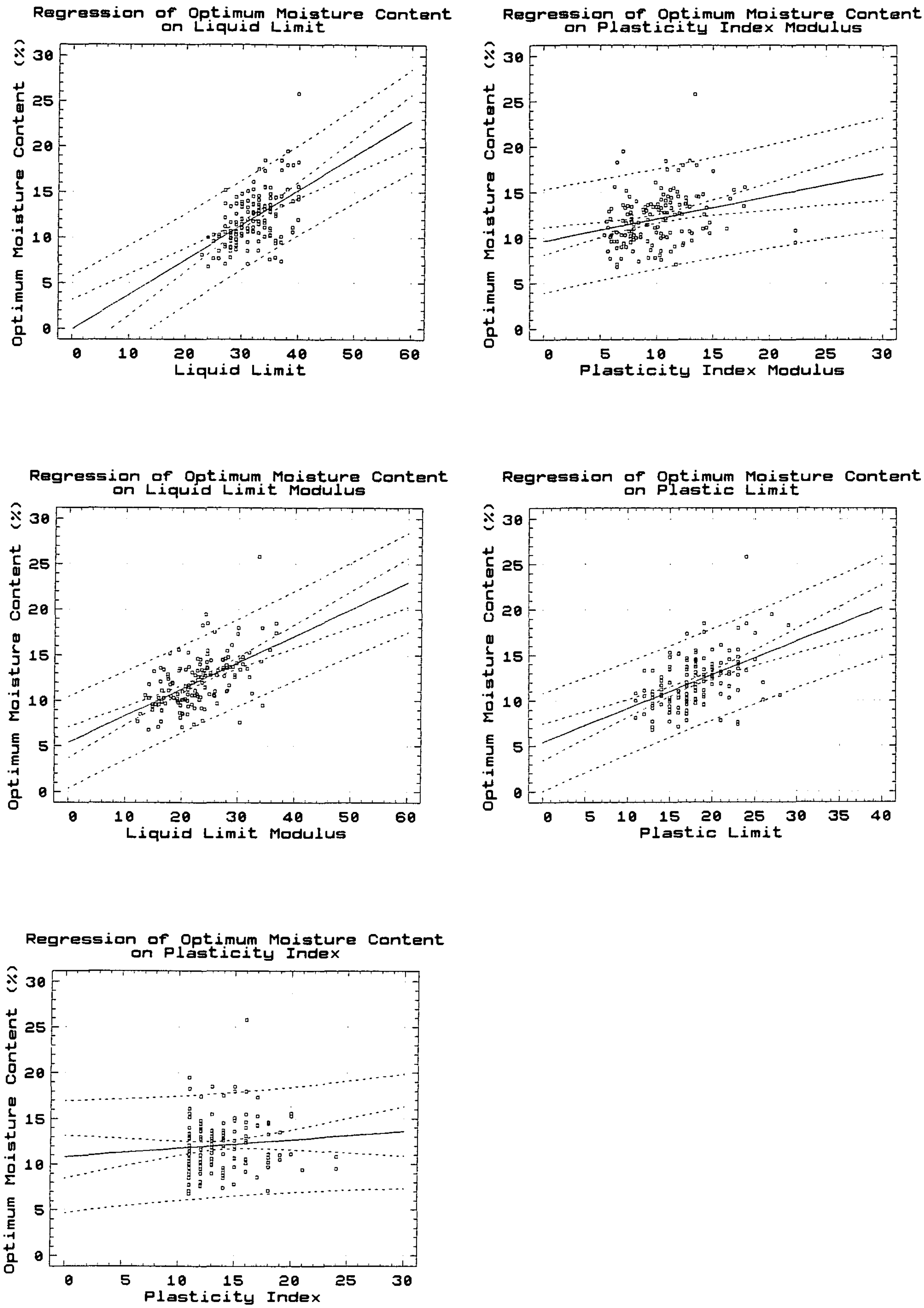


Figure D.31: Regression analysis for AASHTO Class A-6

Appendix E

Results of Correlation Analyses

In the tables in this appendix, the following symbols are used:

> n = number of observations
>
> r = coefficient of correlation
>
> z = Fisher's statistic z = arc tanh(r)
>
> x_r = (z - 0)$\sqrt{}$(n-3). x_r is normally distributed, with μ=0,σ=0. A value greater than 1.96 indicates that r is significant (>0) at the 95% level of probability.
>
> x = (z-Z)$\sqrt{}$(n-3), where Z is Fisher's statistic z for a group of observations. x is normally distributed, with μ=0,σ=0. A value greater than 1.96 indicates that z is significant at the 95% level of probability, ie that the coefficient of correlation r differs significantly from the coefficient of correlation of the group. A positive value indicates a greater correlation, and a negative value a smaller correlation.

Table E.1: Correlation of OMC and liquid limit by horizon

Horizon	n	r	z	x_r	x	
C-Pd	177	0.398	0.4211	5.55*	0.16	
Jd	1247	0.361	0.3785	13.35*	-1.08	
Nmp	518	0.301	0.3112	7.06*	-2.22	-*
O-Sn	484	0.428	0.4579	10.04*	1.07	
Pa	291	0.448	0.4826	8.19*	1.25	
Pp	239	0.304	0.3143	4.83*	-1.46	
Pv	470	0.520	0.5759	12.45*	3.61	+*
Pvo	272	0.616	0.7181	11.78*	5.07	+*
Qb	147	0.322	0.3336	4.00*	-0.91	
TRt	255	0.566	0.6419	10.19*	3.70	+*
ZB	262	0.302	0.3117	5.02*	-1.57	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.2: Correlation of OMC and liquid limit modulus by horizon

Horizon	n	r	z	x_r	x	
C-Pd	177	0.350	0.3658	4.82*	-1.72	
Jd	1247	0.531	0.5920	20.88*	3.38	+*
Nmp	518	0.513	0.5672	12.87*	1.62	
O-Sn	484	0.463	0.5016	11.00*	0.12	
Pa	291	0.625	0.7325	12.43*	4.01	+*
Pp	239	0.232	0.2362	3.63*	-3.99	-*
Pv	470	0.566	0.6412	13.86*	3.14	+*
Pvo	272	0.661	0.7942	13.03*	4.89	+*
Qb	147	0.287	0.2952	3.54*	-2.41	-*
TRt	255	0.243	0.2483	3.94*	-3.93	-*
ZB	262	0.486	0.5311	8.55*	0.56	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.3: Correlation of OMC and plasticity index by horizon

Horizon	n	r	z	x_r	x	
C-Pd	177	0.283	0.2908	3.84*	0.10	
Jd	1280	0.120	0.1210	4.32*	-5.80	-*
Nmp	575	0.242	0.2468	5.90*	-0.87	
O-Sn	656	0.322	0.3339	8.53*	1.29	
Pa	326	0.234	0.2385	4.29*	-0.80	
Pp	240	0.046	0.0459	0.71	-3.65	-*
Pv	499	0.361	0.3783	8.43*	2.12	+*
Pvo	273	0.253	0.2582	4.24*	-0.41	
Qb	256	0.515	0.5697	9.06*	4.56	+*
TRt	259	0.170	0.1714	2.74*	-1.79	
ZB	269	0.285	0.2931	4.78*	0.16	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.4: Correlation of OMC and plasticity index modulus by horizon

Horizon	n	r	z	x_r	x	
C-Pd	177	0.302	0.3112	4.10*	-1.98	-*
Jd	1280	0.409	0.4342	15.52*	-0.97	
Nmp	575	0.386	0.4074	9.74*	-1.29	
O-Sn	656	0.416	0.4432	11.33*	-0.46	
Pa	326	0.481	0.5243	9.42*	1.13	
Pp	240	0.092	0.0925	1.42	-5.68	-*
Pv	499	0.548	0.6161	13.72*	3.45	+*
Pvo	273	0.532	0.5925	9.74*	2.15	+*
Qb	256	0.515	0.5692	9.05*	1.72	
TRt	259	0.162	0.1633	2.61*	-4.77	-*
ZB	269	0.470	0.5106	8.33*	0.80	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.5: Correlation of OMC and plastic limit by horizon

Horizon	n	r	z	x_r	x	
C-Pd	177	0.276	0.2830	3.73*	-0.26	
Jd	1247	0.407	0.4318	15.23*	4.55	+*
Nmp	518	0.151	0.1525	3.46*	-3.41	-*
O-Sn	484	0.321	0.3329	7.30*	0.66	
Pa	291	0.441	0.4740	8.04*	2.91	+*
Pp	239	0.384	0.4044	6.21*	1.56	
Pv	470	0.397	0.4206	9.09*	2.55	+*
Pvo	272	0.606	0.7027	11.53*	6.56	+*
Qb	147	0.187	0.1887	2.26*	-1.37	
TRt	255	0.689	0.8464	13.44*	8.63	+*
ZB	262	0.149	0.1501	2.42*	-2.46	-*

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.6: Correlation of OMC and grading modulus by horizon

Horizon	n	r	z	x_r	x	
C-Pd	177	-0.170	-0.1717	-2.26*	1.01	
Jd	1305	-0.373	-0.3919	-14.14*	-5.19	*+
Nmp	616	-0.505	-0.5560	-13.77*	-7.63	*+
O-Sn	763	-0.393	-0.4153	-11.45*	-4.61	*+
Pa	327	-0.532	-0.5929	-10.67*	-6.21	*+
Pp	240	-0.076	-0.0762	-1.17	2.65	*-
Pv	503	-0.331	-0.3440	-7.69*	-2.15	*+
Pvo	278	-0.503	-0.5533	-9.18*	-5.06	*+
Q	53	-0.284	-0.2920	-2.06*	-0.31	
Qb	613	-0.018	-0.0180	-0.44	5.68	*-
TRt	261	0.010	0.0100	0.16	4.14	*-
ZB	269	-0.468	-0.5075	-8.28*	-4.23	*+

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.7: Correlation of OMC and grading factor by horizon

Horizon	n	r	z	x_r	x	
C-Pd	177	0.070	0.070	0.92	-0.51	
Jd	1305	0.283	0.291	10.50*	6.59	*+
Nmp	616	0.462	0.500	12.38*	9.69	*+
O-Sn	763	0.332	0.345	9.51*	6.52	*+
Pa	327	0.469	0.509	9.16*	7.21	*+
Pp	240	0.058	0.058	0.89	-0.78	
Pv	503	0.215	0.218	4.88*	2.46	*+
Pvo	278	0.501	0.551	9.13*	7.33	*+
Q	53	-0.022	-0.022	-0.16	-0.92	
Qb	613	-0.06	-0.060	-1.48	-4.16	*-
TRt	261	-0.073	-0.073	-1.17	-2.92	*-
ZB	269	0.424	0.453	7.38*	5.61	*+

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.8: Correlation of OMC and liquid limit by rock type

Rock Type	**n**	**r**	**z**	x_r	**x**
Dolerite	1247	0.361	0.3785	13.35*	-1.08
Granite	780	0.301	0.3109	8.67*	-2.74*-
Mudstone	213	0.597	0.6888	9.98*	4.05*+
Sand	149	0.303	0.3126	3.78*	-1.17
Shale	699	0.444	0.4773	12.59*	1.80
Sandstone	1013	0.378	0.3981	12.65*	-0.35
Tillite	177	0.398	0.4212	5.56*	0.16

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.9: Correlation of OMC and liquid limit modulus by rock type

Rock Type	**n**	**r**	**z**	x_r	**x**
Dolerite	1247	0.531	0.5920	20.88*	3.38 *+
Granite	780	0.493	0.5398	15.05*	1.22
Mudstone	213	0.251	0.2565	3.72*	-3.47 *-
Sand	149	0.322	0.3335	4.03*	-1.96 *-
Shale	699	0.463	0.5010	13.22*	0.13
Sandstone	1013	0.441	0.4730	15.03*	-0.73
Tillite	177	0.350	0.3658	4.83*	-1.72

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.10: Correlation of OMC and plasticity index by rock type

Rock Type	n	r	z	x_r	x	
Dolerite	1280	0.120	0.1210	4.32*	-5.80	*-
Granite	844	0.258	0.2639	7.65*	-0.56	
Mudstone	216	0.211	0.2144	3.13*	-1.00	
Sand	258	0.489	0.5346	8.54*	4.01	*+
Shale	703	0.169	0.1710	4.53*	-2.97	*-
Sandstone	1247	0.239	0.2437	8.60*	-1.39	
Tillite	177	0.283	0.2907	3.83*	0.10	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.11: Correlation of OMC and plasticity index modulus by rock type

Rock Type	n	r	z	x_r	x	
Dolerite	1280	0.409	0.4342	15.52*	-0.97	
Granite	844	0.412	0.4383	12.71*	-0.67	
Mudstone	216	0.149	0.1504	2.20*	-4.54	*-
Sand	258	0.505	0.5565	8.89*	1.52	
Shale	703	0.374	0.3925	10.38*	-1.82	
Sandstone	1247	0.363	0.3807	13.43*	-2.85	*-
Tillite	177	0.302	0.3112	4.10*	-1.98	*-

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.12: Correlation of OMC and plastic limit by rock type

Rock Type	n	r	z	x_r	x
Dolerite	1247	0.407	0.4318	15.23*	4.55 *+
Granite	780	0.147	0.1484	4.14*	-4.30 *-
Mudstone	213	0.577	0.6577	9.53*	5.14 *+
Sand	149	0.195	0.1974	2.39*	-1.27
Shale	699	0.447	0.4811	12.69*	4.71 *+
Sandstone	1013	0.358	0.3747	11.91*	2.29 *+
Tillite	177	0.276	0.2830	3.73*	-0.26

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.13: Correlation of OMC and grading modulus by rock type

Rock Type	n	r	z	x_r	x
Dolerite	1305	-0.373	-0.3919	-14.14*	-5.19 *+
Granite	885	-0.489	-0.5358	-15.88*	-8.52 *+
Mudstone	216	-0.047	-0.0470	-0.69	2.93 *-
Sand	669	-0.049	-0.0490	-1.27	5.13 *-
Shale	708	-0.332	-0.3451	-9.16*	-2.58 *+
Sandstone	1360	-0.330	-0.3428	-12.63*	-3.49 *+
Tillite	177	-0.170	-0.1717	-2.26*	1.01

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.14: Correlation of OMC and grading factor by rock type

Rock Type	**n**	**r**	**z**	**x_r**	**x**
Dolerite	1305	0.283	0.2909	10.50*	19.45 *+
Granite	885	0.446	0.4797	14.25*	21.61 *+
Mudstone	216	-0.081	-0.0812	-1.18	2.43 *-
Sand	669	-0.016	-0.0160	-0.41	5.99 *-
Shale	708	0.334	0.3473	9.22*	15.81 *+
Sandstone	1360	0.149	0.1501	5.53*	14.66 *-
Tillite	177	0.070	0.0701	0.92	4.20 *-

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.15: Correlation of OMC and liquid limit by Weinert's Classification

Weinert's Classification	n	r	z	x_r	x	
Acid	780	0.301	0.3109	8.67*	-2.74	*-
Argillaceous	996	0.539	0.6026	18.99*	6.10	*+
Arenaceous	1162	0.337	0.3503	11.92*	-2.00	*-
Basic	1247	0.361	0.3785	13.35*	-1.08	
Diamictites	177	0.398	0.4212	5.56*	0.16	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.16: Correlation of OMC and liquid limit modulus by Weinert's Classification

Weinert's Classification	n	r	z	x_r	x	
Acid	780	0.493	0.5398	15.05*	1.22	
Argillaceous	996	0.495	0.5427	17.10*	1.47	
Arenaceous	1162	0.445	0.4779	16.27*	-0.62	
Basic	1247	0.531	0.5920	20.88*	3.38	*+
Diamictites	177	0.350	0.3658	4.83*	-1.72	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.17: Correlation of OMC and plasticity index by Weinert's Classification

Weinert's Classification	n	r	z	x_r	x	
Acid	844	0.258	0.2639	7.65*	-0.56	
Argillaceous	1004	0.190	0.1918	6.07*	-2.89	*-
Arenaceous	1505	0.247	0.2524	9.78*	-1.19	
Basic	1280	0.120	0.1210	4.32*	-5.80	*-
Diamictites	177	0.283	0.2907	3.83*	0.10	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.18: Correlation of OMC and plasticity index modulus by Weinert's Classification

Weinert's Classification	n	r	z	x_r	x	
Acid	844	0.412	0.4383	12.71*	-0.67	
Argillaceous	1004	0.355	0.3716	11.76*	-2.84	*-
Arenaceous	1505	0.381	0.4010	15.54*	-2.34	*-
Basic	1280	0.409	0.4342	15.52*	-0.97	
Diamictites	177	0.302	0.3112	4.10*	-1.98	*-

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.19: Correlation of OMC and plastic limit by Weinert's Classification

Weinert's Classification	n	r	z	x_r	x	
Acid	780	0.147	0.1484	4.14*	-4.30	*-
Argillaceous	996	0.536	0.5988	18.87*	9.33	*+
Arenaceous	1162	0.313	0.3243	11.04*	0.74	
Basic	1247	0.407	0.4318	15.23*	4.55	*+
Diamictites	177	0.276	0.2830	3.73*	-0.26	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.20: Correlation of OMC and grading modulus by Weinert's Classification

Weinert's Classification	n	r	z	x_r	x	
Acid	885	-0.489	-0.5348	-15.88*	-8.52	*+
Argillaceous	1009	-0.345	-0.3598	-11.41*	-3.55	*+
Arenaceous	2029	-0.278	-0.2855	-12.85*	-1.69	
Basic	1305	-0.373	-0.3919	-14.14*	-5.19	*+
Diamictites	177	-0.170	-0.1717	-2.264*	1.01	

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.21: Correlation of OMC and grading factor by Weinert's Classification

Weinert's Classification	**n**	**r**	**z**	x_r		**x**	
Acid	885	0.446	0.4797	14.25	*	21.61	*+
Argillaceous	1009	0.308	0.3183	10.10	*	17.96	*+
Arenaceous	2029	0.155	0.1563	7.03	*	18.19	*-
Basic	1305	0.283	0.2909	10.50	*	19.45	*+
Diamictites	177	0.070	0.0701	0.92		4.20	*-

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.22: Correlation of OMC and liquid limit by AASHTO Classification

AASHTO Classification	n	r	z	x_r	x
A-1-a	238	0.220	0.2234	3.43*	-2.85 *-
A-1-b	692	0.215	0.2183	5.73*	-5.01 *-
A-2-4	2023	0.205	0.2074	9.32*	-9.06 *-
A-2-6	1008	0.250	0.2550	8.08*	-4.89 *-
A-4	175	0.382	0.4020	5.27*	-0.09
A-6	152	0.518	0.5729	6.99*	2.00 *+

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.23: Correlation of OMC and liquid limit modulus by AASHTO Classification

AASHTO Classification	n	r	z	x_r	x
A-1-a	238	0.060	0.0601	0.92	-6.68 *-
A-1-b	692	0.228	0.2324	6.10*	-6.92 *-
A-2-4	2023	0.304	0.3139	14.11*	-8.19 *-
A-2-6	1008	0.350	0.3653	11.58*	-4.14 *-
A-4	175	0.197	0.1993	2.61*	-3.89 *-
A-6	152	0.549	0.6164	7.52*	1.47

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.24: Correlation of OMC and plasticity index by AASHTO Classification

AASHTO Classification	n	r	z	x_r	x	
A-1-a	288	0.063	0.0633	1.07	-3.71	*-
A-1-b	852	0.027	0.0265	0.77	-7.48	*-
A-2-4	2252	0.072	0.0722	3.43*	-10.01	*-
A-2-6	1008	0.027	0.0265	0.84	-8.14	*-
A-4	178	0.027	0.0265	0.35	-3.40	*-
A-6	152	0.090	0.0902	1.10	-2.36	*-

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.25: Correlation of OMC and plasticity index modulus by AASHTO Classification

AASHTO Classification	n	r	z	x_r	x	
A-1-a	288	0.061	0.0609	1.03	-6.76	*-
A-1-b	852	0.076	0.0756	2.20*	-11.24	*-
A-2-4	2252	0.251	0.2567	12.17*	-9.71	*-
A-2-6	1008	0.260	0.2663	8.44*	-6.18	*-
A-4	178	0.010	0.0100	0.13	-5.97	*-
A-6	152	0.265	0.2713	3.31*	-2.32	*-

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.26: Correlation of OMC and plastic limit by AASHTO Classification

AASHTO Classification	n	r	z	x_r	x	
A-1-a	238	0.218	0.2218	3.40*	-1.24	
A-1-b	692	0.201	0.2040	5.35*	-2.59	*-
A-2-4	2023	0.236	0.2410	10.83*	-2.78	*-
A-2-6	1008	0.300	0.3093	9.81*	0.21	
A-4	175	0.384	0.4049	5.31*	1.34	
A-6	152	0.478	0.5199	6.35*	2.65	*+

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.27: Correlation of OMC and grading modulus by AASHTO Classification

AASHTO Classification	n	r	z	x_r	x	
A-1-a	313	0.121	0.1216	2.14*	6.51	*-
A-1-b	956	-0.196	-0.1986	-6.13*	1.52	
A-2-4	2424	-0.128	-0.1287	-6.33*	5.87	*-
A-2-6	1008	-0.259	-0.2650	-8.40*	-0.54	
A-3	298	-0.170	-0.1717	-2.95*	1.31	
A-4	180	0.086	0.0862	1.15	4.45	*-
A-6	152	-0.400	-0.4237	-5.17*	-2.14	*+

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Table E.28: Correlation of OMC and plastic limit by AASHTO Classification

AASHTO Classification	n	r	z	x_r	x	
A-1-a	313	-0.160	-0.1614	-2.84*	-4.75	*-
A-1-b	956	0.126	0.1267	3.91*	0.56	
A-2-4	2424	0.035	0.0350	1.72	-3.61	*-
A-2-6	1008	0.180	0.1820	5.77*	2.33	*-
A-3	298	0.083	0.0832	1.43	-0.43	
A-4	180	-0.155	-0.1563	-2.08*	-3.52	*-
A-6	152	0.293	0.3018	3.68*	2.36	*+

* indicates a coefficient of correlation is significant

+* indicates a coefficient of correlation significantly larger than the coefficient of correlation of all the results taken together

-* indicates a coefficient of correlation significantly smaller than the coefficient of correlation of all the results taken together

Appendix F

Regression Analyses based on Semmelink's Model

Abbreviations

The following abbreviations are used in this appendix.

OMC = Optimum Moisture Content

A = (%pass 0,425mm/100).$(LL/100)^{0,1}$

LL = Liquid Limit

PI = Plasticity Index

GF = Grading Factor

The grading factor is expressed as

GF = Σ(% passing sieve size/nominal sieve size (mm))/100

for sieve sizes 75mm, 63mm, 53mm, 37,5mm, 26,5mm, 19mm, 13,2mm, 4,75mm and 2,00mm

ALL = All results

a_0, a_1, a_2, a_3, a_4 = regression coefficients

r = coefficient of correlation

* indicates that r is statistically significant at the 95% level of confidence

Conf Lim = Minimum 95% confidence limits for prediction of OMC

Table F.1: Multiple Linear Regression analysis by horizon.

Horizon	N.Obs	a_0	a_1	a_2	a_3	a_4	r	Conf Lim
ALL	4362	7.83	-2.94	6.83	0.169	-1.22	0.438*	4.13
C-Pd	177	9.67	-3.25	0.49	0.152	7.67	0.330*	3.34
Jd	1247	6.39	1.90	1.45	0.082	11.19	0.430*	3.50
Nmp	518	0.43	7.06	4.49	0.087	-3.11	0.512*	2.69
O-Sn	484	4.17	4.57	-2.57	0.155	7.38	0.445*	3.33
PA	291	8.85	-0.35	1.12	0.055	5.35	0.549*	3.64
PP	239	11.90	-6.16	13.70	-0.048	-13.33	0.205*	3.74
PV	470	6.59	1.84	-2.49	0.196	8.32	0.554*	3.28
PVo	272	-1.51	13.59	1.23	0.311	-0.78	0.562*	6.31
QB	147	7.55	-4.28	9.66	0.233	-4.60	0.332*	2.41
TRt	255	11.84	-8.87	9.59	0.210	-1.64	0.185*	5.16
ZB	262	2.37	6.87	-2.91	0.115	6.93	0.522*	2.50

Regression Equation: $OMC = a_0 + a_1(GF)^{0.85} + a_2A + a_3(PI) + a_4A^3$

Table F.2: Multiple Linear Regression analysis by rock type.

Rock Type	N.Obs	a_0	a_1	a_2	a_3	a_4	r	Conf Lim
ALL	4362	7.83	-2.94	6.83	0.169	-1.22	0.438*	4.13
Clay	51	1.29	5.07	11.27	0.209	-10.01	0.000	8.29
Dolerite	1247	6.39	1.90	1.45	0.082	11.19	0.430*	3.50
Granite	780	1.19	7.37	0.44	0.102	2.50	0.507*	2.64
Mudstone	213	16.23	-19.41	20.12	0.145	-6.37	0.403*	4.38
Sand	149	0.45	4.38	8.70	0.235	-5.33	0.340*	2.46
Shale	699	5.62	5.57	-0.85	0.116	3.62	0.376*	4.43
Sandstone	1013	8.87	-1.75	0.86	0.102	6.39	0.414*	3.52
Silt	33	28.80	8.58	-51.92	-0.014	40.85	0.000	1.18
Tillite	177	9.67	-3.25	0.49	0.152	7.67	0.330*	3.34

Regression Equation: $OMC = a_0 + a_1(GF)^{0.85} + a_2A + a_3(PI) + a_4A^3$

Table F.3: Multiple Linear Regression analysis by Weinert's Classification.

Weinert's Classification	N.Obs	a_0	a_1	a_2	a_3	a_4	r	Conf Lim
ALL	4362	7.83	-2.94	6.83	0.169	-1.22	0.438*	4.13
Acid	780	1.19	7.37	0.44	0.102	2.50	0.507*	2.64
Argillaceous	996	7.92	0.27	5.19	0.107	-0.70	0.355*	5.26
Arenaceous	1162	7.76	-2.05	5.35	0.122	-0.58	0.399*	3.45
Basic	1247	6.39	1.90	1.45	0.082	11.19	0.430*	3.50
Diamictites	177	9.67	-3.25	0.49	0.152	7.67	0.330*	3.34

Regression Equation: $OMC = a_0 + a_1(GF)^{0.85} + a_2A + a_3(PI) + a_4A^3$

Table F.4: Multiple Linear Regression analysis by AASHTO Classification.

AASHTO Classification	**N.Obs**	a_0	a_1	a_2	a_3	a_4	**r**	**Conf Lim**
ALL	4362	7.83	-2.94	6.83	0.169	-1.22	0.438*	4.13
A-1-a	238	10.73	-4.97	0.84	0.053	41.62	0.139*	3.67
A-1-b	692	8.95	1.16	-11.18	0.055	48.65	0.195*	3.15
A-2-4	2023	8.99	-4.84	8.16	0.151	-3.03	0.327*	3.56
A-2-6	1008	9.75	-3.38	8.63	-0.012	-2.90	0.293*	3.82
A-2-7	44	0.99	24.96	-10.21	-0.091	-7.15	0.426*	9.67
A-4	175	21.47	-10.39	-7.42	0.070	10.00	0.207*	4.56
A-6	152	9.52	0.15	0.63	0.022	5.96	0.336*	5.35

Regression Equation: $OMC = a_0 + a_1(GF)^{0.85} + a_2A + a_3(PI) + a_4A^3$

Appendix G

Regression Analyses based on Size Properties

Abbreviations

The following abbreviations are used in this appendix.

OMC = Optimum Moisture Content

GM = Grading Modulus

The grading modulus is expressed as

GM = Σ(100-% passing sieve size)/100

for sieve sizes 2,00mm, 0,425mm and 0,075mm

GF = Grading Factor

The grading factor is expressed as

GF = Σ(% passing sieve size/nominal sieve size (mm))/100

for sieve sizes 75mm, 63mm, 53mm, 37,5mm, 26,5mm, 19mm, 13,2mm, 4,75mm and 2,00mm

ALL = All results

Sdv = Standard Deviation

a_0, a_1 = regression coefficients

r = coefficient of correlation

t_r = Student's t for r

Conf Lim = Minimum 95% confidence limits for prediction of OMC

Table G.1: Regression analysis OMC vs grading modulus by horizon

Horizon	N.Obs	Mean GM	Mean OMC	Sdv GM	Sdv OMC
All	5405	1.7	9.3	0.5	2.3
Jd	1305	2.2	9.0	0.4	1.9
O-Sn	763	1.5	8.7	0.3	1.7
Nmp	616	1.8	7.9	0.3	1.6
Q	53	1.1	9.6	0.1	2.5
Qb	613	0.9	9.6	0.1	1.7
Pv	503	1.5	9.6	0.5	2.0
Pa	327	1.6	10.5	0.6	2.1
Pvo	278	2.0	11.2	0.5	3.8
ZB	269	1.8	8.1	0.3	1.5
TRt	261	1.7	11.1	0.5	2.6
Pp	240	2.0	10.9	0.4	1.9
C-Pd	177	1.7	9.3	0.4	1.8

Horizon	a_0	a_1	r	t_r	Conf Lim
All	11.06	-1.025	-0.243	18.43*	4.28
Jd	13.24	-1.975	-0.373	14.51*	3.55
O-Sn	11.64	-1.988	-0.393	11.79*	3.16
Nmp	13.15	-2.896	-0.505	14.51*	2.69
Q	21.69	-11.383	-0.284	2.12*	4.88
Qb	9.83	-0.248	-0.018	0.45	3.37
Pv	11.68	-1.349	-0.331	7.85*	3.67
Pa	13.57	-1.987	-0.532	11.31*	3.52
Pvo	18.89	-3.843	-0.503	9.67*	6.55
ZB	11.61	-1.974	-0.468	8.65*	2.57
TRt	11.05	0.051	0.010	0.16*	5.23
Pp	11.69	-0.376	-0.076	1.18	3.84
C-Pd	10.67	-0.824	-0.170	2.29*	3.50

Regression Equation: $OMC = a_0 + a_1 GM$

Table G.2: Regression analysis OMC vs grading factor by horizon

Horizon	N.Obs	Mean GF	Mean OMC	Sdv GF	Sdv OMC
All	5405	0.7	9.3	0.2	2.3
Jd	1305	0.6	9.0	0.1	1.9
O-Sn	763	0.8	8.7	0.1	1.7
Nmp	616	0.8	7.9	0.1	1.6
Q	53	1.0	9.6	0.0	2.5
Qb	613	1.0	9.6	0.0	1.7
Pv	503	0.8	9.6	0.2	2.0
Pa	327	0.7	10.5	0.1	2.1
Pvo	278	0.6	11.2	0.1	3.8
ZB	269	0.8	8.1	0.1	1.5
TRt	261	0.7	11.1	0.2	2.6
Pp	240	0.6	10.9	0.1	1.9
C-Pd	177	0.7	9.3	0.1	1.8

Horizon	a_0	a_1	r	t_r	Conf Lim
All	8.26	1.437	0.108	8.01*	4.39
Jd	6.73	3.717	0.283	10.67*	3.67
O-Sn	3.93	5.689	0.332	9.71*	3.24
Nmp	0.77	9.343	0.462	12.89*	2.77
Q	33.09	-24.510	-0.022	0.16	5.09
Qb	13.77	-4.394	-0.060	1.50	3.37
Pv	7.64	2.568	0.215	4.92*	3.80
Pa	5.31	7.262	0.469	9.57*	3.67
Pvo	3.03	12.953	0.501	9.62*	6.56
ZB	3.04	6.583	0.424	7.65*	2.63
TRt	11.89	-1.131	-0.073	1.18	5.22
Pp	10.42	0.873	0.058	0.89	3.85
C-Pd	8.47	1.136	0.070	0.93	3.54

Regression Equation: $OMC = a_0 + a_1 GF$

Table G.3: Regression analysis OMC vs grading modulus by rock type

Rock Type	N.Obs	Mean GM	Mean OMC	Sdv GM	Sdv OMC
All	5405	1.7	9.3	0.5	2.3
Sandstone	1360	1.5	9.2	0.4	1.9
Sand	669	1.0	9.6	0.1	1.8
Silt	33	1.2	15.2	0.3	5.3
Shale	708	2.0	10.4	0.5	2.4
Mudstone	216	1.8	11.4	0.5	2.4
Clay	52	0.9	13.1	0.4	4.0
Granite	885	1.8	8.0	0.3	1.6
Dolerite	1305	2.2	9.0	0.4	1.9
Tillite	177	1.7	9.3	0.4	1.8

Rock Type	a_0	a_1	r	t_r	Conf Lim
All	11.06	-1.025	-0.243	18.43*	4.28
Sandstone	11.60	-1.657	-0.330	12.88*	3.50
Sand	10.22	-0.667	-0.049	1.27	3.51
Silt	13.35	1.626	0.103	0.58	11.21
Shale	13.95	-1.766	-0.332	9.35*	4.50
Mudstone	11.78	-0.221	-0.047	0.68	4.78
Clay	14.06	-1.060	-0.103	0.74	8.17
Granite	12.51	-2.526	-0.489	16.64*	2.66
Dolerite	13.24	-1.975	-0.373	14.51*	3.55
Tillite	10.67	-0.824	-0.170	2.29*	3.50

Regression Equation: $OMC = a_0 + a_1 LL$

Table G.4: Regression analysis OMC vs grading factor by rock type

Rock Type	N.Obs	Mean GF	Mean OMC	Sdv GF	Sdv OMC
All	5405	0.7	9.3	0.2	2.3
Sandstone	1360	0.8	9.2	0.1	1.9
Sand	669	1.0	9.6	0.0	1.8
Silt	33	0.8	15.2	0.1	5.3
Shale	708	0.6	10.4	0.1	2.4
Mudstone	216	0.6	11.4	0.2	2.4
Clay	52	0.9	13.1	0.1	4.0
Granite	885	0.8	8.0	0.1	1.6
Dolerite	1305	0.6	9.0	0.1	1.9
Tillite	177	0.7	9.3	0.1	1.8

Rock Type	a_0	a_1	r	t_r	Conf Lim
All	8.26	1.437	0.108	8.01*	4.39
Sandstone	7.35	2.246	0.149	5.57*	3.67
Sand	10.66	-1.130	-0.016	0.42	3.51
Silt	23.29	-9.499	-0.128	0.72	11.18
Shale	6.69	6.144	0.334	9.43*	4.50
Mudstone	12.14	-1.250	-0.081	1.19	4.77
Clay	6.61	7.510	0.137	0.98	8.14
Granite	1.63	8.285	0.446	14.81*	2.73
Dolerite	6.73	3.717	0.283	10.67*	3.67
Tillite	8.47	1.136	0.070	0.93	3.54

Regression Equation: $OMC = a_0 + a_1 GF$

Table G.5: Regression analysis OMC vs grading modulus by Weinert's Classification

Weinert's Classification	N.Obs	Mean GM	Mean OMC	Sdv GM	Sdv OMC
All	5405	1.7	9.3	0.5	2.3
Acid	885	1.8	8.0	0.3	1.6
Basic	1305	2.2	9.0	0.4	1.9
Arenaceous	2029	1.3	9.3	0.4	1.9
Argillaceous	1009	1.9	10.9	0.5	2.9
Diamictites	177	1.7	9.3	0.4	1.8

Weinert's Classification	a_0	a_1	r	t_r	Conf Lim
All	11.06	-1.025	-0.243	18.43*	4.28
Acid	12.51	-2.526	-0.489	16.64*	2.66
Basic	13.24	-1.975	-0.373	14.51*	3.55
Arenaceous	11.02	-1.314	-0.278	13.02*	3.52
Argillaceous	14.34	-1.823	-0.345	11.65*	5.27
Diamictites	10.67	-0.824	-0.170	2.29*	3.50

Regression Equation: $OMC = a_0 + a_1 GM$

Table G.6: Regression analysis OMC vs grading factor by Weinert's Classification

Weinert's Classification	N.Obs	Mean LM	Mean OMC	Sdv LM	Sdv OMC
All	5405	0.7	9.3	0.2	2.3
Acid	885	0.8	8.0	0.1	1.6
Basic	1305	0.6	9.0	0.1	1.9
Arenaceous	2029	0.9	9.3	0.1	1.9
Argillaceous	1009	0.6	10.9	0.2	2.9
Diamictites	177	0.7	9.3	0.1	1.8

Weinert's Classification	a_0	a_1	r	t_r	Conf Lim
All	8.26	1.437	0.108	8.01*	4.39
Acid	1.63	8.285	0.446	14.81*	2.73
Basic	6.73	3.717	0.283	10.67*	3.67
Arenaceous	7.27	2.385	0.155	7.06*	3.62
Argillaceous	7.24	5.833	0.308	10.26*	5.34
Diamictites	8.47	1.136	0.070	0.93	3.54

Regression Equation: $OMC = a_0 + a_1 LLM$

Table G.7: Regression analysis OMC vs grading modulus by AASHTO Classification

AASHTO Classification	N.Obs	Mean GM	Mean OMC	Sdv GM	Sdv OMC
All	5405	1.7	9.3	0.5	2.3
A-1-a	313	2.4	8.3	0.2	1.8
A-1-b	956	1.8	8.2	0.2	1.6
A-2-4	2424	1.6	9.3	0.5	1.9
A-2-5	3	1.5	10.4	0.5	1.1
A-2-6	1008	2.1	9.6	0.4	2.0
A-2-7	44	2.1	12.5	0.4	5.2
A-3	298	1.0	9.7	0.1	2.1
A-4	180	1.0	10.9	0.3	2.3
A-5	3	1.3	23.7	0.2	3.0
A-6	152	1.0	12.1	0.3	2.9

AASHTO Classification	a_0	a_1	r	t_r	Conf Lim
All	11.06	-1.025	-0.243	18.43*	4.28
A-1-a	5.07	1.369	0.121	2.15*	3.50
A-1-b	11.03	-1.522	-0.196	6.17*	3.05
A-2-4	9.98	-0.454	-0.128	6.34*	3.60
A-2-5	13.11	-1.797	-0.877	1.83	13.74
A-2-6	12.43	-1.366	-0.259	8.50*	3.87
A-2-7	19.97	-3.558	-0.308	2.10*	10.29
A-3	13.57	-3.725	-0.170	2.97*	4.07
A-4	10.21	0.685	0.086	1.15	4.61
A-5	17.76	4.553	0.371	0.40	71.51
A-6	15.48	-3.540	-0.400	5.35*	5.22

Regression Equation: $OMC = a_0 + a_1 GM$

Table G.8: Regression analysis OMC vs grading factor by AASHTO Classification

AASHTO Classification	N.Obs	Mean GF	Mean OMC	Sdv GF	Sdv OMC
All	5405	0.7	9.3	0.2	2.3
A-1-a	313	0.5	8.3	0.1	1.8
A-1-b	956	0.8	8.2	0.1	1.6
A-2-4	2424	0.8	9.3	0.2	1.9
A-2-5	3	0.8	10.4	0.1	1.1
A-2-6	1008	0.6	9.6	0.1	2.0
A-2-7	44	0.6	12.5	0.2	5.2
A-3	298	1.0	9.7	0.0	2.1
A-4	180	0.9	10.9	0.1	2.3
A-5	3	0.8	23.7	0.1	3.0
A-6	152	0.9	12.1	0.1	2.9

AASHTO Classification	a_0	a_1	r	t_r	Conf Lim
All	8.26	1.437	0.108	8.01*	4.39
A-1-a	10.14	-3.337	-0.160	2.85*	3.48
A-1-b	6.56	2.200	0.126	3.92*	3.09
A-2-4	8.96	0.382	0.035	1.71	3.63
A-2-5	0.78	11.466	0.956	3.25*	8.41
A-2-6	8.07	2.569	0.180	5.80*	3.94
A-2-7	4.64	13.137	0.427	3.06*	9.78
A-3	0.69	9.435	0.083	1.43	4.12
A-4	14.69	-4.402	-0.155	2.09*	4.57
A-5	39.08	-18.918	-0.362	0.39	71.79
A-6	2.24	11.368	0.293	3.75*	5.45

Regression Equation: $OMC = a_0 + a_1 GF$