THE ENGINEERING PROPERTIES AND ROAD BUILDING CHARACTERISTICS OF MUDROCKS, WITH SPECIAL REFERENCE TO SOUTHERN AFRICA

by

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Submitted in partial fulfilment of
the requirements for the degree of
Doctor of Science in the
Faculty of Science
University of Pretoria
PRETORIA

May 1980

ABSTRACT

Mudrocks occur in many parts of southern Africa and large quantities are used in road construction. This study involved research on the "state of the art" of the road construction aspects of mudrocks in southern Africa, as well as the general engineering-geological properties of such rocks and the assessment of the most appropriate tests for classifying mudrocks for road construction purposes.

The "state of the art" investigation, done by means of interviews with users of the material, revealed much confusion about the terminology related to these rocks. It was therefore decided to use the term "mudrock" as the all-embracing term with "shale" and "mudstone" indicating fissile and massive varieties respectively. The survey also found mudrock to be an important construction material, especially in the Cape Province and Natal, where it is used up to subbase level. Large differences of opinion exist regarding the general road-building qualities of mudrocks. No particular problem pertaining to construction with mudrock was identified, but the break-down phenomenon on exposure gave rise to most of the concern expressed. It was felt that other tests, additional to the standard ones used in road construction, are necessary to characterize mudrocks.

A wide variety of property investigations and tests was performed on 14 mudrocks, sampled as soon as possible after excavation, from different geological formations throughout South Africa. Although the samples were selected to cover a wide range of engineering geological properties, since they were limited in number it cannot be claimed that they are necessarily representative of the whole range of southern African mudrocks.

Standard road construction tests showed some samples to be of subbase standard. Plasticity indices were usually low. The addition of four per cent lime generally caused a marked increase in the CBR strength. An "accelerated weathering" test, in which CBR compactions were followed by wet-dry cycles, indicated the different rates of break-down of the samples. Extensive free swell tests on cubes, pretreated differently before immersion in water, showed that the majority of samples expand less than one per cent during immersion after oven-drying. Some weathered rocks and those which tended to break down expanded more. Air-drying increased the expansiveness of the rocks to levels similar to those obtained after oven-drying. The mudrocks were found to absorb water at different rates. In an experiment

during which test cubes were subjected to temperature and humidity changes, it was found that the mudrocks were more sensitive to humidity changes, both as far as volume changes and moisture adsorption were concerned. However, even large variations in temperature and humidity were not able to produce a visual break-down such as was observed for some samples when they were immersed in water.

The results from classification tests were investigated and correlated to select tests which showed the best possibilities for mudrock classification. It is considered that a road construction material needs to be resistant to crushing, abrasion, and decomposition. The 10 per cent FACT, carried out on dried and soaked samples, is preferred for testing the resistance to crushing. A wet ball mill test was developed for testing resistance to abrasion. This test was more successful in separating samples of different qualities than the Los Angeles abrasion test and the results correlated well with those obtained from an ultrasonic disaggregation test. The sand equivalent test is recommended to determine the presence of deleterious material in the crushed mudrock. The break-down of mudrocks at various rates on exposure is not fully evaluated by the above tests, nor by the standard road construction tests. Two varieties of the break-down phenomenon were observed although there appears to be a gradation between the two processes, i.e. the break-down of the rock into hard fragments (disintegration) and the break-down into silt or clay-sized particles (slaking). It is considered that slaking can be measured by means of the slake durability test, but disintegration should be evaluated qualitatively by performing a five-cycle wet-dry test, using water. Tests, such as the Washington degradation, ethylene glycol soaking, methylene blue adsorption, sodium sulphate soundness, rate of slaking and conductivity, were found to be unsuitable for general classification purposes.

SAMEVATTING

Modderrots word in verskeie dele van suidelike Afrika aangetref en groot hoeveelhede daarvan word in padbou gebruik. In hierdie studie is die huidige gebruike, sowel as die algemene ingenieurs-geologiese eienskappe van sodanige rots en die beoordeling van die mees geskikte toetse met betrekking tot die klassifikasie van modderrots vir padbou-doeleindes in suidelike Afrika, ondersoek.

Die ondersoek na die huidige gebruike wat verband hou met modderrots, gedoen deur onderhoude met gebruikers van die materiaal te voer, het getoon dat daar heelwat verwarring bestaan oor die terminologie wat betrekking het op hierdie rotse. Daar is dus besluit om die term "modderrots" as die allesomvattende term te gebruik met "skalie" en "moddersteen" onderskeidelik as fissiele en massiewe tipes. Die opname het ook getoon dat modderrots 'n belangrike konstruksie-materiaal is, veral in die Kaapprovinsie en Natal waar dit tot in die stutlaag gebruik word. Daar bestaan groot meningsverskille oor die algemene padboueienskappe van modderrots. Geen besondere probleem behorende tot the gebruik van modderrots in padbou is waargeneem nie maar die verskynsel van opbreek na blootstelling wek die meeste kommer. Daar is gevoel dat, benewens die standaardpadboutoetse, nog bykomende toetse nodig is vir die karakterisering van modderrotse.

'n Groot verskeidenheid ondersoeke na en toetse van die eienskappe is uitgevoer op 14 modderrotse, waarvan monsters so gou moontlik na uitgrawing uit verskillende geologiese formasies dwarsoor Suid-Afrika verkry is. Alhoewel die monsters gekies is om 'n wye reeks ingenieurs-geologiese eienskappe te dek, is hulle vanweë die beperkte getal nie noodwendig verteenwoordigend van die hele reeks suider Afrikaanse modderrotse nie.

Standaard padboutoetse het getoon dat sommige van die monsters van stutlaaggehalte was. Plastisiteitsindekse was oor die algemeen laag terwyl die byvoeging van vier persent kalk gewoonlik 'n aansienlike KDV sterktetoename tot gevolg gehad het. 'n Versnelde verweringstoets waartydens KDV-verdigting gevolg is deur nat-droogsiklusse het die verskillende tempo's van opbreking van die monsters getoon. Uitgebreide vrysweltoetse, uitgevoer op kubusse wat verskillend behandel is voor indompeling in die water, het getoon dat meeste van die monsters minder as een persent swel tydens indompeling na oonddroging. Sommige verweerde rotse en diegene wat geneig

was om op te breek het egter meer geswel. Lugdroging het die uitswelvermoë van die rotse verhoog tot op dieselfde vlak as dié wat na oonddroging verkry is. Daar is gevind dat modderrotse water teen verskillende tempo's absorbeer. In 'n eksperiment waartydens toetskubusse aan temperatuur- en humiditeitsveranderinge blootgestel is, is daar gevind dat modderrots meer gevoelig is vir humiditeitsveranderinge. Dit geld vir beide volume-veranderinge en vogadsorpsie. Nietemin, kon selfs groot wisselings in temperatuur en humiditeit nie sigbare opbreking te weeg bring nie, soos wat wel waargeneem is by sommige van die monsters by indompeling in water.

Die resultate verkry uit klassifikasietoetse is ondersoek en gekorreleer om die mees geskikte toetse vir modderrots-klassifikasie te kies. Daar word geag dat 'n padboumateriaal bestand moet wees teen vergruising, afskuring en ontbinding. Die 10 persent FAVT, uitgevoer op gedroogde en geweekte monsters, word vir die toets van bestandheid teen vergruising verkies. 'n Nat balmeultoets is vir die toets van bestandheid teen afskuring ontwikkel. Hierdie toets was meer suksesvol in die skeiding van monsters van verskillende kwaliteite as die Los Angeles-afskuurtoets, en die resultate het goed gekorreleer met dié wat verkry is uit 'n ultrasoniese disaggregasietoets. Die sand-ekwivalenttoets word aanbeveel om die teenwoordigheid van skadelike materiaal in die vergruisde modderrots te bepaal. Die opbreking van modderrots teen verskillende tempo's as gevolg van blootstelling word nie deur bostaande toetse of deur die standaardpadboutoetse geëvalueer nie. Twee variasies van die opbreekverskynsel is waargeneem alhoewel dit blyk dat daar nie 'n definitiewe skeiding tussen die twee prosesse is nie; d.i. opbreking van die rots tot harde stukkies (disintegrasie) en opbreking na slik- of kleigrootte partikels (blus). Daar word geag dat blus deur middel van die blusduursaamheidstoets bepaal kan word, maar disintegrasie moet kwalitatief evalueer word deur 'n vyfsiklus nat-droogtoets met water uit te voer. Toetse soos Washingtondegradasie, weking in etileenglikol, metileenblou-adsorpsie, natriumsulfaatgaafheid, tempo van blus en geleidingsvermoë is as ongeskik vir algemene klassifikasie doeleindes bevind.

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GLOSSARY OF ABBREVIATIONS AND TERMS

AASHTO	American Association for State Highway and Transportation Officials
ACV	Aggregate Crushing Value
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BS	British Standard
CBR	California Bearing Ratio
C.I.	Confidence Interval
CSIR	Council for Scientific and Industrial Research
ISRM	International Society for Rock Mechanics
MDD	Maximum Dry Density
NBRI	National Building Research Institute
NITRR	National Institute for Transport and Road Research
NMERI	National Mechanical Engineering Research Institute
NP	Non-plastic
OFS	Orange Free State
OMC	Optimum Moisture Content
PI	Plasticity Index
R.H.	Relative Humidity
10%FACT	10 per cent Fines Aggregate Crushing Test
r	Correlation coefficient
1V:2H	1 Vertical:2 Horizontal (Slope)

Natural moisture content (NMC) - moisture content as sampled (samples stored in sealed plastic bags to prevent losses as far as possible)

Break-down (of rocks) - term to describe general breaking of rock into smaller fragments or grains

Disintegration - break-down into plates, flakes or large grains

Slaking - break-down into silt and/or clay

CHAPTER 1

INTRODUCTION

Wide-spread areas in southern Africa are underlain by mudrocks and large quantities are used in road construction. In some parts there are no alternative materials available, forcing those involved with the construction to use it even in the designed layers of roads. Many persons, however, have doubts about the general quality of the material. No work including the whole spectrum of southern African mudrocks has previously been carried out. As a first step towards such an undertaking, this study describes the investigation of the properties of mudrocks and their classification for use in road construction.

The information available in southern Africa on the construction aspects of mudrocks was collected through a series of interviews with persons experienced in the use of the material. This was used to compile the current "state of the art" and to identify problems related to construction in and with mudrock. A literature study was carried out to aid in the selection of appropriate tests and a pilot study was conducted to develop and investigate certain test methods and procedures.

In contrast to most other generally used road-building materials, certain detrimental properties of mudrocks are not pinpointed by the standard specification tests and additional tests are needed. Tests considered to have possibilities for classification were therefore carried out. These included rock strength tests, crushing strength tests, an impact crushing test, wet and dry abrasion tests, slake durability tests, as well as other tests such as Washington degradation, sodium sulphate soundness, ethylene glycol soaking, sand equivalent, methylene blue adsorption, specific gravities and absorption, rate of slaking, porosity, conductivity and pH. The "weathering" effects of water, calgon and a saturated sodium sulphate solution were also compared in a wet-dry test and an ultrasonic disaggregation test was investigated.

The test results were compared using graphical plots and linear regression analyses. This enabled the selection of the most appropriate tests to be used for classification and for further study of mudrocks in southern Africa.

The tests were carried out on 14 mudrock samples collected from various geological formations throughout South Africa. The detailed investigation of a limited number of samples with a wide variation in properties was considered to be the most profitable approach as the results could be used to select the most promising tests and would also provide an overall view of mudrock properties.

The properties investigated included grading, compaction, California bearing ratio (treated and untreated material) and plasticity tests, and the change of these after the materials had been submitted to wet-dry cycles. Free swell behaviour, absorption characteristics and volume and moisture changes, caused by temperature and humidity changes, were also studied in detail.

CHAPTER 2

NOMENCLATURE AND CLASSIFICATION OF MUDROCKS

2.1 Nomenclature

The classification of the fine-grained sedimentary rocks has been a problem for a long time and the reason is not difficult to understand. The rocks are so fine-grained that little can be seen with the naked eye and individual grains generally cannot even be resolved with the ordinary optical microscope. There are therefore few characteristics which can be used as a basis for visual classification.

If one looks at the more important terms used to describe these rocks, one finds that even dictionaries differ in their interpretations. The two most important terms are defined as follows under the heading of argillaceous rocks (Whitten and Brooks, 1974):

"Shale has a well marked bedding plane fissility, primarily due to the orientation of the clay mineral particles parallel to the bedding planes. Shales do not form a plastic mass when wet, although they may disintegrate when immersed in water.

Mudstone is a term used for rocks which are similar to shales in their non-plasticity, cohesion and lower water content, but lack the bedding plane fissility."

Mudrock is a term that has come into favour during the last few years and includes all the fine-grained sedimentary rocks composed dominantly of silt-size particles and smaller.

Another important aspect is the meaning of some of the terms used when describing or classifying these materials. Some of the more important terms are as follows (partly after Gamble, 1971, and Whitten and Brooks, 1974):

Arenaceous rocks: A group of sedimentary rocks, typically sandstones, in which the particles range in size from 1/16 mm to 2 mm*.

Argillaceous rocks: A group of sedimentary rocks, commonly clays, shales, mudstones, siltstones and marls. Two grades of particle size are recognized, the silt grade in which the particles range from 1/16 to 1/256 mm, and the clay grade with particles less than 1/256 mm* in size.

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* 2,0; 0,074 and 0,002 mm preferred. See next paragraph.

Fissile: Denotes the ability to split approximately parallel to the bedding.

Flaggy: Denotes the ability to split in such a fashion that the length and the width of the slabs are much greater than their thickness.

Flaky: Denotes the tendency to break into chips, small flakes, or wedges.

Indurated: Denotes a rock hardened by pressure, cementation, or heat. It therefore includes hardening due to baking by igneous intrusions.

Massive: Used to denote non-fissile or non-shaly rocks which break in apparently random directions to give blocky or irregular shapes.

The particle size boundaries between sand, silt and clay present problems because of the different systems being used by various authorities. The Committee on Soil Properties of the Soil Mechanics and Foundation Division, ASCE (1969) investigated this problem and found the following to be in use:

Clay-silt boundary at 0,002 mm, 0,0039 mm or 0,005 mm

Silt-sand boundary at 0,053 mm (270 U.S. #), 0,0625 mm (230 U.S. #) or 0,074 mm (200 U.S. #)

Sand-gravel boundary at 2,0 mm (10 U.S. #) or 4,76 mm (4 U.S. #)

The Committee recommends that the clay-silt boundary should be set at 0,002 mm. There is a slight preference for the silt-sand boundary at 0,074 mm and moderate to good agreement that the sand-gravel boundary should be set at 2,0 mm.

These dimensions are then the particle-sizes referred to when the terms sand, silt or clay are used in the text.

2.2 Geological classification

Blatt, Middleton and Murray (1972) classify the mudrocks according to Table 2.1. In their book they prefer "mudrock" as the general term with "mud" referring to a mixture of clay and silt. This classification system seems logical and does not require any drastic changes to the

existing definitions; it closely resembles the systems of Ingram (1953) and Folk (1968). Pettijohn (1975) does not introduce terms such as mudrock or claystone into his diagrammatic scheme.

TABLE 2.1: CLASSIFICATION OF MUDROCKS ACCORDING TO BLATT et al (1972)

Ideal size definition	Field criteria	Fissile mudrock	Non-fissile mudrock
> 2/3 silt	Abundant silt visible with hand lens	Silt-shale	Siltstone
> 1/3 < 2/3 silt	Feels gritty when chewed	Mud-shale	Mudstone
> 2/3 clay	Feels smooth when chewed	Clay-shale	Claystone

Gamble (1971) carried out work on the classification of mudrocks for engineering purposes. His proposed classification is shown in Table 2.2.

TABLE 2.2: CLASSIFICATION OF MUDROCKS ACCORDING TO GAMBLE (1971)

Unindurated	Indurated group		After incipient metamorphism	Metamorphic equivalents
	Mudrocks (shales or mudstones)			
	Breaking characteristics			
	Massive	Fissile or shaly		
Silt	Siltstone	Silty shale		
Mud (mixture of undetermined amounts of silt and clay with minor amount of sand)	Mudstone	Shale	Argillite	Slate, Phyllite or Schist
Clay	Claystone	Clayey shale		

This classification strongly resembles that of Blatt, Middleton and Murray (1972). Though it has not found universal acceptance, all the more recent publications on the engineering classification of mudrocks take note of it and follow most of its terminology. This is also the system adopted by the National Institute for Transport and Road Research in its research work on southern African mudrocks. The terms used by Blatt et al (1972) i.e. clay-shale rather than clayey shale are preferred.

CHAPTER 3

SURVEY OF INFORMATION IN SOUTHERN AFRICA

3.1 Introduction

A review of the use of mudrock in road construction in South Africa was done by Purnell and Netterberg (1975). The author's survey was carried out by going through a list of previously compiled questions (Chapman and Wood, 1974) with various knowledgable people in a series of personal interviews. All the conversations were tape-recorded and given afterwards in a verbatim report. The personal interviews and later work were time-consuming but nevertheless very rewarding because points of interest could be pursued and maximum information extracted.

Thirty-seven interviews were conducted with 53 different people. The people interviewed included representatives of all the Provincial Roads Departments, the National Roads Branch, the South West Africa-Namibia Roads Department and prominent consulting engineers and engineering geologists. Enquiries about possible information from Zimbabwe-Rhodesia indicated that very little use had been made of mudrock in that country.

3.2 Method of analysing data

Appropriate headings covering the aspects discussed in one or more questions were chosen and the comments were analysed under these headings, often using tables (Venter, 1978a). The following general discussion is mainly a combination of these conclusions.

3.3 General discussion of findings

3.3.1 Terminology

Relevant questions:

How do you, your firm or department classify the fine-grained sedimentary rocks, i.e. which terms are used and what do they mean?

Are there criteria to describe a rock as a shale, slate, mudstone or siltstone that distinguish one from the other? If so, what are these criteria?

The overwhelming impression of the reaction to these questions is that there is great confusion on the matter. The confusion is of such a degree that in most of the interviews terminology first had to be established before meaningful discussion could take place. Even geological dictionaries are not completely in agreement on definitions. Terminology was therefore studied and a system recommended. This system (see Table 2.1) is logical and does not go against any well-established usage of the terms.

The use of the term mudrock to include all the fine-grained sedimentary rocks composed dominantly of silt-size particles and smaller was approved by the Steering Committee of the Materials and Design Branch of the National Institute for Transport and Road Research (NITRR) of the Council for Scientific and Industrial Research (CSIR).

It is accepted that it is very difficult for someone not specializing in material classification to use all the terms correctly. The fine-grained character of the rocks complicates the application of the criteria. Generally, only the terms shale and mudstone need to be used, but in any detailed material evaluations the use of the correct terms is essential. The use of uniform terminology will without doubt aid the study of these materials.

3.3.2 Frequency of occurrence in road projects and percentage of mudrock used in roads

Relevant questions:

In what percentage of your road projects do you encounter some or other form of mudrock?

From your experience with roads can you estimate the percentage use of mudrocks up to now in these roads?

Estimates of the percentage of road projects in which mudrocks have been encountered varied from 50 to 100 per cent in the Cape Province. In Natal estimates were similar or more specifically in the 60 to 70 per cent range, but estimates in the Transvaal were much lower. The answer lies, as some people commented, in the geological maps of southern Africa. Mudrock-containing geological formations cover vast areas of southern Africa and mudrock is encountered along almost any road built in such

areas. The only province of South Africa in which the estimates dropped below 50 per cent is the Transvaal where a large part of the area is underlain by metamorphic and igneous rocks.

On the question concerning the percentage of mudrocks used in road pavements and fills, people were naturally reticent to venture a guess. However, in the Cape Province estimates of 50 per cent were common and in Natal they were about 70 per cent. Estimates in the Transvaal, the Orange Free State (O.F.S.) and South West Africa-Namibia were much lower.

From the above it is clear that mudrock is a very important road construction material in southern Africa, and especially in the Cape Province and Natal.

3.3.3 Attitude on the use of mudrock in roads

Relevant questions:

Do you only use mudrock when circumstances demand it, i.e. when such a material is available from a cutting, or do you open borrow pits in mudrock or certain types of mudrock?

What is then your general policy towards mudrock? Do you use materials like shale, siltstone, slate and mudstone only in cases where no alternative exists?

A wide range of reactions was encountered. Opinions ranged from nothing being wrong with the material to mild criticism of it, and even further to highly critical views of mudrock. The first group view mudrock as they would any other material while the moderately critical group prefer to use another material if available. The highly critical group would only open borrow pits if they were forced to. Most opinions expressed fell within the first two groups.

3.3.4 Use in various road layers

Relevant question:

In which pavement layers have mudrocks been used, e.g.

Base
Subbase
Selected layers

Rock fill
Compacted fill
Wearing course in gravel roads?

Base Mudrock is almost never used as a base material. This only occurs when there is no alternative or where the material has been indurated by the heat from a dolerite intrusion.

Subbase Mudrock is frequently used in subbase construction, often stabilized. There are clear differences in policy between the provinces. In Natal and the Cape Province the material is often used in a subbase while it is very seldom used for this purpose in the Transvaal, Orange Free State (O.F.S.) or South West Africa-Namibia. This is probably due to the availability of other materials in these areas. The National Roads Branch has recently started using mudrock for subbase, but it is always stabilized.

Consultants follow almost the same pattern. Those in the Cape Province and in Natal are generally more liberal with the use of mudrocks in subbase than their Transvaal or O.F.S. counterparts. The reason is probably that Cape and Natal engineers have been forced to use the material and have found it to perform satisfactorily. In contrast Transvaal and O.F.S. engineers have so far succeeded in getting along without the material and are thus avoiding the unknown.

Complaints tend to be confined to certain regions in that persons who worked in the vicinity of the Drakensberg (particularly the eastern O.F.S. and Transkei) with materials of a poor quality are very wary of mudrock.

Selected layers Mudrock is generally considered suitable for use in selected layers. Only a few authorities, such as the O.F.S. and Transvaal Roads Departments are not in favour of this. With few exceptions consulting engineers are of the opinion that mudrock can be used in this layer.

Rockfill About half the people questioned do not disfavour the use of mudrock in rockfill while the remainder, to a varying degree, do not favour it. The main objection to its use is that voids are left between the rock fragments which can lead to further weathering and disintegration, and possibly settlement, with some mudrocks.

Compacted fill There is almost no opposition to the use of mudrock in compacted fill.

Wearing course in gravel roads Mudrock is used fairly generally in wearing courses but there is some opposition. It is not used in the O.F.S. and where it is used certain conditions are set e.g. that the disintegration and plasticity properties should be investigated for use in wet areas and that certain types of mudrock are definitely not suitable.

3.3.5 Problems connected with the use of mudrock

Relevant questions:

What do you see as the major problem or problems regarding roadworks where these materials occur? Is it:

(a) the breaking down of certain materials into clay or small block-like particles which can lead to settlement of the road?

(b) the failure of embankment slopes?

(c) the occurrence of hard layers between the mudrock layers which lead to problems regarding the evaluation and use of the material as a whole?

(d) problems regarding the protection of the cutting slopes against erosion?

(e) the failure or blocking of drainage structures?

(f) the expansion of in-situ materials below the road surfaces?

(g) any other?

What problems regarding compaction do you encounter, e.g. is fissility a problem?

Do you experience major problems with cutting slopes through these materials?

Disintegration or slaking of mudrock into small blocks or clay (Plates 1 and 2) Although the majority of engineers know about this, they do not regard it as a problem. It seems as if people who have a lot of experience with these materials are of the opinion that the disintegration process stops as soon as the material is compacted and covered in the road. Some are sceptical about the long-term performance of the material, while a few think that disintegration continues after construction.

Another complaint relevant to disintegration is that hard mudrock does not break up during construction and this hinders compaction. On the other hand, some weaker types break up excessively during construction.

Failure of embankment slopes There is a reasonable consensus that this is not a problem. If it occurs, it is due to bad construction. Longitudinal cracks do occur, but it is uncertain whether this is connected with the use of mudrock.

Sequences of hard and soft layers (Plate 3) The general opinion is that these mixtures of material of varying qualities do present some problems. However, these materials are usually encountered in cuttings and are then used in fills. They present a bigger problem in borrow pits, but there they can be avoided to a certain extent by looking for more homogeneous material.

Other problems caused by mixed material of this kind are that layers of a poor quality often decrease the quality of the harder layers and that harder rocks often present problems during compaction by not breaking up in the same way as the softer material.

Interesting comments were that these sequences should be evaluated by testing the worst material, and that the contact planes between hard and soft layers generally have very low cohesion.

Erosion Erosion is not regarded as a serious problem connected with mudrocks except in the regions where the Burgersdorp Formation of the Tarkastad Subgroup or the Elliot Formation occur. Problems do exist in the Durban area where vegetated surface material slides down from the slopes of cuttings after heavy rains.

A further problem is that mudrock layers weather more rapidly than sandstone layers. This leads to undercutting and subsequent collapse of the unsupported blocks (Plate 4).

An important observation is that it is in many instances only a thin surface layer of the mudrock which crumbles due to weathering. If this layer is not removed through water or some other agent, weathering does not proceed deeper.

Blocking of drainage structures Very little comment was received. The majority of people do not consider it a problem. The problems which do exist are maintenance problems, but these are no worse than with other materials.

Expansion of in-situ mudrock underneath road pavements The majority of people have not encountered any problems which could be ascribed to the swelling of in-situ mudrock. One person was of the opinion that compacted mudrock expands with changes in moisture content.

Compaction of mudrock during construction The lack of fines generated during the compaction of some mudrocks is a problem. Quite a number of people mentioned that this problem is frequently encountered and that a binder has then to be added to improve grading and to make a dense packing possible. The opposite also happens and then the material slakes completely during construction so that it becomes unsuitable and has to be removed.

During compaction it may be difficult to break up the rock as it breaks into large fragments which resist crushing by the rollers. A similar problem occurs when softer mudrock is intermixed with harder sandstone. During compaction the rollers then tend to ride on the sandstone blocks without compacting the broken-up mudrock.

The amount of moisture absorbed by mudrocks causes problems in some cases. A few engineers mentioned that large-scale construction problems are created when an uncompacted layer is adversely affected by unexpected rain, or if the moisture content of the material is too high. It was also mentioned that drying out of the material is not desirable as it is difficult to get it back to the optimum moisture content.

Fissility, according to the people interviewed, does not generally occur, and if it does, it does not create compaction problems.

Problems with slopes of cuttings

(a) Erosion and protection of slopes

Erosion of the slopes of cuttings is not a serious problem but it does take place in the coastal regions of the Cape Province and Natal and in the interior, especially where rocks of the Burgersdorp Formation and the Elliot Formation are found (Plate 4). It is, however, possible to establish vegetation on mudrock slopes. Various methods such as using logs to keep the surface material stable, hydroseeding and sodding are employed on roads of a higher standard. The City Engineer's Department in Durban feels that it is difficult to establish vegetation on 1V:1½H (1 Vertical:1½ Horizontal) slopes as slumping of the surface material takes place during the rainy

season. This leads to a loss of vegetation (Plate 5). 1V:2H slopes are more suitable. In the interior of Natal vegetation is usually established naturally. In the eastern O.F.S. the completed slopes are covered with topsoil or weathered dolerite and locally occurring tufts of grass are planted. The establishment of vegetation is usually successful but slumping takes place if the slopes are too steep.

(b) Stability

Slides involving large volumes of material seem to occur predominantly in the coastal region of Natal where the Karoo strata dip from the horizontal. In other areas Karoo strata are close to horizontal and slope failures are not common.

Slides in the above-mentioned region usually take place when side cuts are constructed. If the strata (sandstone and mudrock layers) dip with the slope, sliding is probable. Slides take place on bedding planes covered by a thin layer of clay which is usually highly plastic because of seepage (Plate 6). The volume of material involved is partly determined by the pattern of the joint sets. Evidence is available that slides had taken place on planes dipping only 8° and some people are of the opinion that sliding can happen on even flatter surfaces.

Other stability problems, such as in the case of alluvial fans on mudrock slopes, also occur. However, in this survey only problems connected with the structure and weathering of the rock itself were considered.

(c) Other problems

A problem often mentioned is that of seepage in cuttings. The seepage leads to the development of hydrostatic pressures underneath the pavement which can cause failure of the pavement. It can be overcome by breaking the in-situ material to a reasonable depth during construction, thus providing good drainage. Seepage on the slopes of cuttings can also cause slumping during the rainy season.

3.3.6 Dip of cutting slopes

Relevant question:

What slope do you use in cuttings?

Slopes in mudrock (and in other materials) are usually not designed. Standard slopes are used, and the dip of the slope depends, among other factors, on the climate, the standard of road and the depth of the cutting.

In the Great Karoo region in the Cape Province vertical slopes are generally used in the shallow cuttings and very steep slopes in the deeper cuttings. In rocks of the Bokkeveld Group and in weak material in the eastern Cape Province, slopes of 1V:1½H are used, although flatter slopes such as 1V:2H are also found. The 1V:1½H slope is, however, the most popular among people working in the Cape Province.

In the O.F.S. steep slopes are also used in the stronger materials, such as in alternating layers of sandstone and mudrock. In weak materials a slope of 1V:1½H is used.

In Natal steep slopes such as 1V:1H in ordinary mudrock and 1V:½H in indurated rock are used if the bedding is horizontal. In disintegrating material a slope of 1V:1½H may be used. On major roads and in deeper cuttings there is a strong preference among consulting engineers in Natal for a slope of 1V:1½H.

The Transvaal has a lower percentage of cuttings in mudrock than the other three provinces. The Roads Department prefers steep slopes, e.g. 1V:¾H.

A standard slope of 1V:1½H is used for all materials in South West Africa-Namibia whereas the National Roads Branch in the Republic uses 1V:1H as the standard slope, with steeper slopes (1V:½H) in better material and flatter slopes (1V:1½H) in worse material.

3.3.7 Differences in properties of mudrocks from different geological formations

Relevant question:

Do you usually identify the mudrock according to the name of the geological formation or is this ignored e.g. do you treat an Ecca shale from the Karoo Supergroup in the same way as a Bokkeveld shale from the Cape Supergroup?

With reference to the above question, are there any areas or layers that you can define as good or bad?

Identification of formation Many people do not identify mudrock according to geological formations but the majority consider it to be important or very important. Among those who consider it as very important, people with an engineering-geological background predominate. Those who consider it as important ascribe certain properties to different formations. This is probably because they are always aware of the formation in which they are working and therefore have a frame of reference.

Properties of formations Facts which emerged included the following:

(a) Bokkeveld mudrock does not disintegrate or weather in the same way as Karoo mudrock. The behaviour in tunnels should also be different.

(b) What were formerly known as Dwyka shales or mudstones are not widespread but where they do outcrop, such as in the eastern Cape Province and Natal, they are poor materials.

(c) In Natal, Ecca mudrock is generally considered a better material than Beaufort mudrock.

(d) Thick, purplish mudstone layers are present in the Burgersdorp Formation and in the Elliot Formation. These materials are of a poor quality as they slake to a silt when exposed to the elements.

3.3.8 Crushing in the laboratory, test methods and standards

Relevant questions:

Which methods are used in the laboratory to break up the mudrocks for testing?

Do you use the usual "green book" (Department of Transport, 1971) methods for determining the use of a certain type of mudrock and which standards then apply for the different pavement layers?

Do you have any special way of determining the engineering or construction characteristics of mudrocks? If so, which methods are or have been used?

Crushing in the laboratory Mudrock cannot be used for testing in its natural form as it is a rock and therefore has to be crushed. Eighty-five per cent of the people questioned generally use a jaw crusher although some also use hammers, especially in field laboratories. The other 15 per cent usually use hammers.

From this it is obvious that results from different laboratories cannot easily be compared. Comparison with construction results is also difficult as it is highly improbable that the grading after field compaction would be the same as, for example, during the CBR test. The application of grading specifications to a crushed mudrock therefore does seem a bit far-fetched.

Laboratory test methods and standards Replies to questions concerning the test methods revealed that almost without exception the "green book" methods (Department of Transport, 1971) were used to test if the mudrocks were of the standards set by the respective provincial authorities or by the National Roads Branch, Department of Transport. As far as standards are concerned there are some variations in the degree to which the standards are applied. Whereas the Transvaal Roads Department feels that one standard applies to all materials and therefore also to mudrock, the Cape Roads Department feels that grading envelopes should only be used as guidelines when evaluating mudrock. The rock as a whole is evaluated and some standards are flexible. For subbase, for example, only maximum diameter, CBR and plasticity index are taken into account.

Special tests Special tests are very rarely done. Visual inspection of local excavations is recommended by some while other tests, such as a rough free swell, behaviour in water and determination of plasticity index on crushed material were also mentioned.

3.3.9 Methods of excavating borrow pits and cuttings

Relevant question:

Which methods are used to excavate the mudrock? Do you generally use explosives, ripping, scraper, tractor scraper, etc.?

The general feeling is that a ripper is almost always capable of excavating mudrock. In rare cases it is necessary to use explosives to break the hard types in cuttings (Plate 7). Some other aspects which emerge are:

(a) Some contractors find it advantageous to break the rock by using explosives before excavation. This is done especially when a hard layer, which has to be blasted in any case, is present.

(b) During borrow pit exploration, material which does not need blasting is preferred.

(c) Equipment such as bulldozers and tractor scrapers is also used, the latter especially in soft, more weathered materials.

(d) During excavation with a ripper cognizance should be taken of the strike and dip of the layers. This can be used to advantage during ripping.

3.3.10 Construction methods and equipment

Relevant questions:

Do you advocate or use a special standard method of construction for these materials or does the construction method vary from contractor to contractor, e.g. is the material compacted immediately after excavation from the borrow pit or quarry?

What equipment is used or do you prefer for compaction, a smooth roller, sheepsfoot roller, grid roller, rubberwheel roller, etc.?

Methods The general feeling is that no special methods of construction are used in the case of mudrock. Views were, however, given on construction with disintegrating material. Quite a few people are of the opinion that this property can be used to great advantage and that some hard types cannot be worked effectively until they have had time to disintegrate. Another view is that if circumstances, e.g. the construction programme and the grading allow, it is preferable to compact and cover the material immediately in the road.

Equipment The grid roller is generally considered as a very suitable roller for breaking up mudrock (Plate 8). Almost all other rollers, e.g. vibrating, flatwheel, tamping and pneumatic, were mentioned for further compaction. The sheepsfoot roller is not popular and is considered more suitable for clayey materials.

3.3.11 Stabilization (chemical and mechanical)

Relevant questions:

What stabilizing agents did or do you use?

In which layers and under which circumstances are they used? Have you got any recommendations in this regard?

The following emerged:

(a) Almost everyone considered lime to be the proper chemical agent for stabilizing mudrock.

(b) As far as chemical stabilization is concerned, provinces differ in their approach.

The Cape Provincial Administration is against stabilization if the standards can be reached with natural material or if they can be reached by mechanical stabilization, e.g. by the addition of a binder. In the Orange Free State mudrock is not used in layers which are stabilized and in the Transvaal, Natal and in roads under the jurisdiction of the National Roads Branch, subbase materials are always stabilized chemically.

(c) Similar differences exist in the case of mechanical stabilization. It is quite common in the Cape Province where the admixture of a sandy river deposit is especially popular. Mechanical stabilization is not common in any of the other provinces although some people have had experience of this.

(d) Some people are of the opinion (see 3.3.4) that mudrock should not be used in the pavement layers such as subbase and selected layers, and stabilization therefore does not come under consideration.

3.3.12 Protection and improvement of mudrock in construction

Relevant question:

Are any special efforts made during construction to protect the mudrock material? Do you, for example

(a) use a coarse layer at the bottom to prevent the movement of moisture into the overlying layers?

(b) use soil on the slopes and on top to prevent ingress of moisture into the pavement?

(c) stabilize with lime or cement to reduce the plasticity?

(d) mix with coarser and harder material to improve the grading and quality?

(e) use any other methods?

Methods of improvement such as chemical and mechanical stabilization are used (see 3.3.11), but methods of protection such as the use of coarse, durable material at the base of the fill, or compacted layers on the flanks to keep the moisture regime constant, are very seldom used. Coarse dolerite or sandstone below the fill is sometimes used in the Orange Free State. Topsoil is occasionally used on the sides of fills but mainly for establishing vegetation.

3.3.13 Use of colliery mudrock for road building

Relevant question:

Do you know anything about the use, or investigations into the use of colliery mudrock in southern Africa?

Mudrock from colliery spoil is used in some overseas countries but in South Africa its use seems minimal up to the present. It has, however, been used to a limited extent in northern Natal.

Two basic problems were mentioned. The first is that carbonaceous mudrock usually contains pyrite, especially in joints in the rock. This leads to the formation of sulphates and sulphuric acid when in contact with air and water. Such materials cannot be stabilized successfully and also cause the deterioration of cement structures such as drainage pipes. The second problem is that these materials can ignite spontaneously.

The spoil heaps apparently consist of either mudrock associated with the coal beds being mined or a very low-grade coal. There are also two types of heap, namely heaps consisting of fresh material, and burning or burnt heaps. The burnt material is probably a better roadbuilding material as it has been partially decarbonised and slightly metamorphosed by the burning.

3.3.14 Slaking or disintegration

Relevant question:

Have you encountered mudrocks which disintegrate into a clay or into small pieces if exposed to the atmosphere for a certain time? Can you name any areas or roads where this occurred? Do some of the mudrocks change to a clay without breaking into small blocks first?

This is an important aspect of mudrock which is responsible to a large degree for the uncertainty about the quality of the material. The survey shows that there are differences of opinion about the occurrence, manner, etc. of the break-down of the material. Most people are aware of the fact that certain mudrocks break down when exposed to the atmosphere but there was no agreement as to which types do so and whether the process stops at a certain grain size. Some people are of the opinion that the break-down continues until the material reaches coarse sand size while others think that the process continues until the material becomes a clay.

Some aspects on which there is reasonable agreement are:

(a) that a high percentage of mudrocks from the Karoo Supergroup exhibits the break-down phenomenon;

(b) that the rocks do not break down in the same manner. Some take a long time to start breaking down while others, such as those in the Burgersdorp and Elliot Formations break down quickly and sometimes form a clay or silt;

(c) that the mudrocks of the Bokkeveld Group and of the Transvaal Sequence do not exhibit the break-down phenomenon. A few persons are, however, of the opinion that the Bokkeveld mudrocks do sometimes break down.

An important aspect is that there is strong evidence that the process stops or is greatly inhibited as soon as the material is enclosed and covered in a road.

3.3.15 Information required

Relevant question:

Do you think that the present knowledge, techniques or recommendations are adequate to exploit mudrocks fully?

The majority of people interviewed think that our knowledge about the road building properties of mudrock is inadequate. People who have been involved in detailed investigations, such as for tunnels, are especially aware of the lack of knowledge on the engineering properties of southern African mudrocks.

The most important need is for a test or tests to determine the behaviour or quality of the material for classification purposes. A few people consider mudrock to be a special type of material whose behaviour should be determined by special tests, in addition to the current tests.

3.3.16 Future use of mudrock

Relevant question:

Do you foresee a forced increase in the use of mudrock in the near future owing to the scarcity or unavailability of other materials in certain areas?

The feeling in Natal and the Cape Province is that mudrock is already utilized fully and that its use can only increase if it is used in the base as well. In the other provinces and in South West Africa-Namibia the opinion is that its use will probably increase in certain areas.

3.4 Summary

There was a variety of opinions on almost every aspect. This is probably due to a lack of communication between users and because of a lack of published data. It is hoped that this survey would stimulate further discussion.

The conclusions of the survey can be summarized as follows:

(a) The terminology used has only local significance and this hampers discussion. A logical system of classification is given (see 2.2) and this should be followed to avoid misunderstanding.

(b) Mudrock is one of the most important road building materials in southern Africa and especially in South Africa. It is very common in all the provinces, except in the Transvaal and South West Africa-Namibia. Zimbabwe-Rhodesia has very little of the material.

(c) Opinions about the quality of the materials vary. In some provinces it is in common use in the subbase.

(d) There is no salient problem related to construction with mudrock, but the slaking or disintegration phenomenon causes most concern. Stability problems occur in cuttings in the coastal regions of Natal.

(e) The material is subjected to the standard road building tests but there is a need for further tests for its classification.

(f) Cuttings and borrow pits in mudrock can be excavated using rippers. During compaction the grid roller is very suitable for breaking up the material.

(g) Lime is generally used if the material is stabilized chemically. Mechanical stabilization is very popular in the Cape Province.

(h) The disintegration or slaking of mudrock is not a general phenomenon. The type and speed of disintegration also varies.

(i) Mudrock is already utilized fully in certain areas and an increase in its use is predicted in areas where it has been used to a lesser extent.

Plate 1: Disintegration of Ecca shale at Peter Road cutting on outer ring road, Durban

Plate 2: Slaking of mudstone of the Elliot Formation in road cutting between Ladybrand and Clocolan

Plate 3: Variety of rock types and qualities in road cutting at Nelspoort near Beaufort West

Plate 4: Erosion of mudstone of the Elliot Formation between resistant sandstone layers on the road between Lady Grey and Barkly East

Plate 5: Slips of vegetation and topsoil on slope between Ficksburg and Fouriesburg

Plate 6: Slip of large volume of material on inclined bedding plane in road cutting at Peter Road, outer ring road, Durban *(Photo: D. Weston)*

Plate 7: Drilling and blasting of road cutting between Boston and Merrivale in Natal (Sampling point for M1)

Plate 8: Grid roller being used for construction with mudrock on road between Mooi River and Greytown

CHAPTER 4

SURVEY OF RELATED WORK

4.1 Introduction

In a study such as this where the aim is to provide sound classification tests, it is important to review similar studies. This was done by summarizing these publications under appropriate headings (Venter, 1978b); forty investigations were summarized in this way.

The general conclusion was that no single test or combination of tests was ideal. A particular test performs well in one study but not in another. The inability of any particular test to perform satisfactorily throughout is understandable as the problems being investigated and the rock properties themselves are very variable.

While the survey of similar work therefore could not provide clear indications of which tests should be used for mudrock classification, it did provide a list of methods and information about the performance of the tests allowing one to draw up a comprehensive test programme.

One of the problems in evaluating the performance of test methods in any particular study is the variety of methods used to interpret results. The results of any particular test may be compared statistically with a combination of other test results. Samples can also be rated visually into groups, such as good, fair or poor, or more specific performance figures can be assigned to them. The ability of each test to predict these can then be calculated. Linear regression analyses are often used in these comparisons; and here some people consider a correlation coefficient of 0,6 to be good while others base their recommendations on even lower values. Some studies involve the testing of only a few similar samples while others involve hundreds of samples.

4.2 General rock durability studies

Drew and Woods (1970) investigated the durability of granite rip-rap for shore protection. Some granites failed in practice although they complied with the California specifications. The principal cause of the

rapid deterioration was a clay-like mineral in the granite which expanded and led to the disintegration of the rock. Drew and Woods used various tests. They found that the Los Angeles abrasion and the Deval machine abrasion tests basically determined abrasive resistance and cannot be relied on to predict weathering. The sodium sulphate soundness test acted as an accelerated mechanical weathering test but did not measure the resistance to chemical weathering. A wetting and drying test pinpointed rocks in which the decomposition of hornblende to the expansive clay mineral was well advanced. Compressive strength, sulphuric acid, toughness and autoclave tests did not give promising results. There was a general correlation between absorption and degree of weathering. The authors concluded that poor rock can pass the existing specifications and that good rock can fail them. They proposed that specific gravity, absorption, Los Angeles abrasion, Deval abrasion, soundness and wetting and drying tests should be used and proposed tentative limits.

De Puy (1965) investigated durability tests for various geological materials used as rip-rap in dams in the United States. Results were evaluated by comparing individual tests against a rock quality (petrographic) index and against combinations of other test results. These methods of rating cause bias, e.g. a rock strength test will obtain a higher rating if the results of other rock strength tests are included in the combination. The conclusions should therefore be viewed with this in mind. In this study, petrographic examination, bulk specific gravity and absorption were rated as very good indicators of rock quality. The Schmidt hammer test rated well while compressive and tensile strengths are considered to be valuable for indicating weaknesses in rock. Sodium sulphate soundness did not rate well and Los Angeles abrasion rated very poorly. The results from ultrasonic disaggregation rated below average but it is recommended that this test be considered for future development.

Platts and Lloyd (1966) carried out a study in Alaska to find a simple test to predict the breaking-down (degradation) characteristics of base and subbase material. Various degradation type tests were used. These included the Oregon air degradation test, the Washington degradation test, the California durability test, the Idaho kneading compactor degradation test, the Idaho rattler degradation test and the Alaska degradation test. The results were compared with visual observations of the break-down of the aggregates at various stages of construction. It was

found that the Washington degradation test results correlated excellently with the observed field behaviour. The results of the Oregon air degradation test correlated fairly well for the better materials whereas the other tests' results did not correlate at all. The Washington degradation test is therefore recommended for use in Alaska.

Smith et al (1967) carried out an extensive and well-planned durability study on material for rockslope protection in California. The objectives were to determine how the results of specification tests relate to performance, to recommend changes to specifications and test procedures and to investigate new test methods. The rocks investigated were grouped into intrusive, volcanic, metamorphic and sedimentary categories. The specification tests, sodium sulphate soundness, Los Angeles abrasion, specific gravity and absorption tests were done and in addition, California durability, wet-dry, freeze-thaw and rapid wet abrasion tests. Results were compared with the field performance ratings. Some of the important conclusions were: sodium sulphate soundness losses were highest with the sedimentary rocks, the Los Angeles abrasion test should be discontinued and absorption is dependent on the grading of the sample. The limited data available for the California durability test indicated that this may be a useful test. The wet-dry and freeze-thaw tests did not show promise but the rapid abrasion test did.

The findings of the above study were followed up and more experimental work was done by Smith et al (1969). The main objectives were to develop specifications for the California durability test, a test method and specifications for the rapid wet abrasion test, and a formula for a durability-absorption ratio (a mathematical combination of durability and absorption results). As in the former study the results were compared with the field performance evaluation. The California durability and rapid wet abrasion tests were found to be more accurate in their predictions than the "specification" tests but the durability-absorption ratio rated even better. This ratio was therefore recommended for adoption for quality control.

Miles (1972) carried out a well organized study to find a test which best predicted the performance of most rock types. The specified tests for rip-rap evaluation in Utah were used; these were the Los Angeles abrasion, sodium sulphate soundness and water absorption tests. In addition accelerated soundness tests, using ethylene glycol, potassium

acetate, ammonium acetate and dimethyl sulfoxide solutions for soaking the samples, were done. Regression analyses were used to compare the results with a visual assessment of field performance rating carried out by ten experienced people. The sodium sulphate test gave the best correlation (r^2 = 0,82). The absorption and abrasion tests were less accurate (r^2 = 0,72 and 0,69 respectively) whereas the accelerated soundness tests gave worse correlation coefficients. The results were also grouped into the sedimentary, metamorphic and igneous classes and correlated again. Here it was found that for the sedimentary rocks the results of the sodium sulphate soundness tests showed the highest correlation (r^2 = 0,87). For igneous rocks the results of the absorption test (r^2 = 0,99) and for metamorphic rocks the results of the abrasion test (r^2 = 0,87) showed the highest correlation. Miles therefore concluded that the sodium sulphate soundness test gave the single best estimate of performance but that tests were discriminatory as far as rock types are concerned. He therefore recommended that sedimentary rocks should be evaluated using the sodium sulphate soundness test, while for igneous rocks the absorption test should be used and for metamorphic rocks the abrasion test.

Farjallat et al (1974) did durability studies on samples from dams and other sites in Brazil. Samples were subjected to "ageing" tests to measure their rate of weathering. These consisted of repeated sulphate soundness, wetting-drying, saturation drying with ethylene glycol, soxhlet leaching, and outdoor exposure tests. The performance was measured by doing Treton impact tests before, at various stages during, and on completion of the ageing tests. These results were used to construct curves of strength deterioration with time. From the curves it is evident that the sodium sulphate soundness cycles usually lead to a marked decrease in strength. The ethylene glycol and soxhlet tests also affect some of the samples drastically. No indications of how these curves can be used are, however, given.

A study involving detailed work on the ultrasonic probe was done by Saltzman (1975). Various rock types were tested to develop techniques for predicting the performance of stone used in protective blankets. In addition to the development of the ultrasonic test, other tests, such as the determination of the bulk and apparent specific gravities, absorption, Schmidt hammer impact strength value, certain elastic constants, unconfined compressive strength, Los Angeles abrasion, freeze-thaw, ethylene

glycol and petrographic analyses, were carried out. Linear regression was used to compare the results of these tests.

Determinations of specific gravities and the ethylene glycol test were found to be unacceptable whereas the testing of absorption, some elastic constants, and unconfined compressive and tensile strengths were considered conditionally acceptable for determining durability. The ultrasonic test was the closest to an objective engineering test and the results from this test could be correlated with those from the freeze-thaw and Schmidt hammer tests. Correlation coefficients were generally below 0,6. Saltzman gives criteria for the selection of stone using the ultrasonic, Schmidt hammer, Los Angeles abrasion and freeze-thaw tests.

Gaskin and Raymond (1976) investigated the prediction of the field behaviour of ten types of railroad ballast in Canada. They contended that to perform satisfactorily ballast should (i) withstand weathering without breaking down, (ii) withstand loading without breaking down, (iii) resist lateral movement (be stable), and (iv) remain free-draining. Field and laboratory evaluations were carried out. The field evaluation consisted of a break-down rating and a stability rating whereas the laboratory evaluation included specific gravity, absorption, Los Angeles abrasion, sodium and magnesium sulphate soundness, crushing value, freeze-thaw and Mohs hardness tests. It was concluded that the soundness tests are able to predict chemical break-down and the freeze-thaw test break-down as a result of temperature changes. The mechanical Los Angeles abrasion, crushing value and Mohs hardness tests can indicate break-down caused by repeated loads whereas sphericity and elongation are important factors relating to stability. Limits for the above tests are proposed by the authors. The gradings of the ballast samples were generally not ideal for drainage but more research is required.

4.3 Mudrock durability studies

Relatively few attempts to investigate specifically the engineering testing and classification of mudrocks were made before 1970. Recently, however, there has been an escalation in studies of this kind. Although the vast majority of these studies have been done in the United States of America, very relevant work has also been done in Australia.

Shergold and Hosking (1963) did tests on argillaceous and gritty rocks to find the most suitable test for recognizing the rock types which break up excessively under compaction. Modified 10 per cent FACT, aggregate impact and sodium sulphate soundness tests were used, as well as specific gravity and absorption tests. The results were compared with a three level rating done by engineers who were well acquainted with the materials. No correlation was found with the water absorption and specific gravity test results and only a low correlation with the modified sodium sulphate soundness test results. The modified aggregate impact and 10 per cent FACT tests, done on saturated samples, were most satisfactory and tentative limits were set for these tests.

Croft (1966) tried to determine the relationships between composition, test results, and the performance in pavements, of mudrock in New South Wales, Australia. Various tests were performed. These included X-ray mineralogical analysis, dye adsorption using methylene blue, chemical weathering by leaching with water, physical weathering tests such as wet-dry cycles and tumbling in water, and mechanical strength tests such as the aggregate impact and wet ball mill. It was found that the methylene blue adsorption test reflected the nature of the clay minerals. The results of the mechanical strength tests (aggregate impact and wet ball mill) showed a relation to the total clay content. The wet ball mill test was recommended as it is simpler than the aggregate impact test.

Gamble (1971) did a study aimed at proposing an engineering classification for mudrocks based on significant engineering properties. Slaking behaviour and properties relating to swelling and slope stability were considered to be of particular importance in this study. In addition to determining the Atterberg limits, natural moisture content and specific gravity, tests such as swelling strain, swelling pressure, sodium sulphate soundness and X-ray mineralogical analyses were done. A detailed study was also made of the slake durability test and a two-cycle test was eventually recommended. Other conclusions were that the slake durability index and the natural moisture content are inter-related and that the clay mineralogy strongly influences the plasticity index (PI), strength properties and the slake durability index. Samples with a low to medium PI (from 0 - 25 per cent) usually contained illite and chlorite whereas intermediate durability samples usually had illite and mixed-layer clay minerals. Gamble recommends the two-cycle durability test combined

with PI for classification purposes.

Deo (1972) investigated tests for the use of mudrocks in embankments in Indiana because of the degradation of these materials in this type of construction. The tests used were divided into four types: (i) degradation-type tests including modified slake durability, sodium sulphate soundness and abrasion tests; (ii) soil type and standard identification tests including Atterberg limits, grain size and X-ray analysis; (iii) compaction and load deformation tests which were variations of CBR tests; and, (iv) miscellaneous tests, which included absorption with time, bulk density and a fissility number. From correlations between the test results he came to the conclusion that the slaking, modified soundness, compaction, bulk density and fissility number tests are useful. He therefore proposes a classification system for mudrocks in embankments using a one-cycle slaking test, the modified slake durability test (dry and soaked) and the modified soundness test.

Laguros (1972) investigated the problem of mudrocks whose properties change after they have been removed from the quarry source. The objective was to establish a systematic testing method for the classification of mudrocks for highway construction in Oklahoma. Extensive tests, which included Atterberg limits, grain-size analysis, specific gravity, pH and compaction, were done. These results were used to group the samples and select six representative ones. The six samples were submitted to ultrasonic disaggregation and sand equivalent tests, and to soaking tests in water and hydrogen peroxide. Electron micrographs and X-ray diffraction and fluorescence were used to study the effects of the tests on the fabric and mineralogy of the samples. The sand equivalent test was rated "important". The ultrasonic bath effectively disaggregated the samples and the amount of minus 2 μm clay in the samples was considered to be a "very important" factor. The materials were classified into "problem" and "non-problem" materials, based on the percentage of clay and silt in the samples. An ultrasonic treatment of one hour was recommended for further classification of the "problem" mudrocks.

Laguros et al (1974) continued work on the ultrasonic treatment of mudrocks. In this interesting study they tried to establish how well short-duration ultrasonic cavitation can predict long-term weathering of mudrocks. Identical samples were subjected to two years' outdoor weathering and various periods of ultrasonic cavitation in a tank installed in a

laboratory. Grain-size analysis, the determination of liquid and plastic limits and X-ray diffraction were used to monitor the changes before and after the treatments. It was found that both ultrasonic treatment and field weathering produced disaggregation of mudrocks. Changes in liquid and plastic limits after two years' field weathering corresponded to changes after about one hour of ultrasonic treatment. No change in the nature of the clay minerals was caused by either the field weathering or the ultrasonic treatment. The authors concluded that ultrasonic treatment simulates field weathering as far as engineering properties are concerned. The test may, therefore, prove useful for predicting the durability and weatherability of mudrocks.

Reidenouer (1970) and Reidenouer et al (1974) carried out an extensive study on the classification of shales for road construction. The use of this type of material is severely restricted in Pennsylvania, and the object of the study was to develop tests and a classification which could be used to distinguish between durable and non-durable materials. Many tests were carried out during these studies. The later publication is a continuation of the earlier one. The same and some additional tests were done on extra samples in the second study. Some of the initial conclusions were modified when these results were added.

The tests were divided into durability, property determination and geological hand-specimen and mineralogical studies. Innovative tests in this research included various absorption tests, such as rate of absorption and absorption of water in a vacuum, Coulter counter particle size analysis and the calculation of percentages constituent minerals from quantitative mineralogical X-ray diffraction results and chemical analyses. A durability factor (DF) combining the results of a gyratory compaction test, the Washington degradation test and a wet-dry test was calculated and the results from the various tests were compared with this factor. The lamination thickness of the shales related well with the DF as did the clay factor (a combination of estimates of the quantities of different clay minerals). The DF showed the best relation with the ultrasonic test results and this test was therefore considered the best test for the shales. Other interesting observations were that very few samples yielded fines with a plasticity index and that shales with significant amounts of calcite or dolomite were fairly durable. The classification system recommended includes observation of lamination thickness, soaking in ethylene glycol and a modified Washington degradation test.

Olivier (1979a) developed a system for the classification of mudrocks (and other related sedimentary rock types) during the construction of the Orange-Fish Tunnel. This empirical system is known as the Geodurability Classification and is based on different, arbitrarily chosen ratios of the uniaxial compressive strength and the "Duncan" free swelling coefficient. The durability rating of the rock material is given in terms varying from "excellent" (Class A) to "very poor" (Class E).

Chapman (1975) compared various classification systems, i.e. those of Gamble (1971); Deo (1972); Reidenouer et al (1974); Morgenstern and Eigenbrod (1974) and Saltzman (1975). No system was found to be ideal for the six mudrocks tested. Tests such as slake index, slake durability, rate of slaking and Los Angeles abrasion gave a reasonable spread of values. Chapman is of the opinion that since mudrocks in Indiana, where the study was done, are mainly of the softer type, tests such as slake index, slake durability and rate of slaking should be used in a tentative classification system.

4.4 Discussion

The study by Chapman (1975), although done on a limited number of samples, illustrates the problems of most classification systems. A great number of studies start with similar objectives and include similar tests, but the conclusions and recommendations are very different. There are many reasons for this, perhaps the most important being the difference in the samples used.

From analysis of these research programmes it seems that, for this type of research, the following facts are important:

(a) There is no one test which performed well in all the studies. It is therefore impossible to select an ideal range of tests for a particular study. The best one can do is to include all tests recommended for classification purposes in the various studies and add to them tests which generally perform above average as far as correlations are concerned. Well known tests, already accepted in South Africa or other parts of the world, should also be included. If they are found to be acceptable, they should obviously be preferred as the method and apparatus are more freely available.

(b) The samples selected for a study should include the whole spectrum of sample types for which the classification system is intended. If this is not done there is a very strong possibility that the conclusions or classification system will be wrong or of limited use.

(c) The tests should be done with care. Major studies have been done in which no significant relationships between important parameters were found. However, even a slight inaccuracy in test results, particularly where a small number of samples is used, could mask a significant relationship.

CHAPTER 5

TEST METHODS

5.1 Study of test methods

Table 5.1 was compiled to assist in the selection of tests and test methods and lists types of test and publications in which these are described. The method used cannot always be given in the table as there are numerous deviations from the test methods prescribed by organizations such as the American Society for Testing and Materials, e.g. in the case of the sodium or magnesium sulphate soundness tests the table gives references to studies in which this type of test has been used or is discussed. Test methods ASTM C-88 or AASHTO T104 were generally employed but some of the investigators listed, used modified (usually shortened) versions of these methods.

TABLE 5.1: TEST METHODS WITH RELEVANT REFERENCES

Type of test	Used or discussed by - reference	Remarks
Schmidt hammer	De Puy (1965); Aufmuth (1974); Chapman (1975); Saltzman (1975)	Various types of hammer probably used
Slake durability test	Gamble (1971); Deo (1972); Aufmuth (1974); Chapman (1975); Wood & Deo (1975); Franklin & Chandra (1972)	Used slake durability apparatus but some modified methods
Rate of slaking	Morgenstern & Eigenbrod (1974); Chapman (1975)	
Slake index	Chapman (1975)	
Visual observation of slaking	Deo (1972); Heley & MacIver, (1971); Wood & Deo (1975)	
Quantitative slaking	Morgenstern & Eigenbrod (1974)	

TABLE 5.1: (continued)

Type of test	Used or discussed by - reference	Remarks
Specific gravity and absorption	Drew & Woods (1970); Shergold & Hosking (1963); Dunn (1963); De Puy (1965); Breese (1966); Smith et al (1967); Smith et al (1969); Reidenouer (1970); Reidenouer et al (1974); Gamble (1971); Heley & MacIver (1971); Laguros (1972); Miles (1972); Saltzman (1975); Gaskin & Raymond (1976)	Usually done according to standard methods, such as ASTM C-127 and determining bulk and/or apparent specific gravity
Absorption with time	Dunn (1963); Deo (1972); Reidenouer et al (1974)	
Absorption in vacuum	Dunn (1963); Reidenouer et al (1974)	
Los Angeles abrasion	Drew & Woods (1970); Erickson (1958); Yedlosky & Dean (1961); De Puy (1965); Breese (1966); Smith et al (1967); Deo (1972); Miles (1972); Reidenouer et al (1974); Chapman (1975); Saltzman (1975); Gaskin & Raymond (1976)	Usually standard methods such as ASTM C-131 or AASHTO T-96
Wet ball mill	Melville (1948); Breese (1966); Croft (1966); Smith et al (1969)	Wide variety of methods used
California durability test	Breese (1966); Platts & Lloyd (1966); Smith et al (1967); Smith et al (1969)	California test method 229
Washington degradation	Breese (1966); Platts & Lloyd (1966); Marshall (1967); Reidenouer (1970); Reidenouer et al (1974); Chapman (1975)	
Sand equivalent	Erickson (1958); Platts & Lloyd (1966); Laguros (1972)	
Ethylene glycol soaking	Reidenouer (1970); Miles (1972); Reidenouer et al (1974); Farjallat et al (1974); Chapman (1975); Saltzman (1975)	

TABLE 5.1: (continued)

Type of test	Used or discussed by - reference	Remarks
Ultrasonic cavitation	De Puy (1965); Laguros (1972); Laguros et al (1974); Reidenouer et al (1974); Chapman (1975); Saltzman (1975)	No standard method used
Methylene blue adsorption	Croft (1966); Webber (1972)	
Aggregate impact	Shergold (1955); Shergold & Hosking (1963); Croft (1966)	Method in BS 812 or similar
Treton impact	Farjallat et al (1974)	
10 Per cent fines aggregate crushing test (FACT)	Shergold & Hosking (1959); Yedlosky & Dean (1961); Shergold & Hosking (1963); Loubser (1967)	Standard method but container volume can differ
Aggregate crushing value (ACV)	Shergold (1955); Shergold & Hosking (1959); Gaskin & Raymond (1976)	Method in BS 812 or similar
Mohs hardness	Gaskin & Raymond (1976)	
Sodium sulphate or magnesium sulphate soundness	Garrity & Kriege (1935); Drew & Woods (1970); Dunn (1963); Shergold & Hosking (1963); De Puy (1965); Minty & Monk (1966); Smith et al (1967) Cape Provincial Administration Roads Department (1967); Gamble (1971); Deo (1972); Miles (1972); Reidenouer et al (1974); Farjallat et al (1974); Wood & Deo (1975); Chapman (1975); Gaskin & Raymond (1976)	Various modifications of standard methods ASTM C-88 or AASHTO T-104 used
Wetting and drying (weathering test)	Philbrick (1950); Drew & Woods (1970); Hatcher (1963); Croft (1966); Smith et al ((1967); Reidenouer (1970); Laguros (1972); Reidenouer et al (1974); Laguros et al (1974); Currie et al (1974); Farjallat et al (1974)	Wide variety of methods used

TABLE 5.1: (continued)

Type of test	Used or discussed by - reference	Remarks
Compaction of material	Erickson (1958); Hatcher (1963); Breese (1966); Platts & Lloyd (1966); Reidenouer (1970); Deo (1972); Laguros (1972); Reidenouer et al (1974)	Various methods such as CBR, kneading and gyratory compaction used
Compressive strength	Drew & Woods (1970); Yedlosky & Dean (1961); De Puy (1965); Heley & MacIver (1971); Saltzman (1975); Olivier (1979a)	Testing intact material (not compacted)
Tensile strength	De Puy (1965); Saltzman (1975)	
Wave velocities	Dunn (1963); De Puy (1965); Saltzman (1975)	
Swelling strain	Gamble (1971); Heley & MacIver (1971); Olivier (1979a)	Confined and unconfined samples
Porosity	Yedlosky & Dean (1961); Reidenouer et al (1974)	Various methods and instruments
Estimating performance	Melville (1948); Smith et al (1969); Miles (1972); Currie et al (1974); Gaskin & Raymond (1976)	Estimation of performance of rocks to rate test results
pH	Laguros (1972)	
X-ray diffraction mineralogical analysis	Croft (1966); Reidenouer (1970); Laguros (1972); Deo (1972); Laguros et al (1974); Morgenstern & Eigenbrod ((1974); Reidenouer et al (1974)	Mineralogical and sometimes clay mineralogical analysis
Repeated load testing	Yedlosky & Dean (1961); Currie et al (1974)	To study performance or wear of aggregates

5.2 Pilot studies

5.2.1 General

The purpose of the pilot studies was to investigate the general applicability of certain tests; to develop other test methods and to study the behaviour of a mudrock sample. This information was needed for the compilation of a detailed testing programme. In addition, standardized methods of crushing rock for the tests had to be developed.

Unless otherwize stated, all the pilot studies were carried out on sample M1, a clay-shale from the Ecca Group (Table 6.1).

5.2.2 Influence of mesh size on slake durability index

5.2.2.1 Introduction

The slake durability test involves the rotation of six lumps of rock in a drum partly immersed in water. The slake durability index is the percentage of material left in the drum after a cycle of 200 revolutions in ten minutes. The ISRM (1972b) specifies the slake durability index as the percentage material remaining in the drum after two cycles.

The outside of the drum consists of 2 mm mesh. Olivier (1976a) is of the opinion that many mudrocks disintegrate into small fragments which are larger than 2 mm and although almost complete break-down of the rock may occur, the slake durability index can still be high. The Geomechanics Division, NMERI, CSIR actually use a 4 mm mesh on their slake durability drums. Franklin and Chandra (1972), who developed the test and apparatus, did not experiment with various mesh sizes but performed grading analyses on the broken-down material and decided on the 2 mm mesh. They mentioned, however, that one of their samples broke down to "pea-size" fragments and yielded a misleadingly high slake durability index, even though the material had completely broken down. A description of the sample and possibly further sieve analyses were suggested as a way of overcoming this problem.

Because of the lack of information about the influence of different mesh sizes, particularly in South Africa, it was decided to conduct some

experiments with different types of local, fine-grained sedimentary rocks.

5.2.2.2 Method

A slake durability apparatus with end plates onto which different sieves could be fitted was constructed by the NITRR. Four different mesh sizes were used, i.e. 2, 5, 10 and 15 mm (Plate 9).

Six samples, numbered A to F, collected in the eastern part of the Orange Free State, were used. They ranged from fine-grained sandstones to mudstones. Duplicate portions of one sample (F) were tested to determine the importance of the shape of samples. One of these consisted of angular fragments whereas the shape of the other was roughly spherical. This was done because the test method specifies rounded, roughly spherical lumps and these are often very difficult to prepare.

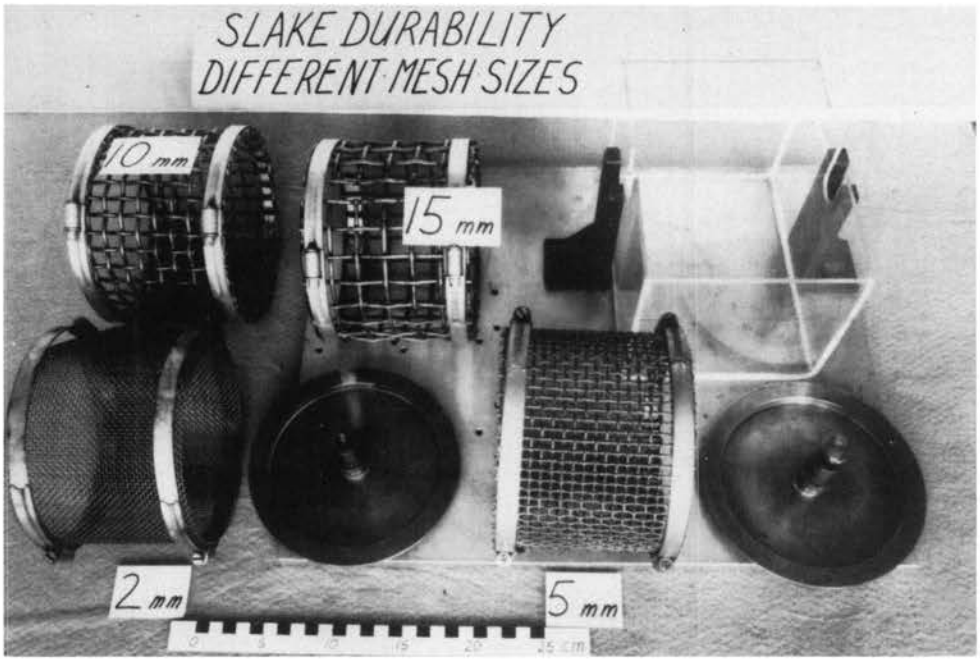


Plate 9: Apparatus used for testing the influence of mesh size on the slake durability index

Various numbers of slake durability cycles were carried out on the six samples. Some samples broke up completely within one or two cycles whereas others lost material gradually. The slake durability indices for the first and second cycles are given in Table 5.2 and Figures 5.1 and 5.2 illustrate the changes during slake durability cycles in the more durable samples for the various mesh sizes.

TABLE 5.2: SLAKE DURABILITY INDICES FOR THE FIRST TWO CYCLES USING VARIOUS MESH SIZES

Sample number		A	B	C	D	E	F(i)	F(ii)
After first cycle	2 mm	0	2,6	11,8	73,2	88,5	98,2	98,3
	5 mm	1,6	4,6	15,3	75,6	89,1	98,2	98,1
	10 mm	0,4	6,7	19,4	67,0	87,3	97,9	97,7
	15 mm	0,9	5,2	22,5	77,1	91,8	97,9	98,3
After second cycle	2 mm	0	0	1,0	60,3	79,4	96,7	97,0
	5 mm	0	0,7	1,5	62,4	78,9	96,7	96,7
	10 mm	0	0	2,4	57,3	78,3	96,3	96,0
	15 mm	0	0	1,2	62,6	85,1	95,9	96,2

5.2.2.3 Discussion

For the purposes of discussion the samples can be divided into three categories.

(a) Fast-slaking materials: (Samples A, B and C)
Here the slaking of the material in water appears to be the most important factor. Agitation plays a lesser role. For these materials Table 5.2 shows surprizingly, that the losses generally increase as the mesh size decreases. The 2 mm mesh is the most severe, probably because the finer mesh with wire of a thin diameter is more abrasive.

(b) Medium-slaking materials: (Sample D)
In the case of this sample slaking still plays a role but agitation and abrasion are more important. Figure 5.1 shows that losses are

the highest in the 15 mm mesh drum. The losses using the other mesh sizes were similar but the 2 mm mesh drum yielded the smoothest curve, i.e. constant losses in every cycle.

(c) Very slow or non-slaking material: (Samples E and F)
With these materials agitation and the accompanying abrasion are the most important factors. Slaking plays a minor role. The curves tend to be more linear, as the mass lost during each cycle is the result of a constant amount of abrasion applied to the samples. The losses for the four mesh sizes are similar and probably lie within the precision of the method.

Figure 5.2 shows the behaviour of the duplicate portions of one sample which were shaped differently to determine the influence of sample shape on slake durability indices. In the first cycle the angular lumps lost slightly more material than the rounded lumps. An average of 11,1 per cent of the angular portion was lost as against 9,7 per cent for the rounded portion (averages for the four mesh sizes). This slight difference is to be expected as protruding sharp corners would abrade more easily. In later cycles the results were very similar for the two samples.

5.2.2.4 Conclusions

The available results show no apparent reason why a change should be made in the mesh size. With fast-slaking materials the 2 mm mesh is the most severe and for medium slaking materials its effect is between those of the other mesh sizes. For non-slaking materials the effect is generally less severe, but since there are almost no real quantitative differences between the results, mesh size is not important enough to warrant changes to the method.

Rounding of corners and protruding edges does not affect the results to any great extent. Shape made very little difference to the non-slaking sample tested and the effect would be even less important with fast-slaking samples. Shape may, however, influence medium-slaking samples and samples should therefore generally be shaped spherically and the corners rounded as far as possible in a reasonable sample preparation time.

An aspect which could not be investigated here because of the way in which samples A to F reacted, is the behaviour of samples which disintegrate into hard fragments. Sample M1, the first sample selected for the mudrock study, was such a sample and was therefore used in further investigations of the slake durability test.

5.2.3 Slake durability investigations on sample M1

5.2.3.1 Introduction

The investigation done in Section 5.2.2 did not include a disintegrating sample. It was therefore decided to carry out further tests on sample M1, the first sample taken for the mudrock study. The former study showed that the larger openings did not produce substantially different results from the smaller openings and tended to be more conducive to erratic losses. In this investigation only the 2 mm and 5 mm mesh drums were used. Olivier (1976b) suggested that a drying temperature of 105 °C could change the micro-structure of mudrocks and it was therefore decided to bring in another two variables, i.e. drying at 50 °C and 105 °C.

5.2.3.2 Method

The test method prescribed by the ISRM (1972b) was followed except that, in addition, a 5 mm drum was used and the samples were dried at 50 °C. The four portions of M1 (M1a - M1d) were subjected to six slake durability cycles. The way in which each portion was treated is set out in Table 5.3 and the results are presented graphically in Figure 5.3.

5.2.3.3 Discussion

From Figure 5.3 it is evident that there is very little difference in the results from the portions which were dried at 105 °C and the portion tumbled in the 2 mm mesh and dried at 50 °C. The portion tumbled in the 5 mm mesh and dried at 50 °C suffered slightly higher losses but, even for this portion, the difference after six cycles was only three percentage points.

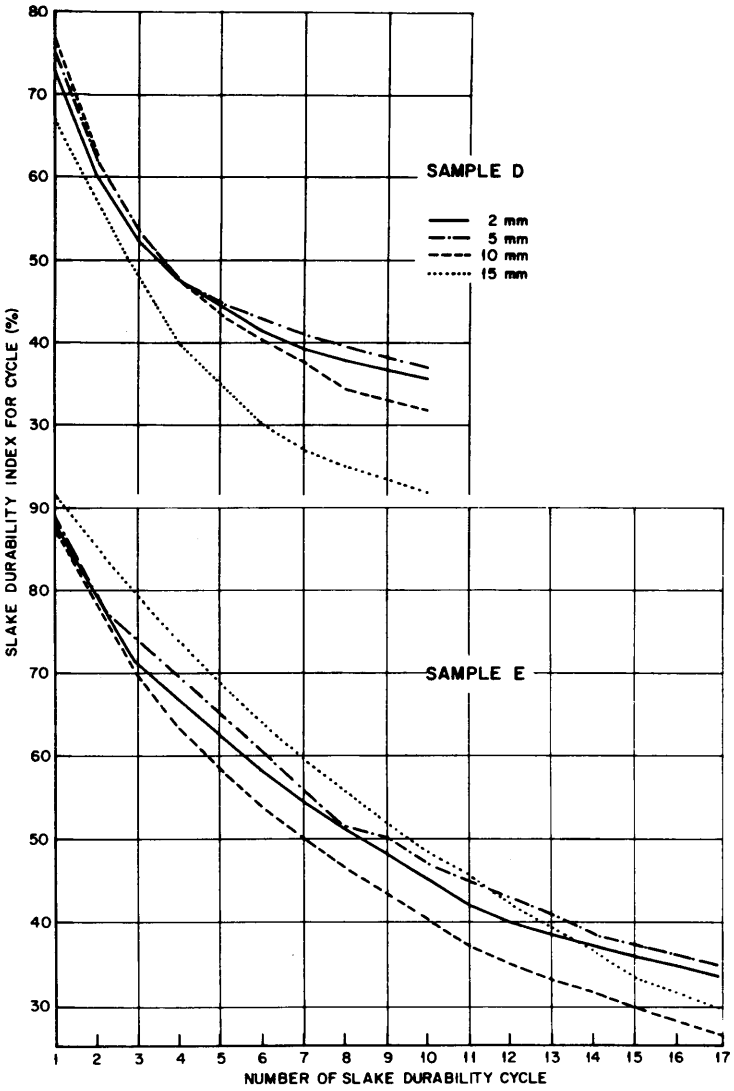


FIGURE 5.1

SLAKE DURABILITY INDICES FOR SAMPLES D AND E

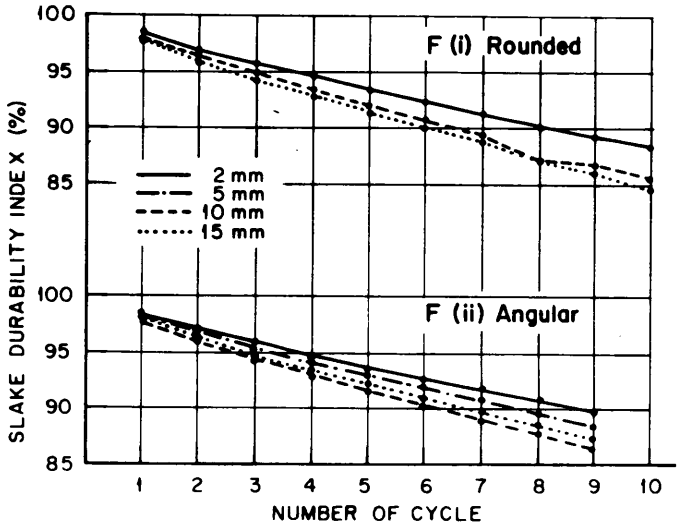


FIGURE 5.2

COMPARISON OF SLAKE DURABILITY INDICES FOR ROUNDED AND ANGULAR SAMPLES

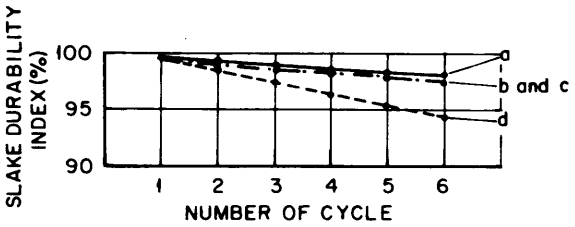


FIGURE 5.3

SLAKE DURABILITY INDICES FOR SAMPLE MI USING DIFFERENT DRYING TEMPERATURES AND MESH SIZES

TABLE 5.3: TREATMENTS FOR SLAKE DURABILITY EXPERIMENT ON M1

Sample number	Mesh size on drum mm	Drying temperature °C
M1a	2	105
M1b	5	105
M1c	2	50
M1d	5	50

5.2.3.4 Conclusions

It was decided to use the standard slake durability method in subsequent tests. The reasons for this decision were:

(a) It is always advantageous to use an international method as this allows comparison with other studies in which the same test has been used.

(b) The test was developed to expose slaking, meaning the break-down of a rock into a sediment when exposed to water. It was not devised to measure disintegration of rocks into hard, larger sized (plus 2 mm) fragments.

(c) The way in which shales and mudstones break down varies to such an extent that a suitable mesh size would have to be determined for almost every new investigation.

For the mudrock investigation it was therefore decided to use the standard ISRM method. Because of the high slake durability index obtained for M1 it was decided to increase the number of cycles to five. To obtain a measure of the disintegration of the plus 2 mm material a sieve analysis was performed on the sample remaining in the drum after the five cycles. The samples were also allowed to cool for 30 minutes after being taken out of the oven. The ISRM (1972b) does not give any directive on this aspect*.

* A stipulation to cool the samples has subsequently been added to the method (International Society for Rock Mechanics. Commission on standardization of laboratory tests, 1979.)

5.2.4 Crushing of samples

5.2.4.1 Introduction

A large amount of crushed rock material is required for tests A1 to A8, B1, B2 (Department of Transport, 1971) and the Los Angeles abrasion and sodium sulphate tests. These requirements and the masses crushed are set out in Table 5.4.

It was necessary to develop a uniform method of crushing the samples to minus 19 mm for the grading, maximum dry density (MDD), optimum moisture content (OMC) and California Bearing Ratio (CBR) tests.

5.2.4.2 Method

Various experiments were performed on the pilot sample M1 before methods of crushing were decided on. About 200 kg of rock lumps were taken out of the plastic bags in which they had been stored since sampling and broken down to 1 to 3 kg fragments using a 6,4 kg hammer. One hundred and twenty kg of rock fragments were selected for the tests where uniform crushing was necessary. The rest of the material was used by taking out the coarse fractions for the Los Angeles abrasion and sodium sulphate tests and dividing the remainder into bags for further crushing for the above and the ACV and 10 per cent FACT tests. A Pegson-Osborn 8 x 5 single toggle breaker at the Transvaal Provincial Administration's (TPA) Roads Laboratory was used to crush the 120 kg sample to minus 19 mm size.

After each crushing, the material was sieved through a 19 mm sieve and the plus 19 mm fraction was crushed again. Five crushings were used after which less than 2 kg of plus 19 mm material remained. This was crushed to minus 19 mm in a smaller crusher at the NITRR. The 120 kg of crushed rock were riffled into the various masses for the tests given in Table 5.4. For the other tests the TPA crusher and the smaller NITRR crusher were used to prepare the various fractions.

During the crushing and sieving the following rules were adhered to:

TABLE 5.4: QUANTITIES NEEDED FOR TESTS

Test no.	Name of test	Fractions needed mm	Mass of fractions needed kg	Mass of material crushed kg
A1 - A6	Grading analysis, liquid limit, plastic limit, linear shrinkage, material passing 0,075 mm sieve, hydrometer analysis	-19	5	
A7	Maximum dry density and optimum moisture content	-19	35	
A8	California Bearing Ratio (untreated) plus wet-dry cycles and more CBRs to follow	-19	45	
Reference sample	Sample for reference purposes	-19	5	
A9	California Bearing Ratio (stabilized with 4 per cent lime)	-19	30	120
B1	Aggregate crushing value	13,2- 9,5	12	
B2	10 % FACT	9,5- 6,7	12	40
ASTM C131-69	Los Angeles abrasion (A-grading)	37,5-26,5	2,5	
		26,5-19,0	2,5	
		19,0-13,2	2,5	
		13,2- 9,5	2,5	20
ASTM C88-73	Sodium sulphate soundness	63,0-53,0	3,00	
		53,0-37,5	2,00	
		37,5-26,5	1,00	
		26,5-19,0	0,50	
		19,0-13,2	0,67	
		13,2- 9,5	0,33	
		9,5- 6,7	0,30	15
			TOTAL	195

(a) The bins and crushers were cleaned thoroughly before each new sample was crushed.

(b) Care was taken not to lose dust when transferring samples from bins into bags or vice versa.

(c) Whenever bags containing crushed samples were not being worked on, they were closed using masking tape. When they were being worked on, the flaps were tucked in. This was done to prevent moisture losses or gains as far as possible. As it was expected that the loss or gain of moisture could play an important part in the behaviour of mudrocks, the samples were always stored in closed plastic bags.

5.2.5 Standard tests (Department of Transport, 1971)

These tests {A1 to A9, B1 and B2 (Department of Transport, 1971)} were carried out on sample M1 to determine if any change should be made to the test methods for mudrock. The standard methods were followed (and therefore a standard procedure) but special instructions were given for each test. The instructions were mainly to ensure that the mudrock samples would be stored in the plastic bags until testing. If drying at 105 °C was required, this was done immediately after the samples had been taken out of the bags and, where possible, testing was done immediately after cooling. If testing had to be delayed, the samples were sealed in plastic bags until they were required.

These precautions were taken as moisture changes could influence the behaviour of the mudrocks. To obtain comparable results it is necessary that all samples should be in an identical state before testing.

All the tests were carried out successfully on sample M1 and the same procedures were therefore adopted for tests on the remaining samples. The tests and results are discussed under the appropriate headings in later Chapters.

5.2.6 Accelerated weathering, using compactions and wet-dry cycles

5.2.6.1 Introduction

The New South Wales Department of Main Roads (1951) and Hatcher (1963), mentioned an "accelerated weathering treatment" for mudrocks which involved ten cycles of wetting and drying followed by Proctor compaction. This "weathered" material was then used for the normal tests. It was felt that a test combining wetting and drying with compaction, would give important information about the road building properties of southern African mudrocks. Weaknesses or cracks which developed during the wetting and drying would be shown up during the compactions by the breaking up of the material.

5.2.6.2 Method

A 35 kg sample of M1 crushed to minus 19 mm was quartered and placed into four rectangular stainless steel containers. These were then oven-dried at 105 °C for 16 - 18 hours before being removed and allowed to cool for two hours. Following this, sufficient distilled water was added to cover the samples in the containers. The samples were allowed to soak for two hours before being put back into the oven for drying at 105 °C. This wetting and drying cycle was repeated ten times. The samples were then submitted to CBR compactions. Modified AASHTO (American Association of State Highway and Transportation Officials), NRB (National Roads Board) and Standard Procter compaction efforts were used. Following this, another ten wet-dry cycles were completed and compactions subsequently carried out. The whole process was repeated four times. Grading, Atterberg limits, and linear shrinkage tests were done at various times during the experiment to obtain information about the rate of break-up of the material. Compactions were performed at optimum moisture content (OMC) for Modified AASHTO compaction throughout the experiment.

5.2.6.3 Discussion

The changes in grading are illustrated in Figure 5.4. This clearly shows that the material broke up steadily throughout the experiment. It shows, for example, that from the fresh sample to the "weathered" sample the percentage passing 13,2 mm increased from 63,3 to 98,8 per cent and material passing 0,075 mm from 1,4 to 8,3 per cent. Hydrometer grain size analyses were performed on the fines of the fresh and weathered material. The results are given in Table 5.5. Substantial increases are shown.

TABLE 5.5: HYDROMETER RESULTS FOR FRESH AND "WEATHERED" M1 SAMPLE

Particle size	Cumulative percentage passing	
	Fresh sample	Final "weathered" sample
0,06 mm	1,5	7,8
0,02 mm	1,2	6,0
0,006 mm	0,8	3,9
0,002 mm	0,4	2,9

Results from Atterberg limits and linear shrinkage tests performed on the samples during the experiment are shown in Table 5.6.

The low values complicated the tests and slightly erratic values could therefore be expected. However, the results show a definite increase in plasticity index (PI) and linear shrinkage due to the wet-dry cycles and compactions.

CBR results for the Modified AASHTO compactions are illustrated graphically in Figure 5.5. Percentage CBR at 2,54, 5,08 and 7,62 mm penetration were plotted. There was a definite increase in strength as the weathering experiment progressed, probably due to improved grading. The freshly crushed rock was very low in fines (1,4 per cent <0,075 mm].

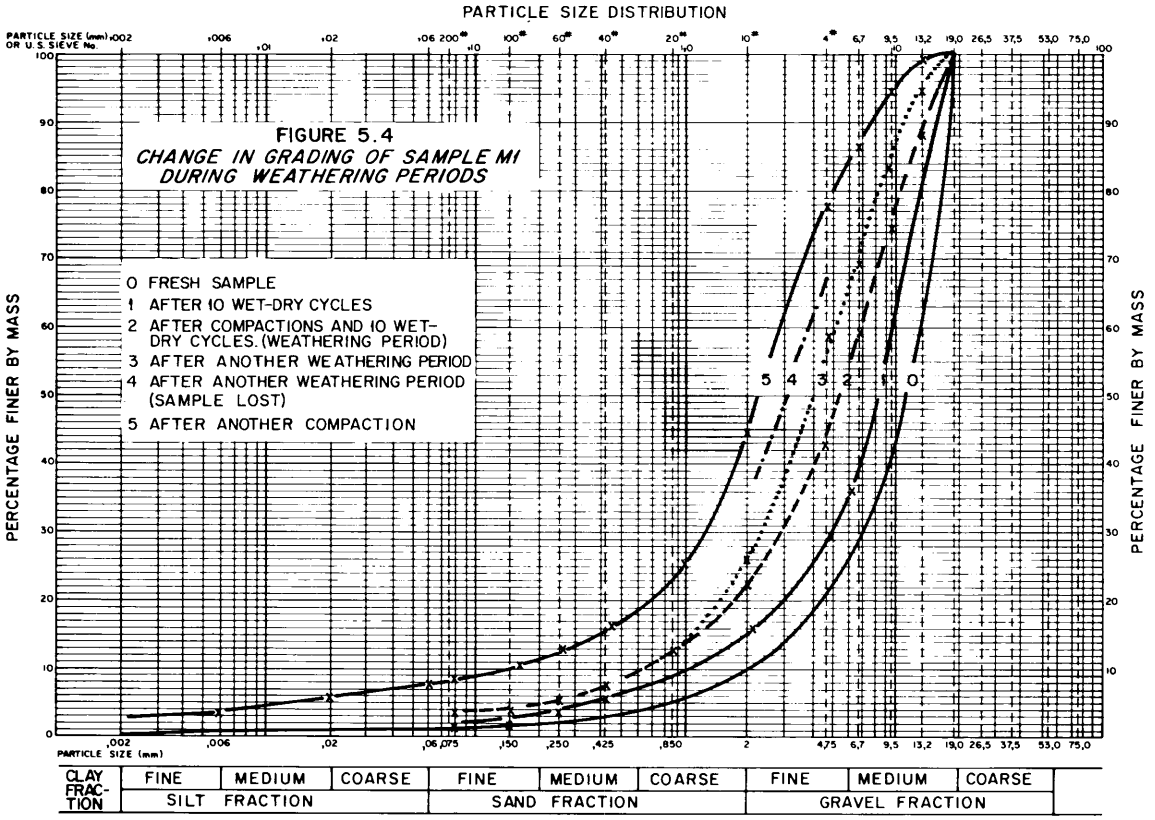


FIGURE 5.4
CHANGE IN GRADING OF SAMPLE M1 DURING WEATHERING PERIODS

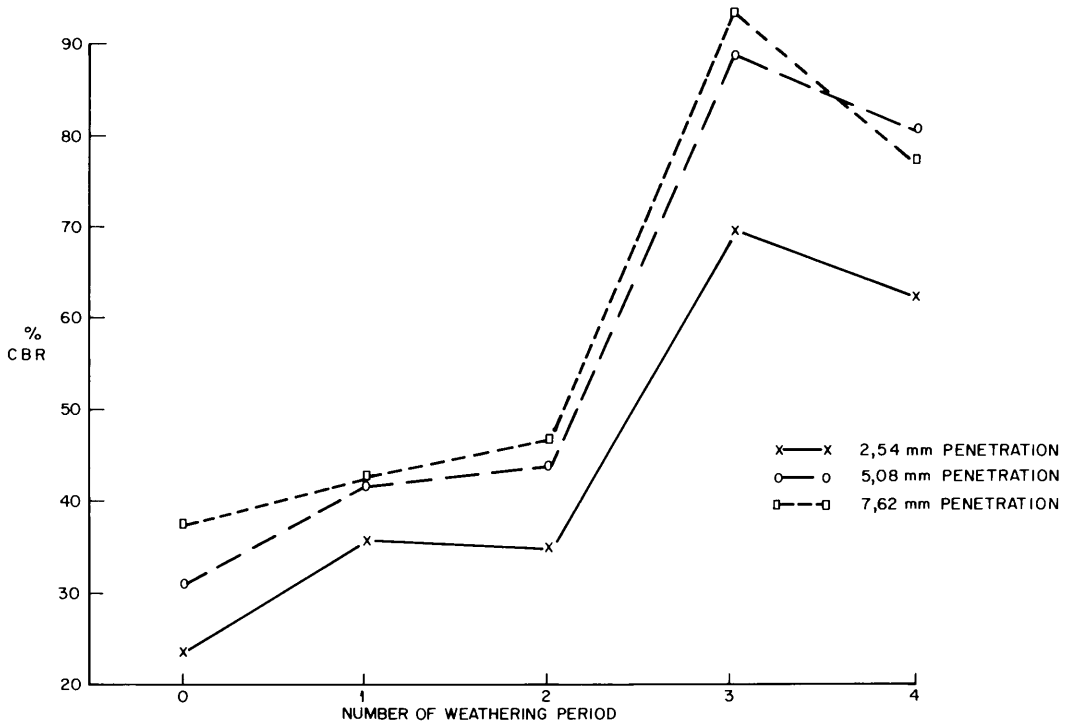


FIGURE 5.5
CHANGES IN PERCENTAGE CBR OF SAMPLE M1 (MOD. AASHTO COMPACTION) DURING WEATHERING PERIODS

TABLE 5.6: CHANGE OF ATTERBERG LIMITS AND LINEAR SHRINKAGE DURING WEATHERING EXPERIMENT ON SAMPLE M1

Test	Fresh sample (0)	After 10 wet-dry cycles (1)	After compaction and 10 wet-dry cycles (2) (weathering period)	After another weathering period (3)	After another weathering period (4)	After another set of compactions (5)
Liquid limit (%)	n.d.	19,5	17,6	18,1		18,0
Plastic limit (%)	n.d.	n.d.	16,0	14,6	Sample	13,9
Plasticity index (%)	NP	NP	1,6	3,5	lost	4,1
Linear shrinkage (%)	0,7*	0,7	1,0	1,7		1,3

* - from a moisture content of 17,5 per cent

n.d. - test not done on account of low plasticity

NP - non-plastic

5.2.6.4 Conclusions

The results from this weathering experiment on sample M1 supplied interesting information on sample behaviour and it was therefore decided to perform this experiment on all the samples. The procedure was, however, changed somewhat by first carrying out the compactions. For the remaining samples it was decided to use a crushed sample of 45 kg. Grading analysis, Atterberg limits and linear shrinkage, hydrometer analysis and CBR compactions were determined on this fresh sample. The samples were extruded from the CBR moulds, divided into three stainless steel containers, dried at 105 °C and then subjected to ten wet-dry cycles as described in Section 5.2.6.2 after which the process was repeated. Additional details of the test are given in Chapter 8.

5.2.7 Rate of absorption

The rate at which mudrocks absorb water or water vapour is an important parameter, e.g. in the weathering test (wet-dry cycles and compactions) it was important to know what time period should be allowed for soaking to ensure that the samples became saturated. An experiment was therefore conducted to determine the rate of absorption.

Deo (1972) determined the rate of absorption of mudrocks which did not break down in water. The test involved the immersion of a lump of rock in water, its removal from the water followed by surface drying and weighing of the lump at regular intervals. A similar test was carried out on sample M1 and ten equidimensional lumps of material, weighing about 50 to 60 g each, were prepared. Five lumps were dried at 50 °C and the other five at 105 °C to determine the effect of drying temperature on absorption. After drying, the samples were put into a desiccator to cool for 30 minutes. After the cooling the first lump was submerged in water. The other lumps were added at one-minute intervals. After 15 minutes' soaking the lumps were removed, surface-dried and weighed at one-minute intervals and replaced in the water. The process was repeated after 30 minutes and thereafter at longer intervals. Moisture contents were calculated as a percentage of the dry mass. Figure 5.6 illustrates the absorption with time for sample M1. The average moisture contents for the five samples dried

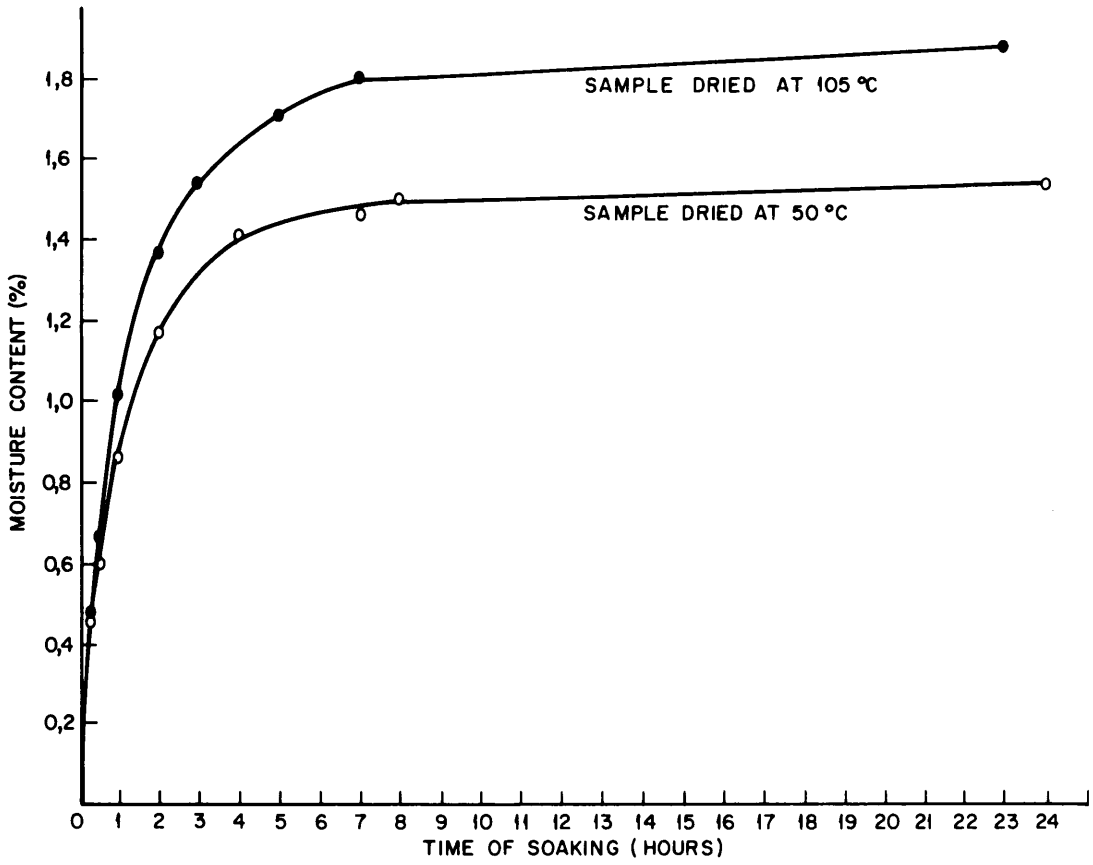


FIGURE 5.6

GRAPH OF ABSORPTION WITH TIME FOR SAMPLE M1

at 50 °C and 105 °C at the various time intervals were plotted in Figure 5.6. From the curves it is clear that:

(a) Lumps dried at 105 °C absorbed more water than lumps dried at 50 °C. During the initial drying of the lumps beforehand the lumps dried at 105 °C lost more moisture than those dried at 50 °C (1,56 against 1,30 per cent). The lumps dried at 105 °C absorbed 0,35 per cent above their natural moisture content whereas the lumps dried at 50 °C gained only 0,25 per cent.

(b) The samples dried at 105 °C absorbed 90 per cent of their final water content within five hours, whereas those dried at 50 °C reached 90 per cent of the total absorption in four hours. There was no visible difference in the behaviour of the samples dried at 105 °C and of those dried at 50 °C. It was therefore decided to use the same method on the other samples with drying only at 105 °C.

5.2.8 Absorption of samples left in a vacuum

Reidenouer et al (1974) performed a test to determine the water absorption of mudrock samples which had been kept under a vacuum. A similar test was carried out on sample M1.

Eight 30 mm cubes, each weighing between 50 and 60 g were cut with a diamond saw. Four more uncut and irregular samples were added to determine the effect of shape on the absorption of water. The twelve samples were divided into two sets of six, one lot being dried at 105 °C while the others were sealed in an airtight plastic bag. After drying, all the samples, both the oven-dried samples and those in their natural state, were put into a desiccator. The desiccator was evacuated by using a vacuum pump and the samples were left in this vacuum for three days. The pump was switched on from time to time because of a leakage of air into the desiccator. This leakage probably took place through a PVC tube fitted into the side of the desiccator as a water inlet. After three days distilled water was allowed in through the PVC tube to cover the samples and the samples were soaked for 16 hours. They were then taken out, their surfaces dried and weighed.

The average absorption of the natural samples was 0,53 per cent whereas the oven-dried samples absorbed an average of 1,73 per cent. The uncut

samples absorbed amounts of moisture similar to those absorbed by the cut samples. Only one large natural sample absorbed somewhat less than average.

Despite leakage through the tube the experiment was satisfactory. It was decided to use a water inlet tube of glass for subsequent tests and to use only cut samples, as it is easier to surface-dry smooth cubes in a consistent manner.

5.2.9 Slake index

This test was proposed by Deo (1972) as a classification test for mudrocks in Indiana. It is similar to the slake durability test but involves a long period of soaking and does not require agitation. Lumps of mudrock with a mass of approximately 150 g each are dried at 105 °C, soaked for 16 hours and then washed on a 2 mm sieve. The procedure is repeated for five cycles. The slake index is the percentage of the original material retained on the 2 mm sieve after five cycles (Indiana State Highway Commission, 1973).

The test was performed on sample M1 with drying at 105 °C and 50 °C. After the first cycle no losses had taken place although some hairline cracks could be observed. It was obvious that very little material would be lost during five cycles and the test was discontinued.

This test would be helpful in measuring "slaking" i.e. the break-down of mudrocks into silt or clay-size particles, but a slake durability test should give better results if the apparatus is available.

5.2.10 Rate of slaking

A "rate of slaking" test was proposed by Morgenstern and Eigenbrod (1974) for classifying mudrocks in Canada. The test measures the amount of water absorbed by lumps of mudrock in a two-hour immersion period. This moisture content is used in a formula, along with the natural moisture content, plasticity index, liquid limit and plastic limit to calculate a liquidity index. The rock is then classified as slow, fast or very fast slaking.

No detailed procedure for this test was available. The test involves the soaking of a few chips of mudrock, weighing a total of 20 g, in filter

paper in a funnel placed in a beaker. A major problem encountered was in the determination of the mass of the soaked material on the filter paper. It was, however, found that the filter paper had constant absorption characteristics and that the mass determined in a trial soaking using only the filter paper could be deducted from the mass of the soaked sample plus the filter paper to give an accurate value for the mass of the soaked sample. The test worked well for sample M1, giving a value of 3,2 per cent. Through enquiries by Van Zyl (1977), it was determined that Chapman (1975), who also experimented with the test, had merely scraped the soaked material from the filter paper for weighing.

5.2.11 Swell

5.2.11.1 Introduction

The only major work done hitherto on the engineering-geological classification of mudrocks in South Africa has been by Olivier (1976a) during studies on such rock types encountered in the Orange-Fish Tunnel. He proposed the determination of the free swell coefficient and uniaxial compressive strength as index parameters for his so-called "Geodurability Classification" (Olivier, 1979a). Free swell work on non-cored samples has, however, not been reported before and pilot studies to determine the best method were therefore necessary. A method was given by Duncan et al (1968). For these tests an apparatus and a method basically similar to that given by the ISRM (1972b) was used. Several aspects had, however, to be investigated before routine testing could commence. Blocks of the pilot sample M1 were used in these investigations.

5.2.11.2 Preparation of samples for the swell test

Samples were sawn dry as the use of water can influence their behaviour. It was also important to know what volume changes took place when a natural sample (sample at field moisture content) was saturated with water. Large diameter diamond saw blades were used. Sawing without water was found to be practical although it required patience: the samples cracked

easily along bedding planes or other planes of weakness when heat was generated or if too great a pressure was applied. Ear muffs were found to be necessary for protection against noise and efficient ventilation and respirators were needed for protection against the large amount of dust generated.

5.2.11.3 Dimensions of samples

Some experiments were done to determine the dimensions of the samples to be used for testing. Figure 5.7 shows the free swell behaviour of two differently sized mudrock blocks: A, 25 x 25 x 50 mm and B, 50 x 50 x 50 mm, sawn from the same sample. The percentage swell shown is the swell perpendicular to the bedding. A1 and B1 are the swell curves when the samples at the natural moisture content were immersed and A2 and B2 are the swell curves after the samples had been dried at 105 °C and immersed again. It is clear that the maximum percentages swell are almost equal. There is, however, a difference in the rate of swell. The smaller sample needed less time to become saturated and therefore revealed more rapid volume changes during the initial period of immersion. It was decided to use 50 mm cubes for free swell testing as larger blocks do not crack or break as easily during sawing or immersion in water. They will also give larger percentage swell values parallel to the bedding because of the larger dimensions in that plane.

5.2.11.4 Method of orienting samples

In order to study the whole process of sawing, orientation and marking of the samples and to determine the best test procedures, it was necessary to carry out a further pilot study on a large block of M1.

A suitable uncracked block kept in a plastic bag at the field moisture content was selected. To mark out all the cubes for the test, the block was divided into 50 mm squares on a plane parallel to the bedding. Each square was numbered and a sketch made of the whole block and the positions of the squares. The block was then sawn into 50 mm cubes and each cube marked in a standard manner as shown in Figure 5.8.

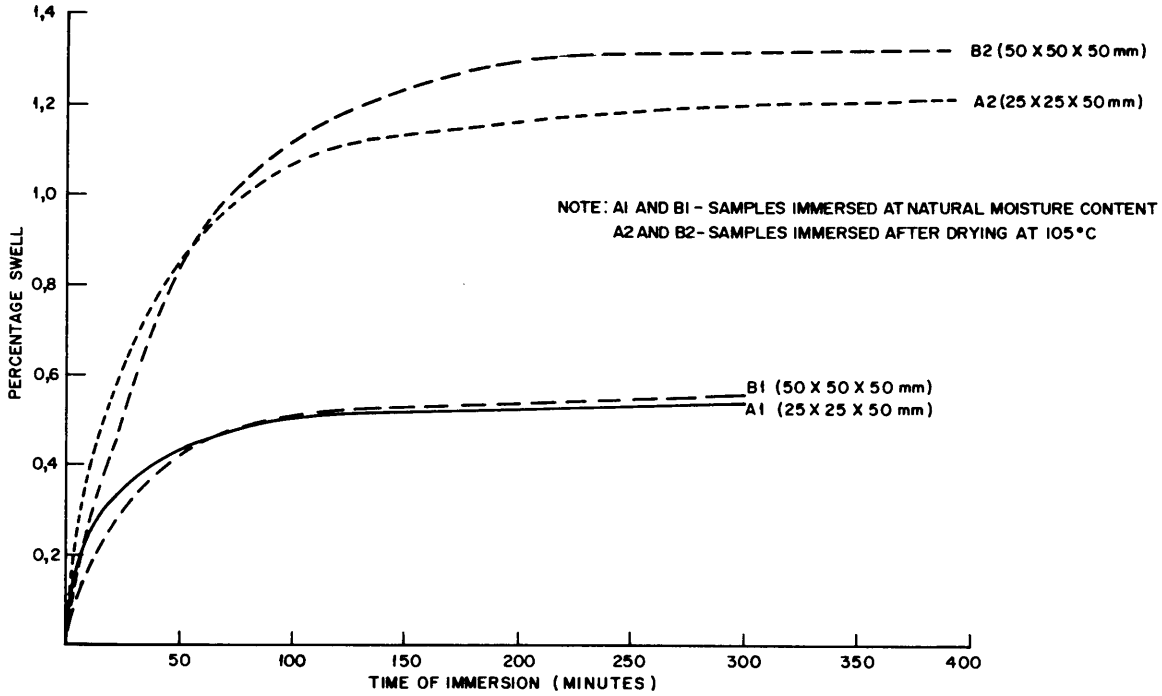


FIGURE 5.7

FREE SWELL OF DIFFERENTLY SIZED MUDROCKS

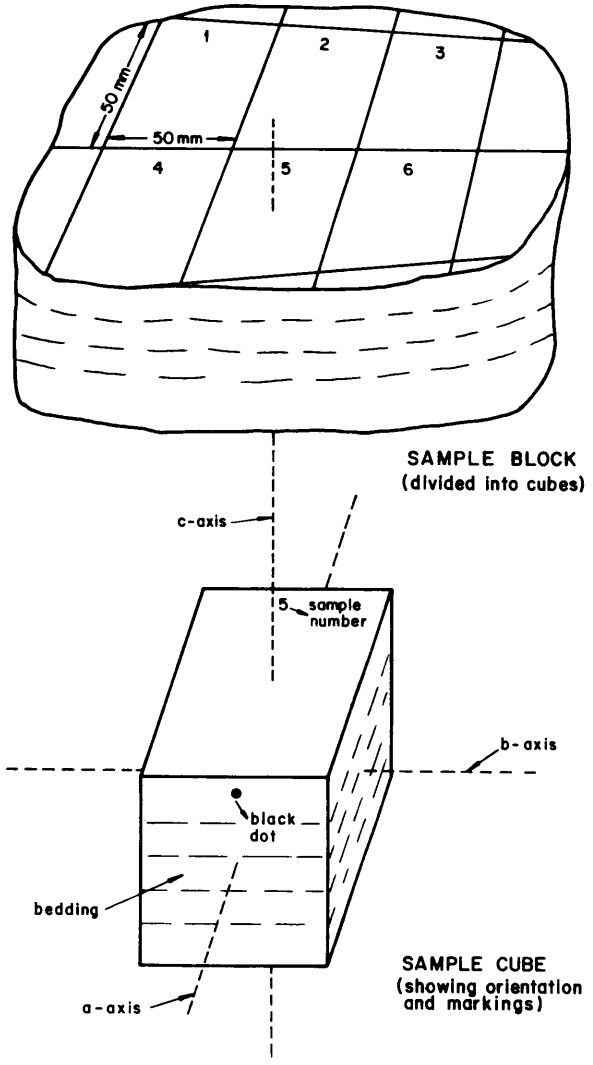


FIGURE 5.8

MARKING AND ORIENTATION OF SAMPLE BLOCK AND SWELL CUBES

5.2.11.5 Comparison of methods of preparation

Table 5.7 lists the methods of preparation used on the 20 cubes sawn from M1.

TABLE 5.7: TREATMENT OF CUBES FOR FREE SWELL PILOT STUDY ON M1

Cube number	Treatment of cubes	Dried at temp. (°C) after first swell	Swells measured - triaxial or uniaxial
1, 10	Natural sample* - immersed after sawing	50	Triaxial
6, 9	Natural sample - immersed after sawing	105	Uniaxial
2, 12	Natural sample - exposed to atmosphere for one day	105	Triaxial
3, 14	Natural sample - exposed to atmosphere for two days	105	Triaxial
17	Natural sample - exposed to atmosphere for five days	105	Triaxial
18	Natural sample - exposed to atmosphere for 14 days	105	Triaxial
19	Natural sample - exposed to atmosphere for 30 days	105	Triaxial
20	Natural sample - exposed to atmosphere for 60 days	105	Triaxial
7, 11	Oven-dried for one day at 50 °C	50	Triaxial
5, 16	Oven-dried for four days at 50 °C	50	Triaxial
8, 13	Oven-dried for one day at 105 °C	105	Uniaxial
4, 15	Oven-dried for three days at 105 °C	105	Triaxial

*By natural sample is meant a sample just taken out of the plastic bag in which it was stored since sampling.

The results of these tests are included together with those of the other samples in the Appendix.

The following information was gathered from this study:

(a) Cubes exposed to the atmosphere swelled more than the cubes immersed immediately after sawing. The former evidently lost moisture during the time of exposure.

(b) It did not make an appreciable difference to the percentage swell whether a cube was dried at 50 or at 105 °C.

(c) The cubes of natural sample immersed immediately after sawing, swelled less that oven-dried cubes. Cubes exposed to the atmosphere (air-dried) for a long time (more than 17 days) yielded swells which were only insignificantly smaller than those of the oven-dried cubes.

(d) Drying for one day at 50 °C was not adequate. An average of 0,69 per cent of water was lost as against 0,99 per cent after four days. On the other hand, drying for one day at 105 °C appeared to be adequate.

(e) When the cubes were immersed for a second time after oven-drying, the natural and short-duration air-dried cubes swelled more than when they were first immersed. In contrast, the longer air-dried and oven-dried cubes swelled less when immersed a second time after having been dried in the oven.

(f) Cubes dried in the oven exhibited more cracks after the immersion period than did the natural samples immersed immediately after sawing.

(g) From graphs showing percentage of swell with time, the time taken to reach half of the eventual maximum swell was calculated. These curves show that the first swell (the first time a cube is immersed) usually takes longer to reach half the maximum swell. During subsequent swells the curves were initially steeper and then flattened out. This was probably caused by the cracks which gave the water quick access to all parts of the cube.

5.2.11.6 Programme for further tests

With the information obtained it was decided to use a test programme for the remaining samples which was similar to the one used for sample M1 as all these different treatments gave valuable information about the behaviour of mudrocks. Information was obtained, not only on the percentage

of swell, but also on moisture changes during air drying, break-down during wetting and drying, rate of swell, percentage moisture absorbed, etc. Drying of some cubes at 50 °C was discontinued after the study on sample M2 as no differences in the visual appearance and swell behaviour could be found.

5.2.11.7 Method and apparatus for further testing

The method used for determining the free swell of mudrock samples is as follows:

A suitable sample block is taken from a plastic bag, the direction of the bedding is determined and 50 mm squares marked out on the plane. The cubes are then cut using a diamond saw, but no water is used. After all the cubes have been weighed the lengths of all the axes are measured using a vernier. Cubes are then selected for the different treatments, i.e. swells at natural moisture content or after various periods of air drying or oven drying.

Natural or air-dried cubes can be immersed immediately after weighing whereas oven-dried cubes should be allowed to cool for 45 minutes in a desiccator after weighing. Fifteen minutes are allowed for installing the cubes before distilled water is poured in to cover them.

For the pilot study on M1 apparatuses to determine uniaxial and triaxial swell were obtained from the Geomechanics Division, NMERI, CSIR. Readings of the dial gauges had to be taken every few minutes at the commencement of the tests and at longer intervals later on to allow the meaningful determination of the time-dependent swell behaviour of the test specimens. This was very time-consuming and apparatuses with which swell could be monitored continuously were therefore built. These uniaxial and triaxial apparatuses incorporated the basic instruments with dial gauges to allow manual monitoring as before, but linear variable differential transformers (LVDT's) were also added to register the swell curve on a chart using a six pen Watanabe Multirecorder. The apparatuses are shown on Plates 15 and 16 in Chapter 9.

5.2.12 Statistical work

Where more than two results for the same sample and test were available, means and standard deviations were calculated. In a large number of cases, tests were carried out in duplicate. The average value was tabulated and the percentage accuracy of these results was given at the 80 per cent confidence interval (80 per cent C.I.). Thus it can be stated with 80 per cent certainty that the actual mean lies within plus or minus the percentage deviation quoted from the tabulated mean.

The formula used was:

$$80 \text{ per cent Confidence Interval} = Mj \pm 1{,}28 \sqrt{\frac{\Sigma\left(\frac{x_{ij} - x_{kj}}{M_j}\right)^2}{4N}}$$

where x_{ij} = 1st member of pair j

x_{kj} = 2nd member of pair j

$M_j = \frac{x_{ij} + x_{kj}}{2}$

N = total number of pairs.

5.3 Test methods selected

With the information gathered from the survey of related work, the references listed in Table 5.1 as well as the pilot studies, a programme of experimental work was drawn up. Table 5.8 lists the tests selected, the test methods employed, short descriptions of the methods, the reason for their selection and the objectives of the tests. More details about the tests are given under the relevant headings in Chapters 7 to 12.

TABLE 5.8: DETAILS OF TESTS USED IN STUDY

Name of test	Test method and reference	Short description of method	Reason for selection and purpose of test
Preparation of samples for sieve analysis and Atterberg constants	A1(a) Department of Transport, 1971	Sieve analysis and separating minus 0,425 mm fraction for determination of Atterberg constants and hydrometer analysis	Standard tests for classifying South African roadbuilding materials (hydrometer test seldom done). The grading curves establish if the material is suitable for dense compaction. Liquid limit, plastic limit and PI give an indication of how the shear strength of the compacted material will change if the moisture regime in the pavement changes. If high percentages of clay and silt-sized particles are present the effect will be more marked. Tests A5 and A6 indicate this. Linear shrinkage is an indication of volume changes to be expected with moisture changes
Liquid limit (LL)	A2 Department of Transport, 1971	Determine the moisture content at which paste of soil fines (minus 0,425 mm) flows a fixed distance after 25 blows in Casagrande apparatus	
Plastic limit (PL) and plasticity index (PI)	A3 Department of Transport, 1971	Determine the lowest moisture content at which soil can be rolled into 3 mm diameter threads. PI = LL - PL	
Linear shrinkage	A4 Department of Transport, 1971	Determine percentage shrinkage of soil when oven-dried from liquid limit	
Percentage passing 0,075 mm sieve	A5 Department of Transport, 1971	Washing the soil fines on a 0,075 mm sieve	
Grain size distribution by means of hydrometer	A6 Department of Transport, 1971	Measuring decreasing densities during sedimentation of a suspension of soil fines	
Maximum dry density (MDD) and optimum moisture content (OMC)	A7 Department of Transport, 1971	Compacting material at standard effort at different moisture contents in moulds	The OMC and MDD test determines for a standard compaction effort that moisture content which should be used to achieve the maximum dry density
California bearing ratio of untreated materials (CBR)	A8 Department of Transport, 1971	Penetrating compacted material with a piston - CBR is load required expressed as a percentage of the California standard values	Results from the CBR test give an indication of the bearing capacity of a material compacted at a certain effort and then soaked. Test A9 shows whether lime treatment is beneficial. Treated compacted samples are allowed to cure for some time before being soaked
California bearing ratio of material stabilized with lime	A9 Department of Transport, 1971	As above but material treated with lime	
Accelerated weathering using CBR compactions and wet-dry cycles	Author's method	Using grading analyses, Atterberg constants, etc. to monitor changes in material compacted and subjected to wetting and drying cycles	The test simulates construction conditions to a certain extent and allows monitoring of the changes that take place
Free swell	International Society for Rock Mechanics (ISRM), 1972b and author's methods	Mounting differently prepared 50 mm rock cubes in swell apparatuses and determining volume changes when water is added	The test allows the study of break-down and swell properties of differently treated mudrocks during repeated immersions in water - also recommended by Olivier (1979a) for classifying mudrocks for tunnel construction
Natural and vacuum saturated absorption	Based largely on Reidenouer et al, 1974	Determine percentage water absorption of natural and oven-dried cubes under atmospheric and vacuum conditions	The tests determine range of absorption of mudrocks and investigate theory of "air breakage"
Rate of absorption	Deo, 1972	Soaking cubes in water and weighing them after various intervals to determine absorption with time	Rate of absorption is an important property, both in testing and construction

TABLE 5.8: (continued)

Name of test	Test method and reference	Short description of method	Reason for selection and purpose of test
Volume change and adsorption with temperature and humidity changes	Author's method	Subject rock prisms to various temperature and humidity conditions and monitor the changes in adsorption and volume	Temperature and humidity changes are thought to be the main causes of the break-down of mudrocks
Uniaxial compressive strength	ISRM, 1972a	Measure load necessary to break prism in compression	Important rock parameters - UCS recommended by Olivier (1979a) as a classification test for mudrocks
Brazilian tensile strength	ISRM, 1977	Measure load required to split disk in tension	
NCB cone indentation	National Coal Board, (UK), 1972	Measuring load required to produce a certain amount of indentation by a cone	Both instruments can be used to obtain a quick estimate of rock strength - NCB cone indenter developed specially for testing fine-grained materials
Schmidt hammer	Proceq Company, 1977	Measure rebound when a spring-loaded plunger is released against a rock	
Aggregate crushing value (ACV)	Department of Transport, 1971, Method B1	Measuring amount of crushing which occurs under a compressive load	The tests measure resistance against crushing which is an important property in road construction - 10 % FACT recommended by Loubser (1967) and Weinert (1979) for classifying mudrocks.
10 Per cent fines aggregate crushing value	Department of Transport, 1971, Method B2	Determine load required to crush a graded aggregate so that 10 per cent passes a specific sieve.	
Treton impact value	Department of Transport, 1971, Method B7	Determine amount of crushing which occurs when the aggregate is subjected to blows of a falling hammer	The test measures resistance to crushing by impact - similar test fared well in study by Shergold and Hosking (1963)
Los Angeles abrasion	American Society for Testing and Materials (ASTM), 1976, Test method C131-69	Measure abrasion which takes place when dry graded aggregate and steel spheres are revolved in a drum	Measure abrasion under dry conditions - best known test to determine this property
Wet ball mill	Author's method	Measure abrasion which occurs when wet aggregate and porcelain balls are tumbled in a jar	The test measures abrasion in a wet environment which probably better resembles the abrasion in a pavement
Slake durability	ISRM, 1972b	Measure loss from a wire mesh drum with lumps of rock in it, which rotate partly immersed in water	Test gaining popularity for testing mudrocks - recommended by Gamble (1971)
Sodium sulphate soundness	ASTM, 1976. Test method C88-73	Submit fractions of rock in baskets to cycles of soaking in saturated sodium sulphate solution followed by oven-drying	This is the most widely used "weathering" test
Ethylene glycol soaking	Author's method, resembles Reidenouer et al, 1974	Soak fragments of rock in ethylene glycol	This is proposed for classifying mudrocks by Reidenouer et al (1974)
Accelerated weathering using water and calgon and sodium sulphate solutions	Author's method	Submit lumps of rock in baskets to wetting and drying cycles in the three aforementioned agents	Test for comparing the effects of three different agents to establish which one, if any, can be used for classifying mudrocks

TABLE 5.8: (continued)

Name of test	Test method and reference	Short description of method	Reason for selection and purpose of test
Ultrasonic disaggregation	Author's method using an ultrasonic probe	Subject rock aggregate in water to periods of ultrasonic cavitation	Effect of cavitation on rock proved to be good indication of weatherability (Laguros et al, 1974)
Sand equivalent	Department of Transport, 1971, Method B19	Measure settlement of minus 4,75 mm material in soil-water-sand equivalent solution suspension	Gives indication of combined effect of quantity and type of clay minerals
Washington degradation	Washington State Highway Commission, 1969. WSHD test method 113A	Measure settlement of minus 0,075 mm material, produced by shaking in a sieve shaker, in a soil-water-sand equivalent solution suspension	Similar to sand equivalent test. Recommended for classification by Reidenouer et al, 1974
Methylene blue adsorption	Webber, 1972	Shake up ground rock with methylene blue solution and determine adsorption by measuring optical density of solution	Recommended by Croft (1966) and Webber (1972) for obtaining information about type of clay minerals present in a material
Bulk and apparent specific gravity and water absorption	Department of Transport, 1971, Method B14 (used different gradings)	Weighing saturated aggregate in air and in water and weighing oven-dried aggregate in air - use formula to calculate	Determine the volume relationships of solids, voids and water in a rock
Porosity	Use mercury penetration porosimeter	Mercury is forced into aggregate at various pressures - data from this allows calculation of pore size distribution	Important rock parameter of which little is known for southern African mudrocks
Conductivity, pH	National Institute for Transport and Road Research (NITRR), 1974 Test method CA-21	Measure conductivity of soil paste, saturated with water, in a special cell. pH measured with pH meter	Test may give information about presence of soluble salts in mudrocks
Rate of slaking	Morgenstern and Eigenbrod, 1974	Determine water absorption of small pieces of rock in filter paper in a funnel	Proposed for classifying certain types of mudrock by Morgenstern and Eigenbrod (1974)

CHAPTER 6

SAMPLING, PETROGRAPHY, MINERALOGY AND CHEMISTRY

6.1 Criteria for sample selection

In a major study of this kind it is obvious that the samples should be selected with great care. The following are some of the criteria which were particularly applicable:

(a) Sampling had to be carried out within hours of excavation while the rocks were still at their natural moisture content. This was necessary because a common initial condition was needed for all the samples to allow comparison between their behaviour in tests or experiments. Mudrocks which tended to break down could deteriorate after a short period of exposure and these samples could then behave differently from similar samples taken earlier on. Furthermore, some of the tests could not be carried out on broken-down samples.

(b) It was also necessary that the samples should come from different geological formations and from various parts of southern Africa. It was believed that in the first mudrock investigation of this kind false correlations should be avoided by sampling a wide variety of formations containing mudrock. If anything meaningful emerged at this stage it would provide a strong basis for follow-up studies. If not, at least an idea of the range of the variation of properties would be gained. It would therefore obviously be wrong to test only a few mudrock samples from the Ecca and Beaufort Groups. Conclusions obtained from such tests might not have been valid when mudrocks of the Bokkeveld Group or the Elliot Formation were included.

6.2 Sampling and sample particulars

Information about possible sampling sites, i.e. places where construction was planned or in progress, was obtained during the series of interviews discussed in Chapter 3. This was followed up and promising sampling sites were selected and investigated. Three sampling trips were undertaken:

one to the southwestern Cape Province and two to Natal. Eleven samples of mudrock were collected during these trips. A twelfth sample was railed after excavation, and another was taken in Pretoria. These, together with the pilot sample M1, made up the 14 samples used for the study. Figure 6.1 shows the localities of the samples.

Notes about various visual properties of the samples were made during sampling and crushing. These are listed with other relevant information, such as sample location and geological formation, in Table 6.1.

A sample of approximately 400 kg in mass was taken in each case. The sample received by rail comprised only about half this mass and tests A1 to A8 (Department of Transport, 1971) could therefore not be carried out on sample M13. Samples were sealed in plastic bags immediately after collection. Large fragments were collected, some weighing more than 50 kg, because such samples would tend to lose less moisture with time. Large blocks were also needed for some tests, such as the free swell and uniaxial compressive strength tests.

6.3 Petrographical description

The preparation of thin sections of mudrocks, especially soft ones, has been found in the past to present many problems. The Geological Survey, Department of Mines, kindly assisted in the preparation of the thin sections. Two thin sections were prepared for samples showing fissility or bedding: one parallel and another perpendicular to the bedding. Only a single randomly oriented thin section was prepared for samples without the above features. In order to strengthen the material before mounting and grinding, the flat surface was subjected to prolonged heating in Canada balsam.

The thin sections were investigated with a petrographic microscope and some photomicrographs were taken. Microscopical examination included the identification of minerals, the examination of the fabric and an estimate of grain size distribution to allow classification of the samples according to Table 2.1. These are listed in Table 6.2.

The photomicrographs on Plates 10 and 11 illustrate the appearance of the 14 mudrock samples under magnification. Personnel from the National Building Research Institute (NBRI) of the CSIR assisted in this work.

FIGURE 6.1

MAP OF SOUTH AFRICA SHOWING LOCATIONS OF MUDROCK SAMPLES

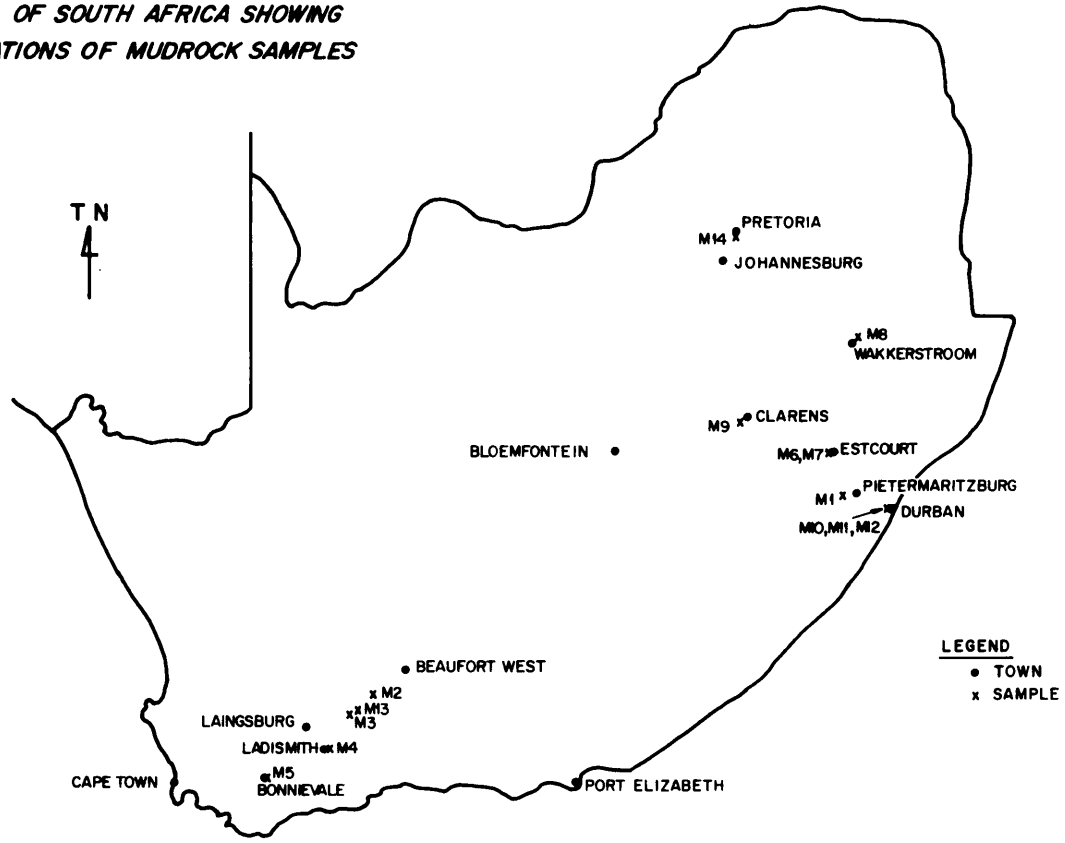


TABLE 6.1: GENERAL DETAILS OF SAMPLES

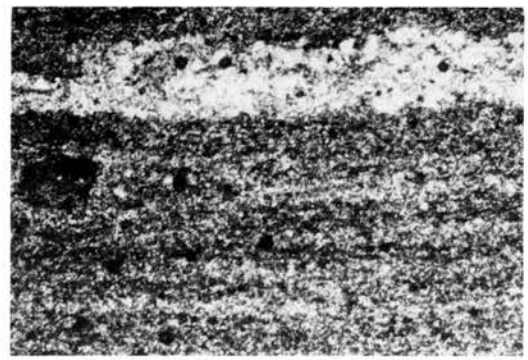
NITRR sample number	Project sample number	Geological formation	Colour and probable mudrock type	Locality	Information about sampling point and use	Bedding and discontinuities	Other characteristics
5827	M1	Karoo Sequence Ecca Group Volksrust Shale Formation	Dark grey clay-shale	km 18,5; Road 135 from Merrivale to Boston, Natal	Deep cutting on hill-slope - material used for fill	Layering difficult to detect but can be determined from way rock breaks or cracks - some stained joint surfaces present	Sampled rock fairly homogeneous but weathered rock near surface shows bedding clearly
6164	M2	Karoo Sequence Beaufort Group Adelaide Subgroup	Reddish grey claystone	km 67,82 from Beaufort West to Laingsburg, Cape Province (C.P.)	From thin layer interbedded with hard sandstones in a cutting	Bedding hard to detect but thin layers are sometimes evident on smooth surfaces - no discontinuities	Fresh hard sample which does not show any preferred breaking planes
6165	M3	Karoo Sequence Beaufort Group	Dusky yellow claystone	km 79,24 from Laingsburg to Beaufort West, C.P.	From steeply dipping strata in a shallow cutting	Stratification visible in coarser grained part - numerous irregular, black stained discontinuities in fine-grained part	Sampled about two months after excavation - removed exposed surface material to sample fresh material - sample grades from very fine grained to coarser siltstone
6166	M4	Cape Supergroup Bokkeveld Group	Greyish olive, mottled brown and grey siltstone	3 km on road to Hoeko after turn-off from Calitzdorp to Ladismith road, C.P.	From cutting 3 m deep on a gravel road	Very difficult to determine bedding - some oriented samples taken - joints and other irregular discontinuities present	Rock slightly weathered - does not show any preferred breaking planes
6167	M5	Cape Supergroup Bokkeveld Group	Pale red mudstone	5 km on road to Gelukshoop after turnoff from Bonnievale to Stormsvlei road, C.P.	From cutting 2 m deep on a gravel road - material uniform	Bedding evident on smooth surfaces - can also be seen from breaking down pattern - very few joints	Samples usually break parallel to bedding but do not yield smooth surfaces - material slightly weathered
6169	M6	Karoo Sequence Beaufort Group Adelaide Subgroup	Greyish olive mudstone	km 2,6 on road N3 Section 5 from Estcourt to Frere, Natal	From cutting 3 m deep through a hilltop	Bedding very difficult to determine - samples break into thick spherical shells with purple-stained surfaces - some flat joint surfaces present	Slightly weathered sample which breaks up into nodules
6180	M7	Karoo Sequence Beaufort Group Adelaide Subgroup	Greyish olive clay-shale	km 0,2 on road N3 Section 5 from Estcourt to Frere, Natal	Samples about 3 m from surface in a deep cutting	Bedding prominent in form of light and dark olive layers of varying thickness - some joint surfaces slightly clayey	Slightly weathered sample which usually breaks along a flat bedding plane
6181	M8	Karoo Sequence Beaufort Group Adelaide Subgroup	Grey claystone	Wakkerstroom to Dirkiesdorp, road P7-2 at chainage 481, B. Pit no 9,2G, Transvaal (Tvl)	Sampled from a cutting 6 m deep	Bedding can only be determined on very smooth surfaces and by way samples break - joints present, some with clayey material	Rock indurated by a dolerite intrusion - breaks along bedding planes but does not form thin slabs
6241	M9	Karoo Sequence Elliot Formation	Pale red siltstone	km 29 from Fouriesburg to Clarens, Orange Free State	Sampled at about 2 m depth from a deep cutting	Bedding seldom visible but some thin layers were observed in some samples - irregular slickensided discontinuities covered by clay	Fresh rock which breaks easily - fine sand and silt are produced when breaking material with a hammer

TABLE 6.1: (Continued)

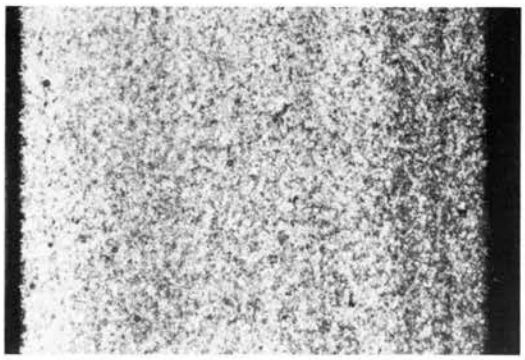
NITRR sample number	Project sample number	Geological formation	Colour and probable mudrock type	Locality	Information about sampling point and use	Bedding and discontinuities	Other characteristics
6287	M10	Karoo Sequence Ecca Group Pietermaritzburg Shale Formation	Dark grey clay-shale	km 21,96 on Durban outer ring road, NR2/25, Natal	Sampled at about 6 m depth from a drainage ditch	Bedding can be detected by way samples crack - otherwise massive - some joints present - no staining	Rock breaks into irregular shapes with rounded surfaces parallel to bedding - cracks perpendicular to bedding have a serrated appearance - fresh rock
6288	M11	Karoo Sequence Ecca Group Pietermaritzburg Shale Formation	Medium grey mudstone	km 25,00 on Durban outer ring road, NR2/25, Natal	Sampled at about 6 m depth from a deep cutting	No distinct layers present but bedding is evident from the texture of the rock - no prominent discontinuities but discolouration along some surfaces	Rock breaks roughly parallel to bedding but does not form smooth surfaces - some large mica flakes present
6289	M12	Karoo Sequence Ecca Group Pietermaritzburg Shale Formation	Dark grey shale	km 25,16 on Durban outer ring road, NR2/25, Natal	Sampled at about 4 m from same deep cutting as M11	Bedding can be detected from way samples break - no layering visible - well developed joint pattern - some small rhombohedral blocks are formed	Flat bedding planes are exposed during breaking with hammer - some slickensided surfaces were found - material fresh
6290	M13	Karoo Sequence Beaufort Group Adelaide Subgroup	Medium dark grey claystone	km 96 from Laingsburg to Beaufort West, C.P.	Sampled from cutting 3 m deep and despatched by rail	No stratification observed - no oriented samples available - some smooth clean joint surfaces present	Hard cemented fresh rock which breaks into irregular fragments
6501	M14	Transvaal Sequence Pretoria Group Timeball Hill Formation	Pale red claystone	Excavations for extensions to University of South Africa, Pretoria	Sampled from about 3 m depth in excavations for new building	Bedding clearly visible in form of thin layers - numerous smooth flat joint surfaces with soapy feel	Weathered rock which breaks easily - breaks along some bedding planes but rock is generally massive - smaller pieces can be broken by hand

TABLE 6.2: PETROGRAPHICAL CHARACTERISTICS OF MUDROCK SAMPLES

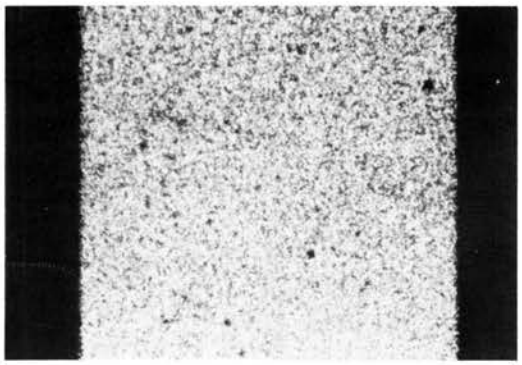
Sample number	Estimate of grain size	Recognizable minerals	Fabric	Probable name
M1	More than 2/3 clay size - remainder fine silt	Quartz, mica, opaques - larger crystals mostly quartz - discolouration near opaques	Clear layering in form of thin layers of coarser quartz grains	Clay-shale
M2	Very fine ground-mass - more than 2/3 clay size	Mica, opaques	Layering can be seen as alternating dark and light layers	Claystone
M3	More than 2/3 clay size - small percentage in fine silt range	Mica	Massive - occasional concentrations of coarser grains	Claystone
M4	More than 2/3 in medium to coarse silt size range - remainder clay size	Quartz, mica, opaques - larger crystals mainly quartz	Massive - fine grained patches - some stained stringer-like structures	Siltstone
M5	About equal amounts of silt and clay sizes	Quartz, mica, chlorite, opaques - various sizes of quartz grains	Layering difficult to detect - some areas have predominantly coarse and others predominantly fine material	Mudstone
M6	About 1/3 medium to fine silt in clay size ground-mass	Quartz, plagioclase, mica and chlorite	Massive - some areas coarser grained - fairly general iron staining - quartz badly sorted	Mudstone
M7	Clay size ground-mass - less than 1/3 fine silt	Too fine for identification - quartz and possibly mica	Layering can be detected in layers of coarser material, usually quartz	Clay-shale
M8	Clay size ground-mass - small percentage fine silt	Occasional larger grains of quartz and plagioclase - also mica and opaques	Well layered - oriented opaques	Claystone
M9	More than 2/3 medium to coarse silt with clay inbetween	Mainly quartz - some opaques	Massive	Siltstone
M10	Less than 1/3 fine silt - remainder clay size	Quartz, mica, opaques	Very dark slide - minerals oriented parallel to bedding - strong iron staining	Clay-shale
M11	More than 1/3 medium to coarse silt - remainder clay size	Quartz, mica, opaques and possibly fine siderite	Massive - poorly sorted angular fragments	Mudstone (possibly siltstone)
M12	About 1/3 fine to medium silt - remainder clay size	Quartz in microscopic black mass of clay size material - unidentifiable brown mineral and mica present	No visible layering - mica may be oriented - very dark slide	Shale (or "mud"-shale)
M13	Very fine clay size ground-mass - less than 10 per cent fine silt	Unidentifiable	Homogeneous - massive	Claystone
M14	About 1/3 fine silt - remainder clay size	Quartz, mica - some darker layers have randomly oriented needles - probably hematite	Clear layering	Mudstone (possibly claystone)



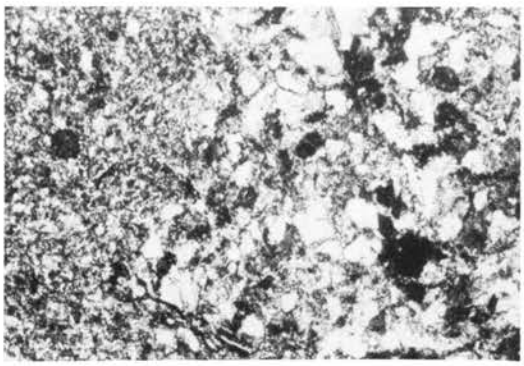
M1(V) (+ Nicols)



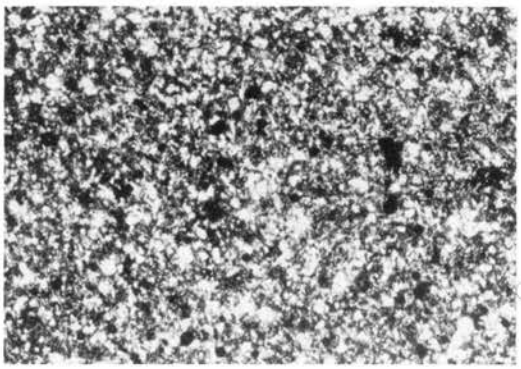
M2(V) (II Nicols)



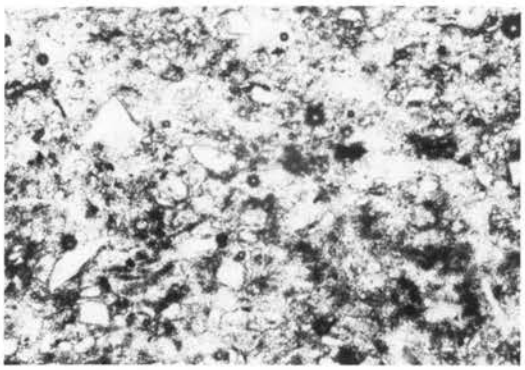
M3(R) (II Nicols)



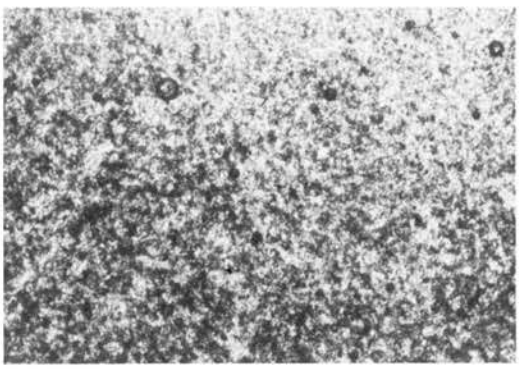
M4(R) (+ Nicols)



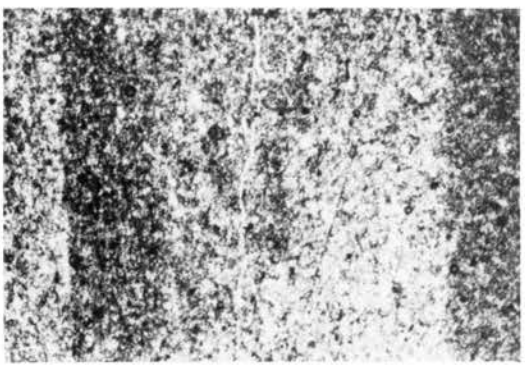
M5(H) (+ Nicols)



M6(R) (II Nicols)

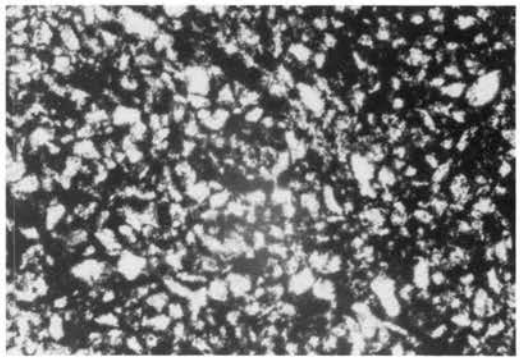


M7(H) (+ Nicols)

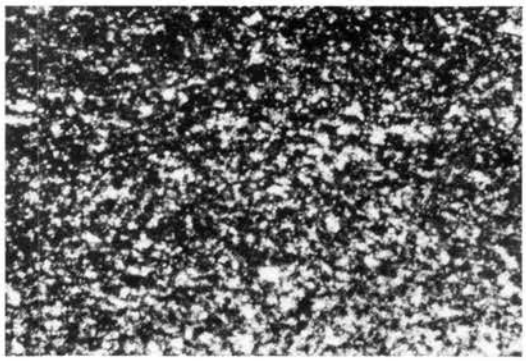


M8(V) (II Nicols)

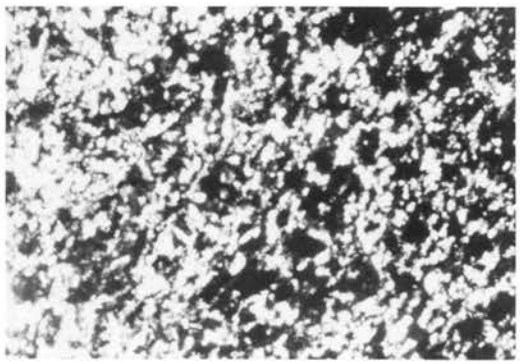
Plate 10: Photomicrographs of the mudrock samples



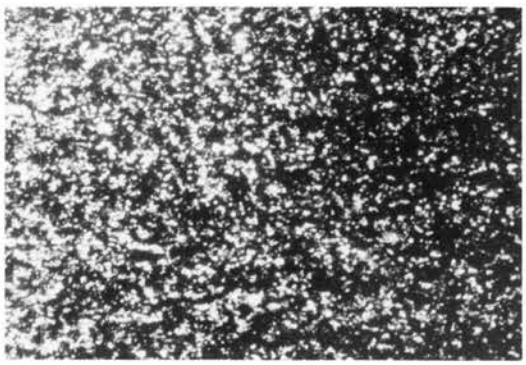
M9(R) (II Nicols)



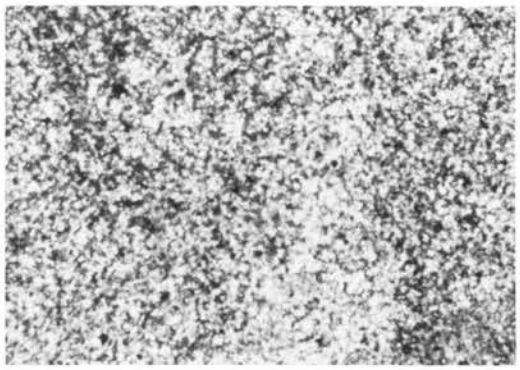
M10(V) (II Nicols)



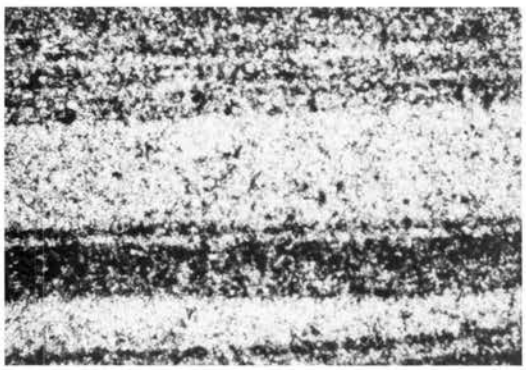
M11(V) (II Nicols)



M12(H) (II Nicols)



M13(R) (II Nicols)



M14(V) (II Nicols)

(V) — Section cut perpendicular to bedding
(H) — Section cut parallel to bedding
(R) — Section cut in random direction

Plate 11: Photomicrographs of the mudrock samples

6.4 Qualitative mineralogical composition

6.4.1 Introduction

Paige-Green (1978) compiled a system of X-ray mineralogical analyses for use at the NITRR. This combined the most applicable techniques of Brown (1961), Carrol (1970), Jackson (1973) and Avery and Bascomb (1974). This system was followed to analyse the 14 mudrock samples.

6.4.2 Sample preparation and analysis

Preparation of powder sample

A sample of about 10 g was taken from the same specimen from which the free swell samples had been sawn. This was ground to minus 200 mesh (< 0,075 mm) with an agate mortar and pestle.

Preparation of minus 2 µm sample

About 2,5 to 3 g of each sample were separated by riffling and put into 75 mm long pill vials. The vials were then filled to within 10 mm from the top with distilled water. The samples were shaken and the water levels topped up to the former level. The vials were marked 20 mm below the water level. These marks represented the level to which the plus 2 µm material would sink in 85 minutes (Tanner and Jackson, 1947 in Jackson, 1973). A few drops of calgon were added to each solution to deflocculate the particles. After the vials had been agitated at one-minute intervals and the solutions had settled for 85 minutes, the top 20 mm of each was sucked off using pipettes.

Preparation of slides for analysis

A rock powder mount was prepared from a representative sample as produced above. The remainder of the slides were prepared from the minus 2 µm material. The water-clay mixes were thoroughly shaken on a mechanical shaker before mounting. A Pasteur pippette was used to spread the specimens evenly over the slides.

The following preparations were submitted to X-ray diffraction:

(a) A sample of minus 2 µm (clay) material on a slide.

(b) The same sample after being heated for one hour at 575 °C in a furnace and cooled in a desiccator.

(c) A minus 2 µm sample which was glycolated, i.e. left for at least 16 hours in an evacuated bell jar in which the drying agent had been replaced by ethylene glycol.

(d) An acid-treated sample. This sample was prepared by transferring about 1 mℓ of minus 2 µm material to a test tube and adding an equal volume of concentrated HCl. This mixture was heated at 100±1 °C for half an hour after which the suspension was centrifuged and the liquid poured off. The remaining material was washed by adding distilled water and shaken to bring it into suspension before centrifuging. This was repeated approximately four times until no acidity remained. Litmus paper was used to check the neutrality.

(e) A sample treated with magnesium chloride. The same procedure as for the acid-treated sample was used but the sample was only washed once.

(f) The same sample as in (e) but a thin coat of glycerol was wiped onto it with a tissue.

Table 6.3 summarizes the preparations, the angles at which they were run and the purpose of the treatment. The results are summarized in Table 6.4. A rough estimate of the proportion of a particular mineral present was made by comparing peak heights and this information is included in the table.

6.4.3 Conclusions

(a) Quartz is present in "very large" percentages in all samples.

(b) Feldspar is present in all samples but one. It is usually present in moderate amounts except in M9 which has more, M14 which has less and M10 which has none. These three samples differ widely in engineering properties. M9 disintegrates into silt and clay when immersed in water whereas M10 produces flakes. M14 is a highly weathered sample.

TABLE 6.3: SUMMARY OF DIFFERENT TREATMENTS USED IN X-RAY DIFFRACTION

Preparation method	Material	Purpose of treatment	Run (degrees)
Crushing whole rock to powder	-200 mesh (-0,075 mm)	To identify major non-clay constituents	1 - 32
Sedimenting +2 µm material	-2 µm (0,002 mm)	To identify clay constituents	1 - 12
Above slide heated at 575 °C for 1 hour	-2 µm (0,002 mm)	To differentiate vermiculite and montmorillonite from chlorite. Vermiculite and montmorillonite show a peak shift from 14 to 10Å. In addition the structure of kaolinite is destroyed and the structure of chlorite usually not	1 - 12
Glycolated sedimented -2 µm material	-2 µm (0,002 mm)	To differentiate montmorillonite from vermiculite and chlorite. The montmorillonite peak shifts from 14 to 17Å while vermiculite and chlorite remain unchanged	1 - 12
Acid-treated -2 µm material	-2 µm (0,002 mm)	To differentiate between chlorite and kaolinite. The chlorite structure is destroyed during acid treatment	1 - 12
$MgCl_2$-treated -2 µm material	-2 µm (0,002 mm)	To saturate all the montmorillonite on the different slides with the same (magnesium) ions for comparison of specimens	1 - 5
Above slide coated with glycerol	-2 µm (0,002 mm)	To distinguish montmorillonite from swelling vermiculite and chlorite. The treatment expands the montmorillonite to 17Å without affecting the vermiculite or chlorite to the same extent	1 - 5

TABLE 6.4: SCHEME OF PRESENCE OF MINERALS IN MUDROCK SAMPLES

Minerals	Sample number													
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
Quartz	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++	++++
Feldspar	++	++	++	++	++	++	++	++-+	+++		++	++	++	+
Mica or illite	+++	++	++	++	++	++	++	++-+	+	+++	+	+++	+	++
Chamosite	++-+	+	Tr			+	+-Tr	+-Tr		++	+	++	+	
Kaolinite			Tr	+	+									++
Chlorite		+[1]		+[2]	+	+[2]	+[4]	Tr		++[6]		Tr	+-Tr	Tr
Montmorillonite				Tr[3]	Tr	+-Tr	+		+[5]					
Vermiculite			+-Tr				+[4]							
Siderite											+++			
Talc														Tr
Unidentified											+[7]		+-Tr[8]	

Remarks

1. Chlorite montmorillonite interlayered
2. Fe-chlorite
3. Probably also chlorite, montmorillonite, illite interlayered
4. Vermiculite or Fe-chlorite
5. Montmorillonite probably mixed with illite
6. Chlorite probably interlayered with illite
7. 2,94Å peak
8. 3,04Å peak

Symbols for quantities present

++++ Very large percentage
+++ large percentage
++ Medium amount
+ Small amount
Tr Trace

(c) All the samples contain mica or illite. It is unfortunately very difficult to distinguish between these minerals in X-ray diffraction analysis.

(d) Chamosite (a chlorite-type clay with properties similar to kaolinite) is present in all but one of the Ecca and Beaufort mudrocks but absent in the Bokkeveld, Pretoria and Elliot mudrocks. Kaolinite is present in the mudrocks of the Bokkeveld and Pretoria Groups and a mixture of chamosite and kaolinite in the other Beaufort mudrock.

(e) Chlorite (often rich in iron) is present in small amounts or traces in 10 of the 14 samples. In the case of M1 it is probably interlayered with montmorillonite and in the case of M7 it may be Fe-chlorite or vermiculite.

(f) Montmorillonite, a highly expansive clay mineral, is not present in appreciable amounts. In four samples M2, M6, M7 and M9 small amounts are present while traces were detected in M4 and M5. M7 and M9 are disintegrating samples whereas M4 and M5 are somewhat weathered but nevertheless stable.

(g) Other minerals detected include a small amount or a trace of vermiculite in M3, a large amount of siderite in M11 and a possible trace of talc in M14.

6.5 Chemical composition

Major element analyses were performed on the 14 mudrock samples by the Geological Survey of South Africa. Fifty grams of representative crushed material from the same sample blocks from which the cubes for the free swell tests were sawn, were supplied for each sample. The X-ray spectrographic method followed was basically that given by Norrish and Hutton (1969) and involved the fusing and cooling of the sample to form a glass. Analyses were done with a Philips 1410 X-ray spectrometer using wavelength dispersive XRF. The results are given in Table 6.5. Table 6.6 gives the averages and the ranges of variation for the mudrocks.

A wide variation in composition is shown. Sample M9, a siltstone from the Elliot Formation which slakes when immersed in water, contains the highest percentage SiO_2 and the lowest percentage Al_2O_3. In contrast

TABLE 6.5: MAJOR ELEMENT ANALYSES OF MUDROCK SAMPLES

Sample no.	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
SiO_2	57,17	62,83	60,88	68,72	67,50	60,42	62,96	64,38	72,03	59,94	43,55	54,29	69,35	54,69
TiO_2	0,82	0,72	1,09	1,15	1,11	0,96	0,99	0,86	0,53	0,81	0,74	0,96	0,77	0,79
Al_2O_3	21,95	16,99	17,98	14,58	15,81	18,71	16,68	16,39	12,79	19,03	15,60	22,20	15,32	25,27
Fe_2O_3 (total iron)	6,25	5,75	6,56	5,71	6,38	5,49	6,39	5,77	2,94	5,16	15,23	5,44	4,99	8,47
MnO	0,07	0,09	0,33	0,16	0,09	0,21	0,14	0,06	0,04	0,09	0,37	0,07	0,09	0,03
MgO	2,26	1,87	6,67	6,02	5,38	5,33	5,48	1,95	1,72	1,91	3,65	2,09	2,20	1,01
CaO	0,67	1,28	1,64	0,59	0,55	0,95	1,14	0,80	1,02	0,44	4,09	0,56	1,37	0,06
Na_2O	1,05	1,87	1,00	0,87	1,18	1,10	0,57	1,50	1,40	0,77	0,60	0,78	1,61	0,25
K_2O	4,66	2,83	1,87	1,83	2,19	1,87	2,38	1,89	1,89	0,62	1,46	1,53	1,48	2,44
P_2O_5	0,30	0,23	0,68	0,60	0,50	0,47	0,50	0,38	0,37	0,57	0,61	0,53	0,38	0,58
Cr_2O_3	0,04	0,05	0,21	0,17	0,11	0,11	0,11	0,04	0,04	0,04	0,04	0,06	0,05	0,05
BaO	0,07	0,04	0,08	0,08	0,05	0,07	0,09	0,07	0,05	0,05	0,05	0,09	0,04	0,06
Total	95,31	94,54	98,99	100,48	100,85	95,80	97,43	94,09	94,82	89,43	85,99	88,60	97,65	93,70

Note: Analyses done by Geological Survey of South Africa

H_2O, C, and CO_2 not determined

sample M13, shown to be a very durable sample in later work, contains the second largest percentage SiO_2 and is also low in Al_2O_3. Samples M1 and M12, largely similar in properties, differ markedly in K_2O content while M2 and M13, also alike, differ in SiO_2 and K_2O content. In the same way samples M7 and M10 contain markedly different quantities of MgO, CaO and K_2O. It therefore seems unlikely that chemical composition can be used as an indicator of mudrock properties.

TABLE 6.6: AVERAGES AND RANGES OF CHEMICAL COMPOSITIONS OF 14 MUDROCK SAMPLES

Element	Average percentage	Range of variation percentage
SiO_2	61,3	43,6 - 72,0
TiO_2	0,9	0,5 - 1,2
Al_2O_3	17,8	12,8 - 25,3
Fe_2O_3	6,5	2,9 - 8,5
MnO	0,1	0 - 0,4
MgO	3,4	1,0 - 6,7
CaO	1,1	0,1 - 4,1
Na_2O	1,0	0,3 - 1,7
K_2O	2,1	0,6 - 4,7
P_2O_5	0,5	0,2 - 0,7
Cr_2O_3	0,1	0 - 0,2
BaO	0,1	0 - 0,1

CHAPTER 7

INDICATOR, COMPACTION AND CBR TESTS

7.1 Introduction

In this chapter the results from standard tests generally carried out when a material is evaluated for use in subbase or below, are discussed. Hydrometer tests were included to investigate the distribution of the fines in more detail. Sample M13 was not subjected to these tests because of a shortage of material. All the tests were done on rocks crushed to minus 19 mm as described in Section 5.2.4. Methods specified by the Department of Transport (1971) were followed.

7.2 Grading and hydrometer analyses

Grading analyses were done using methods A1(a) and A1(b) - wet and dry preparations respectively. The wet preparation is the more standard procedure at the NITRR and other roads laboratories and these grading results are given in Table 7.1 and plotted in Figures 7.1 to 7.4. The results are averages of duplicate or triplicate determinations. The results from hydrometer analyses, carried out on the minus 0,075 mm material of the wet-prepared samples, according to methods A5 and A6, are included. The hydrometer method involves the suspension of the fines in distilled water and the measurement of the specific gravity with a hydrometer at various times during the sedimentation period. These were carried out on single samples.

An ideal grading envelope, which brackets the area in which a grading curve should lie to provide a very dense packing during compaction was calculated from the formula (NITRR, 1970):

$$\left(\frac{P1}{P2}\right) = \left(\frac{D1}{D2}\right)^n$$

Where P1 = 100 (percentage passing D1)

D1 = 19,0 mm (maximum grain size)

P2 = percentage passing specific mesh openings defined in D2

D2 = mesh opening, e.g. 13,2; 9,5; 6,7 mm, etc.

n was taken as 0,50 and 0,33 as in NITRR (1970)

TABLE 7.1: GRADINGS OF FRESHLY CRUSHED MUDROCK SAMPLES (SIEVE AND HYDROMETER ANALYSES)

Sieve opening or grain size (mm)	CUMULATIVE PERCENTAGES PASSING												
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M14
19,0	100	100	100	100	100	100	100	100	100	100	100	100	100
13,2	63,3	61,6	60,5	61,2	61,3	65,1	94,5	58,5	98,1	85,5	62,1	70,8	66,9
9,5	42,0	45,5	38,0	42,2	44,5	41,5	82,7	39,5	94,5	65,5	42,7	49,8	49,4
6,7	29,3	33,0	25,3	30,5	32,4	28,5	66,0	27,1	83,8	46,9	30,6	33,5	41,5
4,75	23,8	27,0	20,6	24,7	26,8	21,2	50,0	21,8	74,1	38,4	25,3	27,3	34,3
2,00	10,9	15,3	9,5	14,3	16,2	11,3	15,5	10,8	52,1	17,1	14,9	13,7	27,7
0,85	5,7	9,6	5,3	9,7	10,9	7,3	8,4	6,1	43,8	9,4	10,2	8,1	25,0
0,425	3,6	7,3	3,4	7,4	8,2	5,6	5,9	4,1	41,6	6,6	8,1	5,7	23,7
0,250	2,6	5,8	2,8	6,7	7,5	5,0	5,4	3,3	40,9	5,6	7,5	5,2	23,2
0,150	1,9	4,6	2,3	5,9	6,6	4,6	4,8	2,5	40,2	4,7	7,0	4,5	22,8
0,075	1,4	3,7	1,9	4,9	5,5	4,3	4,3	1,9	33,6	3,9	6,3	3,8	22,2
0,060	1,5	3,5	1,7	4,3	4,9	3,9	4,0	1,8	30,7	3,1	4,4	2,9	12,3
0,020	1,2	2,8	1,3	3,0	3,4	3,3	3,4	1,4	14,4	2,2	2,8	2,1	11,0
0,006	0,8	2,5	1,0	2,0	2,4	2,2	2,6	1,0	10,2	1,8	1,9	1,5	-
0,002	0,4	1,4	0,7	1,3	1,5	1,6	1,8	0,9	7,3	1,2	1,3	0,9	4,2
% Accuracy (80% C.I.)	-	1,9	5,4	4,1	9,0	1,7	2,7	3,0	9,1	4,1	3,3	3,1	26,4

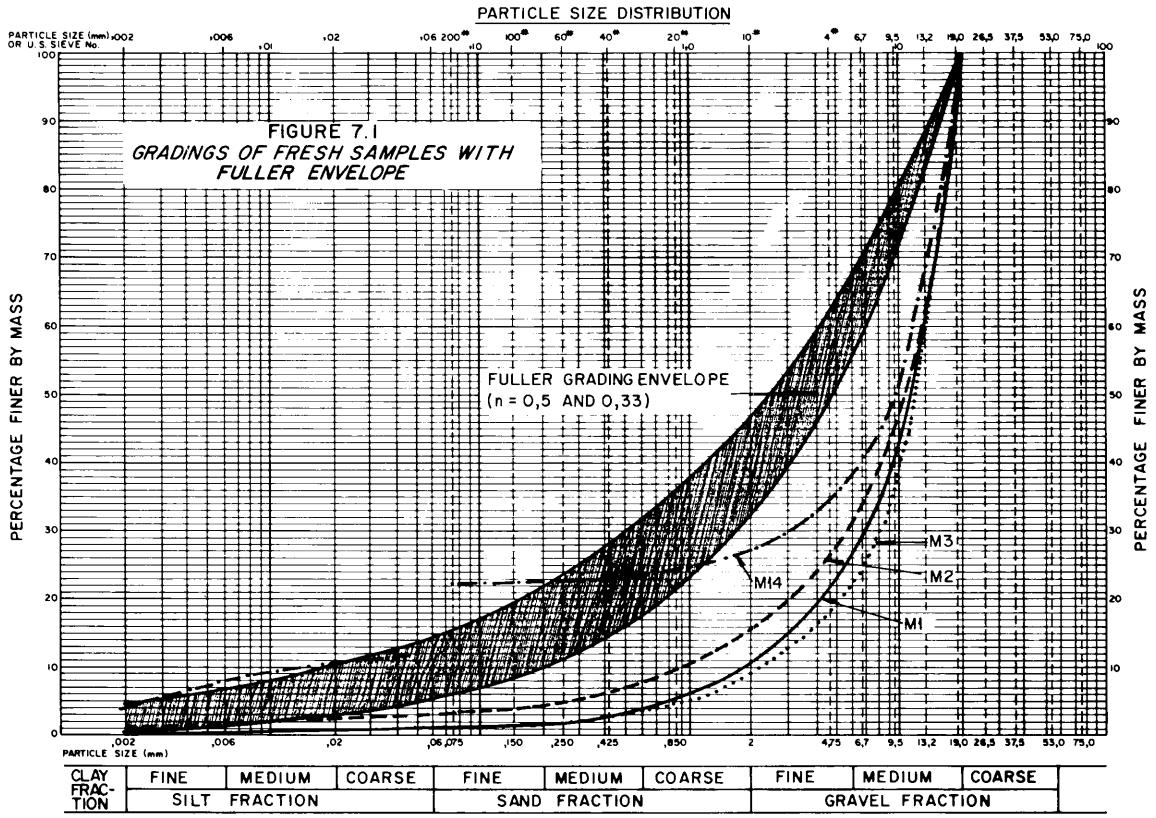


FIGURE 7.1
GRADINGS OF FRESH SAMPLES WITH FULLER ENVELOPE

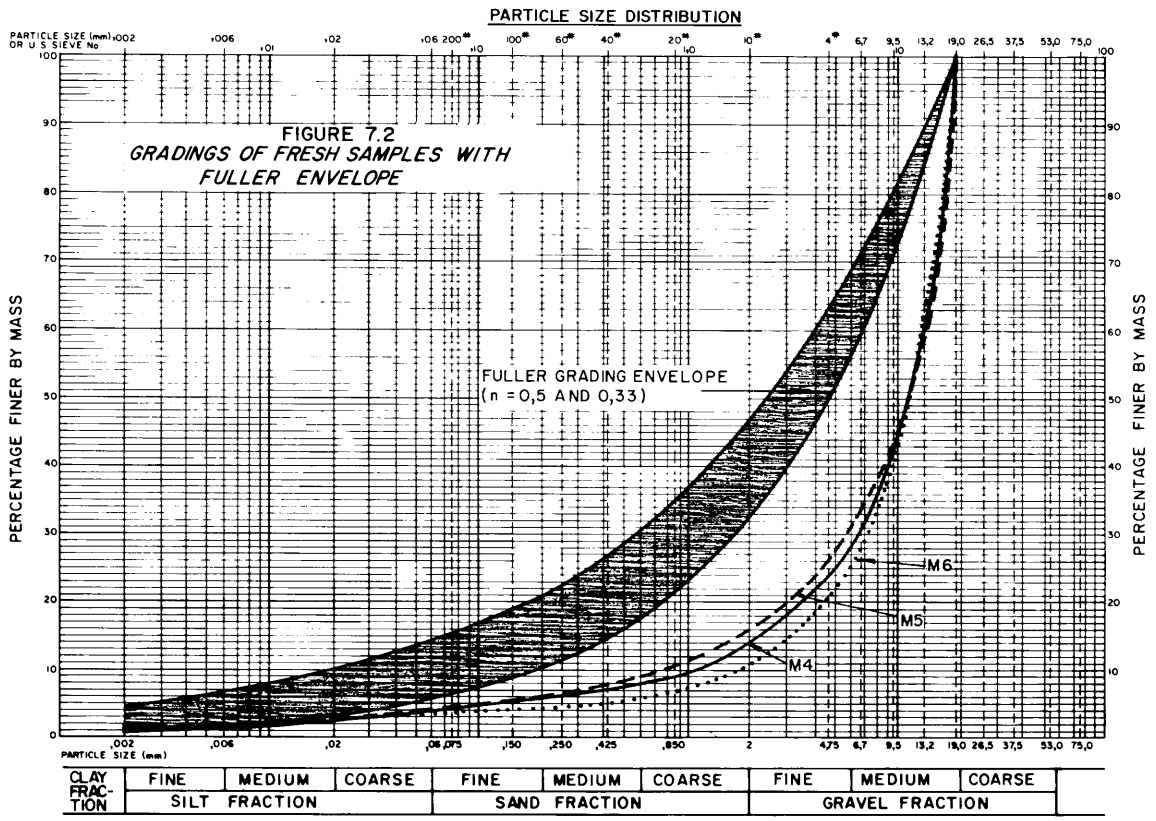


FIGURE 7.2
GRADINGS OF FRESH SAMPLES WITH FULLER ENVELOPE

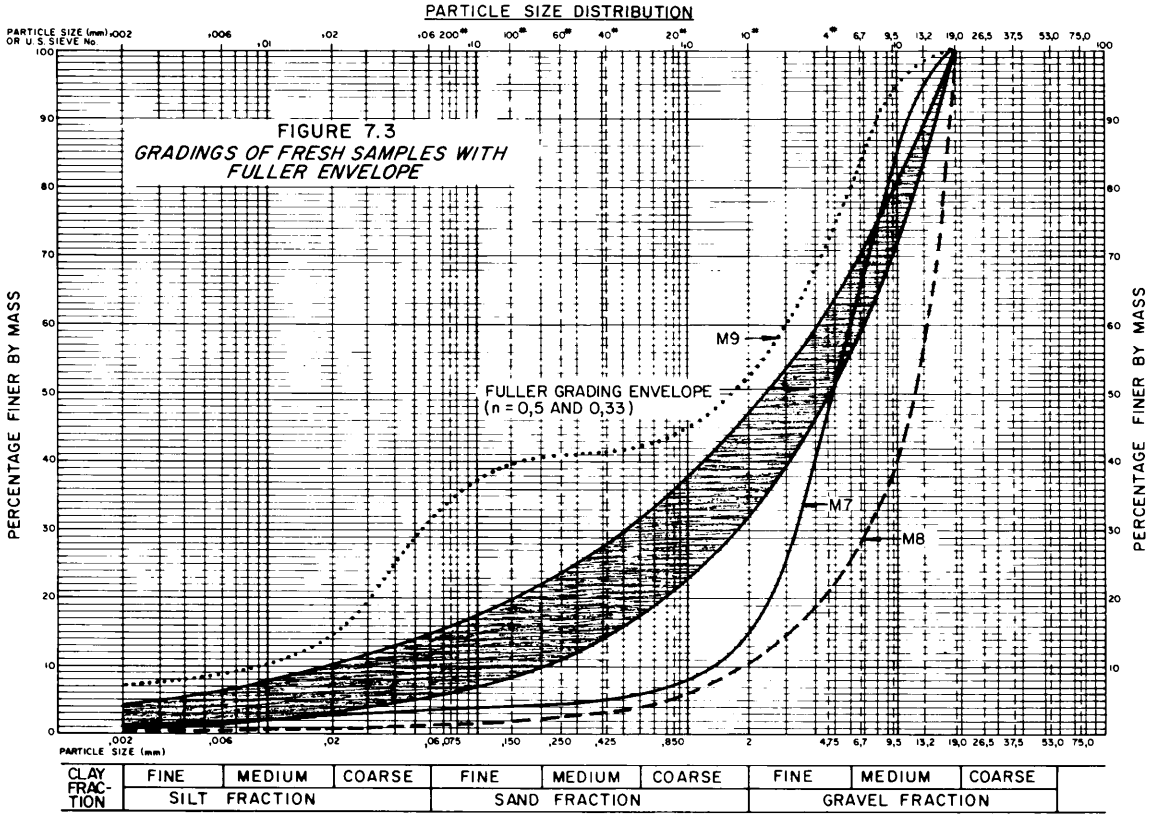


FIGURE 7.3
GRADINGS OF FRESH SAMPLES WITH FULLER ENVELOPE

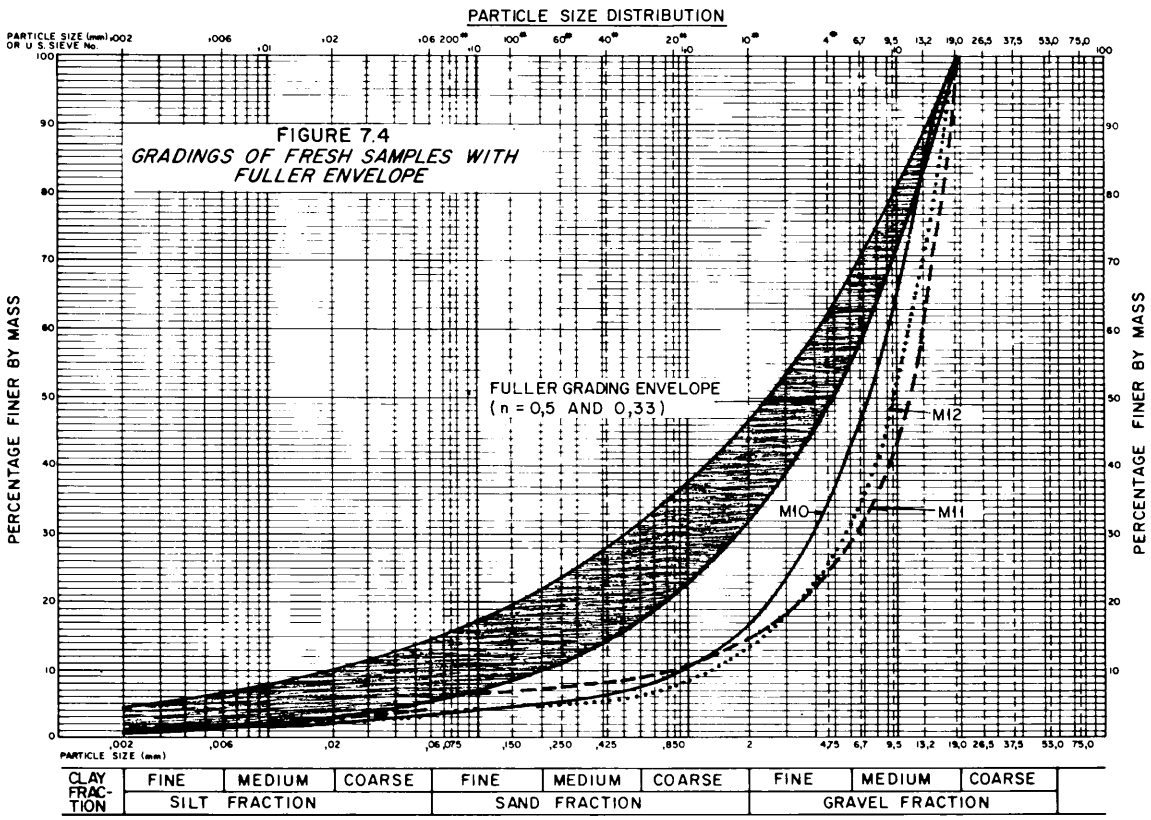


FIGURE 7.4
GRADINGS OF FRESH SAMPLES WITH FULLER ENVELOPE

This envelope is given on each of Figures 7.1 to 7.4. The gradings of samples M1, M2, M3, M4, M5, M6, M8, M11 and M12 - nine of the thirteen samples - are similar, but none of these gradings lies within this envelope. All of them are too coarse. Samples M7 and M10 are finer grained but still outside the envelope while M9 and M14 are completely or partly on the fine-grained side of the envelope. Apart from the latter two samples, all the mudrock samples thus showed a lack of fines. The point is further illustrated in Table 7.2 where the cumulative percentages passing the 2,0; 0,075 and 0,002 mm sizes are listed.

TABLE 7.2: CUMULATIVE PERCENTAGES OF CRUSHED SAMPLES PASSING 2,0; 0,075 AND 0,002 mm

Sample number	Cumulative percentages passing		
	2,0 mm	0,075 mm	0,002 mm
M1	10,9	1,4	0,4
M2	15,3	3,7	1,4
M3	9,5	1,9	0,7
M4	14,3	4,9	1,3
M5	16,2	5,5	1,5
M6	11,3	4,3	1,6
M7	15,5	4,3	1,8
M8	10,8	1,9	0,9
M9	52,1	33,6	7,3
M10	17,1	3,9	1,2
M11	14,9	6,3	1,3
M12	13,7	3,8	0,9
M14	27,7	22,2	4,2

Only two samples, M9, a siltstone which disintegrates in water after drying, and M14, a weathered mudstone, lost more than 18 per cent through

2,0 mm. Excluding the above samples, maximum percentages of 6,3 and 1,8 were lost through the 0,075 and 0,002 mm sizes respectively. This lack of fines in some crushed mudrocks explains why the Cape Provincial Roads Department often finds it advantageous to add a binder for better compaction (Section 3.3.11).

Differences in gradings, resulting from wet and dry preparations, are illustrated in Table 7.3 for a few selected samples and sieve openings.

TABLE 7.3: COMPARISON OF GRADINGS WHEN DRY AND WET PREPARATION METHODS ARE USED

Sample number	Cumulative percentage passing							
	13,2 mm		6,7 mm		2,0 mm		0,425 mm	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
M9	61,6	98,1	33,5	83,8	17,2	52,1	10,8	41,6
M10	72,1	85,5	33,8	46,9	10,4	17,1	2,7	6,6
M11	58,2	62,1	29,4	30,6	13,8	14,9	7,2	8,1
M12	64,9	70,8	30,2	33,5	12,4	13,7	4,8	5,7
M14	62,0	66,9	35,3	41,5	19,0	27,7	7,2	23,7

Samples such as M9 and M14 showed considerably higher losses when prepared wet. The other samples were not affected to the same extent but losses were always higher with the wet-prepared samples. It is recommended that the wet preparation be followed for gradings on mudrocks as this gives a better indication of the nature of the material.

7.3 Liquid limit, plastic limit and linear shrinkage

These tests are used to obtain an idea of the plasticity and volume change characteristics of aggregates. If the fines have a high plasticity and constitute a fair proportion of the aggregate, a low shear strength is indicated if the compacted material in a road should become wet. Likewise a high linear shrinkage would indicate a possible volume change of the compacted material.

These tests were performed according to test methods A2, A3 and A4. The results are given in Table 7.4.

TABLE 7.4: ATTERBERG LIMITS AND LINEAR SHRINKAGE OF CRUSHED MUDROCKS

Sample number	Liquid limit %	Plastic limit %	Plasticity index (PI)	Linear shrinkage %
M1	n.d.	n.d.	NP	n.d.
M2	22,4	n.d.	NP	1,0
M3	21,5	n.d.	NP	1,7
M4	23,1	n.d.	NP	2,0
M5	23,1	19,3	3,8	1,3
M6	29,5	22,5	7,0	4,7
M7	28,9	23,0	5,9	5,3
M8	n.d.	n.d.	NP	n.d.
M9	22,7	17,9	4,8	2,3
M10	23,8	15,9	7,9	3,5
M11	22,3	17,9	4,4	1,7
M12	18,9	17,7	1,2	1,0
M14	38,2	29,0	9,2	3,0

NP = Non-plastic

n.d. = Not done on account of low plasticity

Low values were obtained for the majority of the samples in all the tests. The low values resulted in some erratic results for the plasticity index and linear shrinkage.

The results showed that these mudrocks generally have quite low plasticity indices, contrary to what some engineers believe. Five samples were non-plastic and only four samples had plasticity indices above 5,0. The latter samples were also the only ones with linear shrinkages of 3,0 per cent or more. The relations between PIs and linear shrinkages varied widely, probably because of the generally low values. Netterberg (1971) states that "a commonly used rule of thumb is that the PI is equal to about twice the linear shrinkage". For the eight plastic samples the PIs

were from 1,1 to 3,1 times the value of the linear shrinkages.

NITRR (1970) specifies a maximum PI of 12 for subbase if less than 30 per cent of the material passes the 2,0 mm sieve. All the samples fall well within this specification. In the case of M9 more than 30 per cent passed this sieve but this sample has a PI of only 4,8 and it, therefore, qualifies as well.

7.4 Maximum dry density and optimum moisture content

This test is used to determine the optimum moisture content for a certain compaction effort i.e. the Modified AASHTO effort. The material is compacted in a mould in five successive layers by subjecting each layer to 55 blows with a 4,54 kg hammer. Different lots of material are mixed with various percentages of water. The percentage moisture at which the material is compacted to the highest density is referred to as the optimum moisture content (OMC). The density of the dried compacted material at this point is called the maximum dry density (MDD). Apparatus used in this test is shown in Plate 12 (Chapter 8).

The test were carried out according to test method A7. The dry densities obtained during the compactions at various moisture contents are shown in Figures 7.5 to 7.7. It can be seen that the results for the first eight samples (M1 to M8) were not satisfactory. Laboratory personnel at the NITRR expressed the view that the determination of these constants for mudrocks was a general problem. However, when very strict control was exercised and an experienced technician employed, the results improved markedly for the other samples (M9 to M14). This is clearly evident from the general improvement in percentage accuracy for the latter samples. The additional results obtained during the Modified AASHTO compactions in the California bearing ratio (CBR) tests are also plotted on the graphs. The results are summarized in Table 7.5.

Maximum dry densities and optimum moisture contents for the mudrocks varied considerably; from 1886 to 2310 kg/m^3 and from 3,6 to 15,5 per cent. The average maximum dry density was 2089 kg/m^3.

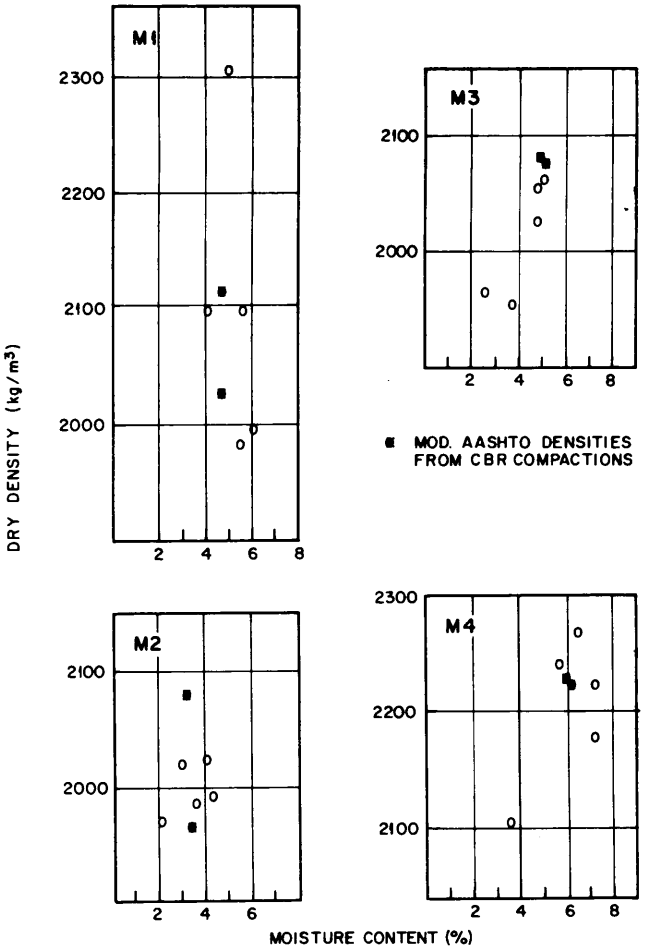


FIGURE 7.5
DRY DENSITY AGAINST MOISTURE CONTENT

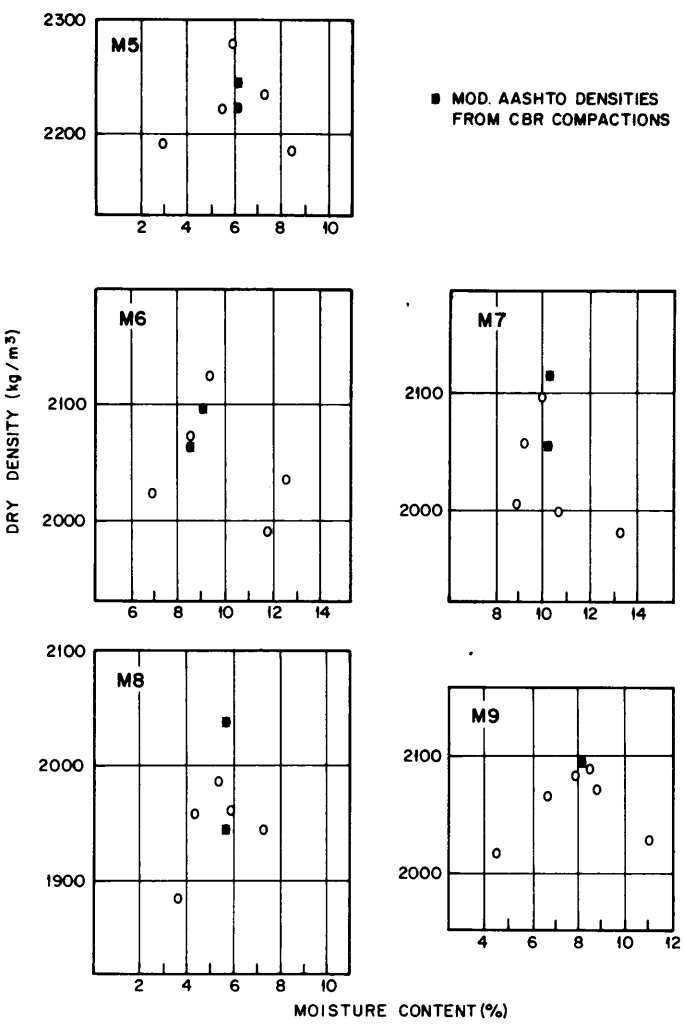


FIGURE 7.6
DRY DENSITY AGAINST MOISTURE CONTENT

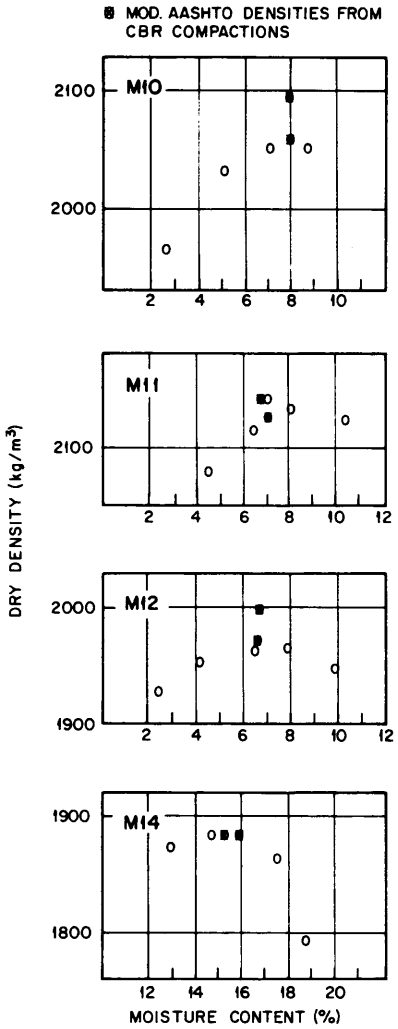


FIGURE 7.7
DRY DENSITY AGAINST MOISTURE CONTENT

TABLE 7.5: MAXIMUM DRY DENSITIES AND OPTIMUM MOISTURE CONTENTS FOR THE CRUSHED MUDROCK SAMPLES

Sample number	Maximum dry density kg/m^3	Optimum moisture content %
M1	2310	5,0
M2	2060	3,6
M3	2065	5,0
M4	2265	6,5
M5	2281	5,8
M6	2130	9,5
M7	2100	10,0
M8	1988	5,3
M9	2092	8,3
M10	2054	8,0
M11	2141	7,0
M12	1964	6,5
M14	1886	15,5

7.5 California bearing ratio

7.5.1 Introduction

The CBR test is used in southern Africa and in many other parts of the world to determine the load bearing capacities of road building aggregates in the compacted state.

7.5.2 Method

Test method A8 was used to determine the CBRs of the mudrock samples. The method involves the compaction of minus 19 mm material in moulds using

standard compaction efforts. Compactions are done at OMC. The three standard efforts used are summarized in Table 7.6 and some of the equipment is shown on Plate 12.

TABLE 7.6: COMPACTION EFFORTS USED IN CBR TEST

Compaction designation	Mass of tamper used kg	Length of drop mm	Number of layers compacted	Number of blows per layer	Compaction energy applied kJ/m^3
Modified AASHTO	4,5	457	5	55	2413
National Roads Board (NRB)	4,5	457	5	25	1096
Standard Proctor	2,5	305	3	55	531

The compacted material in the moulds is soaked for four days to introduce the weakening effect of water and to determine volume changes, i.e. swells or shrinkages. The surface of the material is then penetrated at a uniform rate by a plunger. The loads (Newtons) required to penetrate the material to certain depths are calculated as percentages of standard values. These percentages are called CBRs and are calculated for 2,54; 5,08 and 7,62 mm penetrations. The CBR value most often quoted is for 2,54 mm penetration for Modified AASHTO compacted material.

All the tests were done in duplicate. As in the case of the OMC and MDD determinations, the results for samples M1 to M8 were not entirely satisfactory because of differences in the results for duplicate samples. This again improved markedly for samples M9 to M14 where very strict control was exercised during testing. The results for all the samples (averages of duplicates) are given in Table 7.7. The percentage accuracies for samples M1 to M8 and M9 to M14 were calculated separately to illustrate the improvement in the repeatability of results.

7.5.3 Discussion

CBR values

NITRR (1970) specifies a soaked CBR of at least 45 for subbase at 95

TABLE 7.7: RESULTS OF CALIFORNIA BEARING RATIO TESTS

Sample number		Modified AASHTO					NRB					Standard Proctor				
		Density kg/m^3	% CBR at penetration mm			Swell (+) or shrinkage (-) %	Density kg/m^3	% CBR at penetration mm			Swell (+) or shrinkage (-) %	Density kg/m^3	% CBR at penetration mm			Swell (+) or shrinkage (-) %
			2,54	5,08	7,62			2,54	5,08	7,62			2,54	5,08	7,62	
M1		2069	23	33	38	0,09-	1914	22	27	30	0,01-	1938	29	32	33	0,04+
M2		2023	54	69	78	0,03-	1868	13	22	27	0,16-	1791	17	23	26	0,04-
M3		2079	64	77	76	0,03-	1863	24	31	37	0,07-	1741	12	19	22	0,16-
M4		2226	53	84	86	0,08+	2033	39	44	49	0,01+	2009	41	49	53	0
M5		2235	82	95	-	0,03+	2074	43	53	54	0,01+	2010	35	41	41	0,01+
M6		2084	49	57	64	0,02-	1884	25	26	26	0,01+	1816	20	20	20	0,01+
M7		2087	31	44	48	0,07+	1916	24	29	30	0,01+	1783	19	20	19	0,01-
M8		1993	55	75	76	0,09-	1847	40	49	56	0,17-	1778	11	18	27	0,12-
M9		2083	55	68	70	0,19+	1975	25	28	28	0,17+	1925	19	19	19	0,14+
M10		2078	27	33	36	0,15+	1912	16	19	19	0,11+	1795	10	12	13	0,04-
M11		2134	45	57	64	0,02+	2002	20	26	28	0,01-	1903	15	19	21	0,01+
M12		1986	36	45	52	0,01+	1840	14	18	22	0,02-	1765	14	18	20	0,04+
M14		1894	36	41	55	1,02+	1833	27	30	27	0,92+	1764	18	18	18	0,44+
% accuracy (80% C.I.)	Samples M1-M8	2,1	37,0	32,1	24,9		2,8	41,2	31,0	27,0		2,5	32,3	25,8	23,9	
	Samples M9-M14	7,6	6,3	7,8	21,8		5,1	9,9	6,5	7,5		9,5	18,8	11,9	9,4	

per cent Modified AASHTO compaction for the wetter parts of southern Africa and a CBR of at least 25 at the same conditions for the drier regions. Eight of the mudrock samples satisfy the criterion for the drier regions whereas three are also suitable for use in subbase in the wetter parts. It is also highly likely that the CBR values of samples such as M1, M2, M3, M8 and M12 can be improved by the addition of a binder. All the samples pass the NITRR (1970) specification for the selected layer.

A surprising result is the high CBR value obtained for sample M9. This material was dumped and not used for construction as it was considered unsuitable for use in fill.

CBR swells and shrinkages

These parameters are listed in Table 7.7 and it can be seen that there is an almost equal distribution of samples showing swell and shrinkage. The volume changes very rarely exceed 0,2 per cent. Samples M9 and M10 expanded nearly 0,2 per cent while M14 reached 1,02 per cent in the 100 per cent compacted sample. NITRR (1970) allows an expansion of 0,5 per cent for subbase material. The mudrock samples, except for M14 which is a highly weathered rock, are all well within this limit after soaking for four days.

7.6 California bearing ratio (lime-treated material)

7.6.1 Introduction

From the survey done (Section 3.3.11) it is clear that lime is the most popular and suitable chemical stabilization agent for mudrocks in southern Africa. This is mainly due to changes brought about in the clay minerals and the long-term reactions with these minerals to form cementitious material.

7.6.2 Method

Test method A9 was used to determine the treated CBR values. This method is identical to method A8, apart from the intermixing of a certain

percentage of lime with the crushed material and the use of a seven day curing period before soaking for four days. In this study four per cent lime was added to all the samples. The results, usually averages of duplicate tests, are summarized in Table 7.8. Because of a shortage of material for samples M2 and M3, the material extracted from the moulds in test A7 (OMC and MDD determination) was re-used for these two samples.

7.6.3 Discussion

CBR values

NITRR (1970) requires a minimum CBR of 70 at 95 per cent Modified AASHTO compaction for subbase material. Seven of the samples pass this specification and samples such as M1, M2 and M12 may also improve if a binder, such as a sandy river deposit, is added.

Comparison of untreated and treated CBR values

Table 7.9 lists the average CBR values for 2,54 mm penetration for material compacted by the Modified AASHTO effort for the untreated material and the material treated with four per cent lime.

From the results listed in the table it is evident that lime treatment has a marked positive effect on the strength of compacted mudrock. In 11 of the 13 mudrocks tested, the CBR values more than doubled. In two of these, values trebled while for sample M7 it increased fourfold.

Treated CBR swells and shrinkages

Higher volume changes were observed for the treated than for the untreated samples. Some samples shrank more while others swelled more. The highest volume changes were around 0,5 per cent. For sample M14, however, the expansion was reduced to a negligible amount through stabilization.

Experiments to determine the volume change characteristics of certain roadbuilding materials, including some mudrocks, were performed by Weston and Venter (1978). Unfortunately a relatively large margin of error exists in the determination of volume changes through the CBR method due to the inaccuracy of the measurements. The results indicated, however, that shrinkages could result from treatment of mudrocks with lime and especially

TABLE 7.8: RESULTS OF CALIFORNIA BEARING RATIO TESTS - MATERIALS TREATED WITH 4 PER CENT LIME

Sample number	Modified AASHTO					NRB					Standard Procter				
	Density kg/m^3	% CBR at penetration mm			Swell (+) or shrinkage (-) %	Density kg/m^3	% CBR at penetration mm			Swell (+) or shrinkage (-) %	Density kg/m^3	% CBR at penetration mm			Swell (+) or shrinkage (-) %
		2,54	5,08	7,62			2,54	5,08	7,62			2,54	5,08	7,62	
M1	2041	65	80	77	0,13-	1936	44	55	57	0	1797	26	32	33	0,06-
M2	2015	57	72	-	-	1943	40	54	60	-	1883	28	38	48	-
M3	2084	156	-	-	-	1947	68	69	73	-	1892	55	63	62	-
M4	2164	139	-	-	0,53+	2028	90	101	-	0,54+	1911	60	66	67	0,54+
M5	2150	111	-	-	0,51+	2000	86	97	-	0,66+	1950	56	63	64	0,52+
M6	2020	132	-	-	0,15-	1913	78	85	-	0,14-	1830	61	61	60	0,17-
M7	1946	124	-	-	0,15-	1797	46	49	50	0,10-	1726	45	42	42	0,18-
M8	1941	118	-	-	0,51-	1815	58	63	65	0,50-	1780	57	63	66	0,50-
M9	2010	165	-	-	0,49-	1940	99	94	-	0,50-	1851	44	42	41	0,45-
M10	2039	91	-	-	-	1896	38	41	43	-	1793	31	33	32	-
M11	2066	113	-	-	-	2026	84	82	80	-	1826	23	27	29	-
M12	2022	96	-	-	0,05-	1886	45	47	49	0	1783	32	35	36	0,09-
M14	1849	85	79	69	0,06-	1806	55	54	51	0,02-	1724	33	30	29	0,08-
% accuracy (80% C.I.)	1,2	8,0	-	-		FEW DUPLICATES AVAILABLE					0,2	9,9	8,3	8,5	

TABLE 7.9: COMPARISON OF CBR VALUES FOR TREATED AND UNTREATED MATERIAL

Sample number	CBR for untreated material	CBR for material treated with lime	$\frac{\text{Treated}}{\text{Untreated}} \times 100$ %
M1	23	65	283
M2	54	57	106
M3	64	156	244
M4	53	139	262
M5	82	111	135
M6	49	132	269
M7	31	124	400
M8	55	118	215
M9	55	165	300
M10	27	91	337
M11	45	113	251
M12	36	96	267
M14	36	85	236

lime-slagment. At the moment no limits are set for shrinkages. Further investigations, possibly using more accurate ways of measuring volume changes of compacted, stabilized material, should be carried out as excessive shrinkages may cause cracking of asphalt surfacings of roads.

Atterberg limits and linear shrinkage

Table 7.10 summarizes the changes in Atterberg limits and linear shrinkages for the untreated and treated mudrock samples.

All the liquid and plastic limits increased after the addition of lime, curing and soaking. The majority of PIs also increased. M6 did not change while the values for M9, M10 and M14 decreased.

Increases in liquid limit ranged from slight (M14 - 13 per cent) to more than double (M2 - 105 per cent). The average increase was 55 per cent. In the same way the increases in plastic limit ranged from 23 per cent (M14) to 94 per cent (M2) with an average increase of 64 per cent.

TABLE 7.10: COMPARISON OF ATTERBERG LIMITS AND LINEAR SHRINKAGES BEFORE AND AFTER TREATMENT WITH FOUR PER CENT LIME

Sample number	Liquid limit %		Plastic limit %		Plasticity index (PI)		Linear shrinkage %	
	Before	After	Before	After	Before	After	Before	After
M2*	19,0	39,0	16,8	32,7	2,2	6,3	2,3	1,3
M3*	20,4	40,0	18,6	31,2	1,8	8,8	2,0	2,3
M4	23,1	32,4	n.d.	26,0	NP	6,4	2,0	2,0
M5	23,1	32,0	19,3	25,4	3,8	6,6	1,3	1,7
M6	29,5	45,0	22,5	38,0	7,0	7,0	4,7	3,2
M7	28,9	48,2	23,0	40,3	5,9	7,9	5,3	
M8	n.d.	34,5	n.d.	30,3	NP	4,2	n.d.	2,0
M9	22,7	30,2	17,9	27,0	4,8	3,2	2,3	2,0
M10	23,8	30,6	15,9	29,5	7,9	1,1	3,5	3,0
M11	22,3	38,0	17,9	32,6	4,4	5,4	1,7	2,7
M12	18,9	31,0	17,7	27,9	1,2	3,1	1,0	2,4
M14	38,2	43,2	29,0	35,7	9,2	7,5	3,0	2,0

* Results different from Table 7.4 as extracted MDD, OMC samples were used for stabilization.

n.d. = not determined on account of low plasticity

NP = non-plastic

PI increases ranged from slight to more than fourfold while one sample decreased from about 8 to 1. The increases may be partly due to the addition of a relatively large percentage of very fine-grained lime, which in itself exhibits plasticity, to the relatively low percentage of natural fines. The lime which does not react during the curing and soaking periods, may then be responsible for the increase in plasticity in some of the samples. Linear shrinkages changed randomly. Five samples showed decreases in linear shrinkages and four showed increases.

7.7 Summary

(a) The crushed mudrocks, apart from the weathered and soft types, generally do not contain enough fines for proper compaction. Their grading

curves fall outside the ideal grading envelope (Figures 7.1 to 7.4). This confirms the beneficial effects of the addition of a binder when compacting hard mudrocks.

(b) The wet preparation method should be used for the grading analyses of mudrocks.

(c) Most of the mudrocks sampled were non-plastic or had low plasticities and therefore conformed to most road building specifications. Only two of the mudrock samples yielded values of more than 7,0.

(d) The CBRs (Mod. AASHTO compaction at 2,54 mm penetration) of the freshly crushed samples varied from 23 to 82. Measurements of swells and shrinkages during the soaking period are not very accurate. The values obtained, however, were very low and except for one weathered sample, were well within South African specifications for subbase material.

(e) The addition of four per cent lime lead to an increase in CBR strengths. Values for most of the samples more than doubled while one value increased fourfold (Table 7.9, Mod. AASHTO values at 2,54 mm penetration). All the plastic and liquid limits increased when lime was added, as did most of the PIs.

CHAPTER 8

ACCELERATED WEATHERING USING COMPACTIONS AND WET-DRY CYCLES

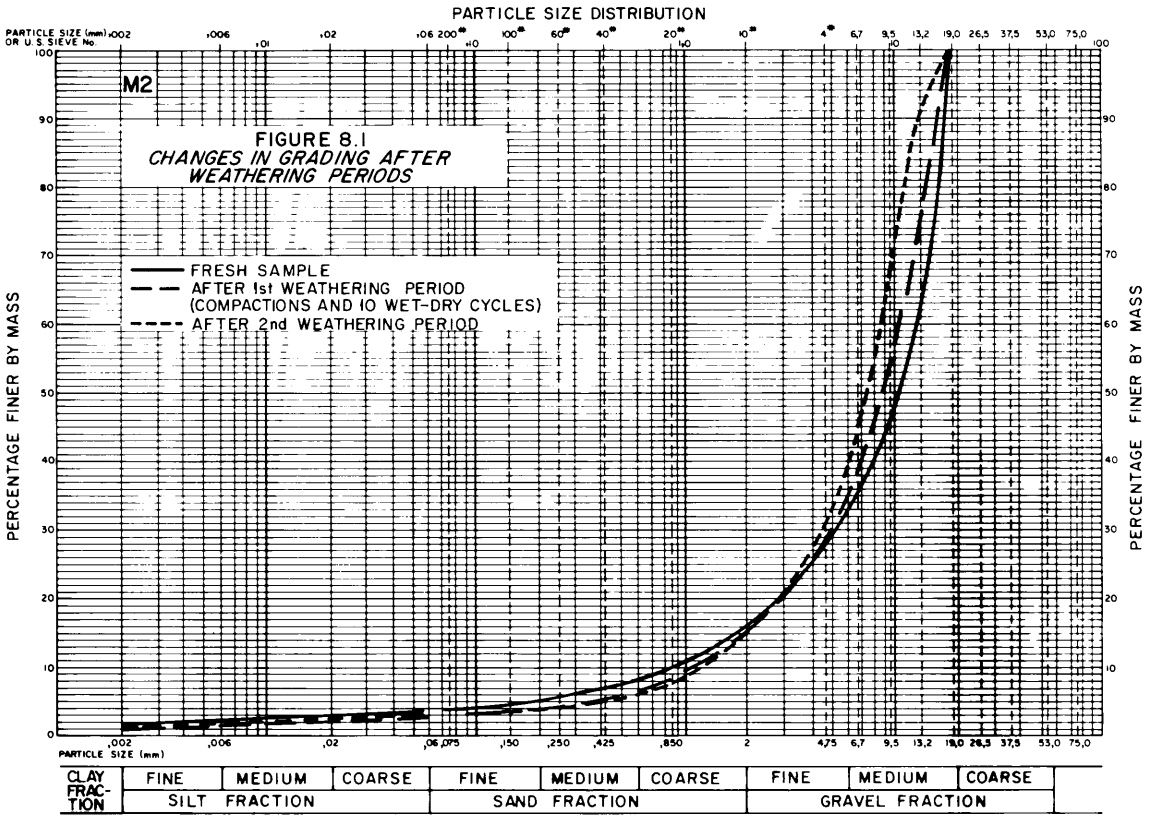
8.1 Introduction

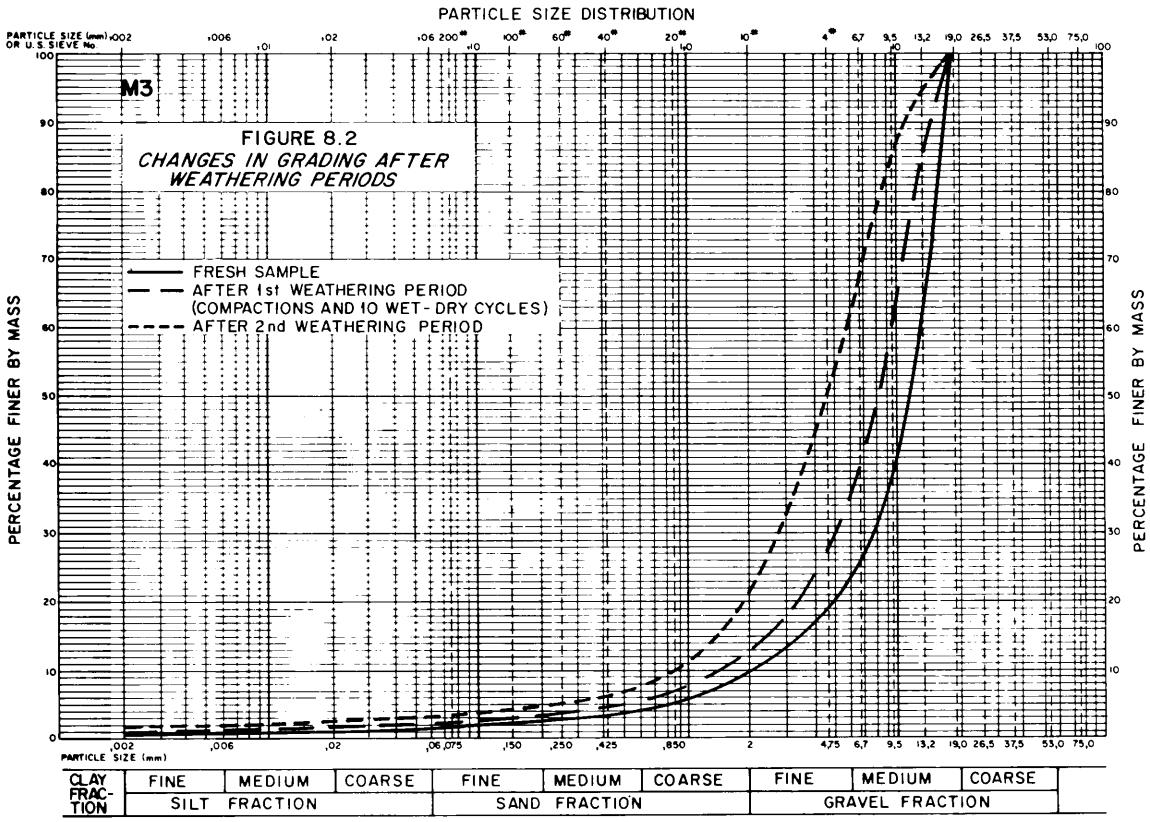
An accelerated weathering test using compactions and wet-dry cycles was developed during the pilot study (Section 5.2.6). This test was performed on samples M2 to M14 (excluding M13). Gradings, hydrometer analyses, Atterberg limits, linear shrinkages and CBR compactions were done on the fresh samples. The results from the tests on the fresh samples are represented by (O) e.g. M2(O) in Table 8.1 The material extracted from the moulds was dried, subjected to ten wet-dry cycles and retested. These results are listed as "after the first weathering period" or as M2(1) in Table 8.1. The whole process was repeated to produce samples which were listed as "after the second weathering period" or M2(2).

8.2 Gradings

The changes in grading (including hydrometer analysis results) are illustrated in Figures 8.1 to 8.12. These graphs give information on a very important property of the mudrocks i.e. the rate and character of break-down due to wetting and drying and compaction. To a certain extent it simulates the behaviour of material which is excavated, exposed to the elements for a certain period and compacted in a road pavement.

All the mudrock samples broke down to some extent during these weathering periods but while samples such as M2 did not change much, samples M14 and especially M9 changed drastically. For sample M9 the percentage passing 0,075 mm changed from 34 per cent in the fresh sample to 89 per cent after the first weathering period. This sample, therefore, slaked almost to its constituent particles. When the curves are studied, differences in the patterns of breaking down can be seen. Samples M7 and M14 suffered a general reduction in aggregate sizes. The same happened to M6, M10 and M11 but not to the same extent. Samples M4 and M5, two samples of the Bokkeveld Group, broke down but showed a tendency towards more





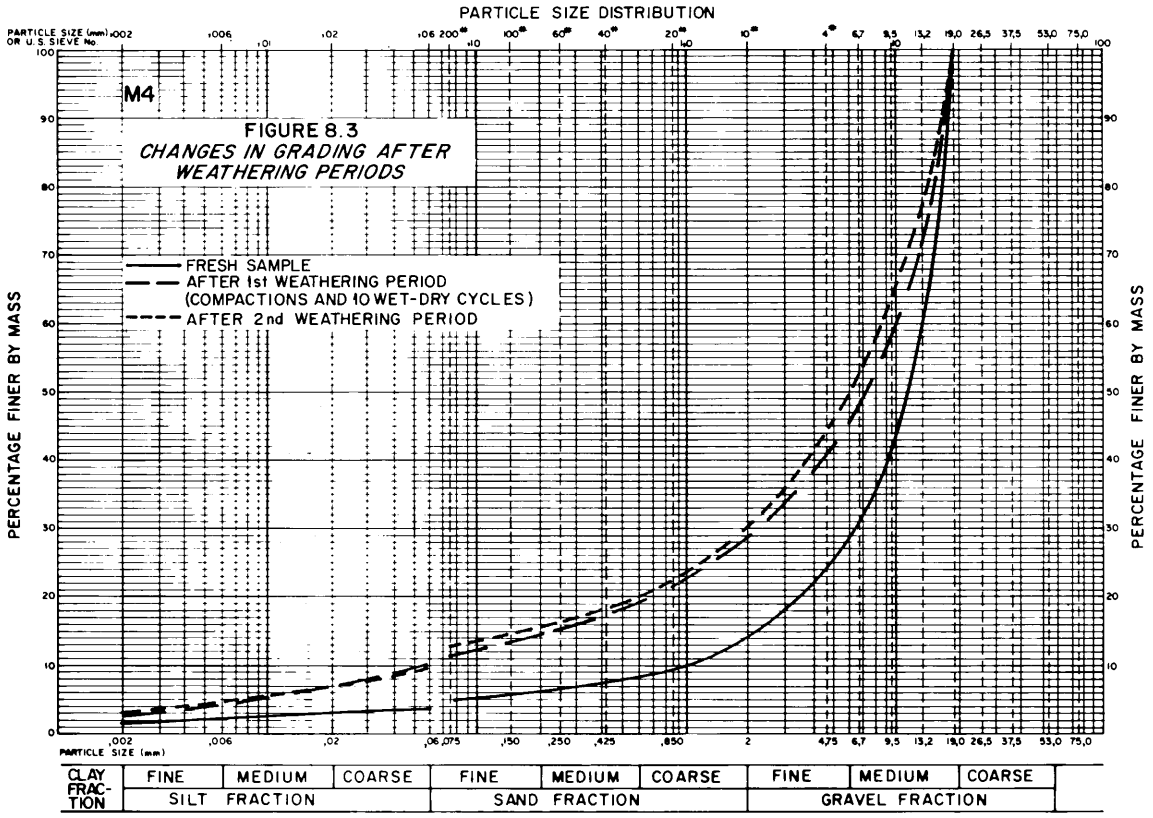


FIGURE 8.3
CHANGES IN GRADING AFTER WEATHERING PERIODS

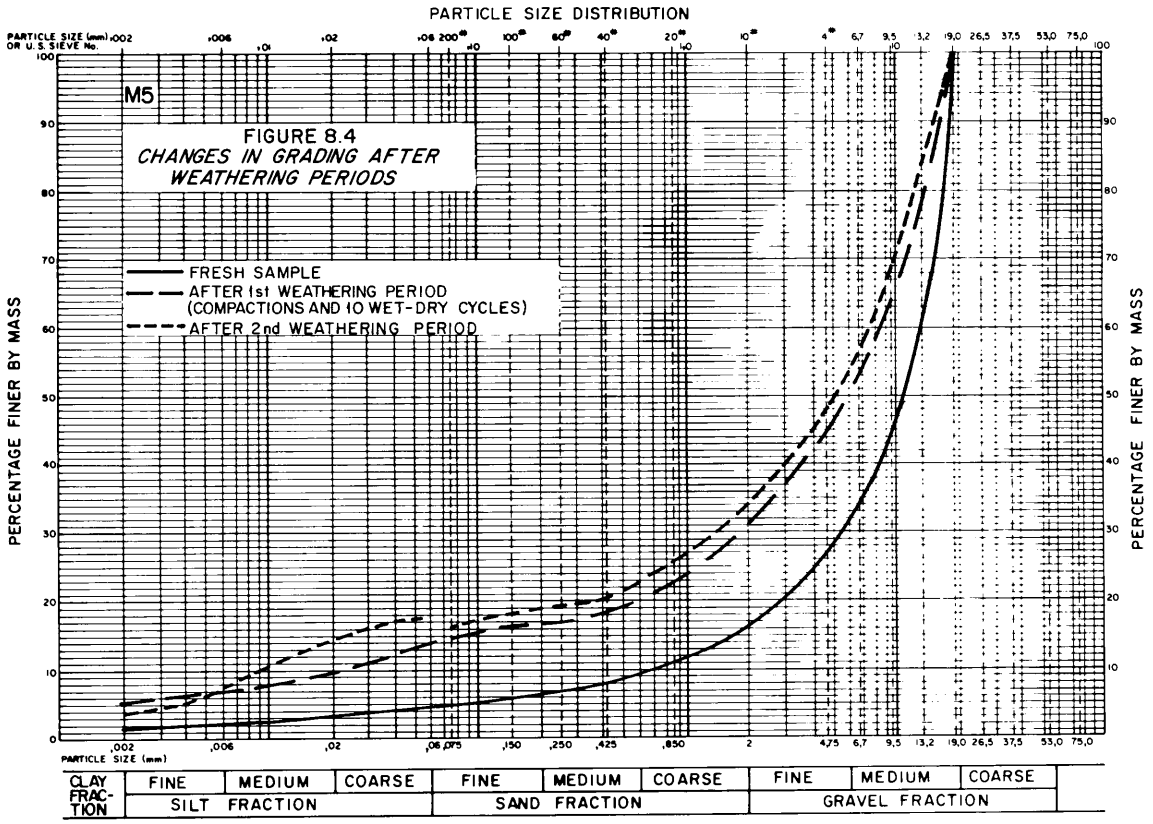


FIGURE 8.4
CHANGES IN GRADING AFTER WEATHERING PERIODS

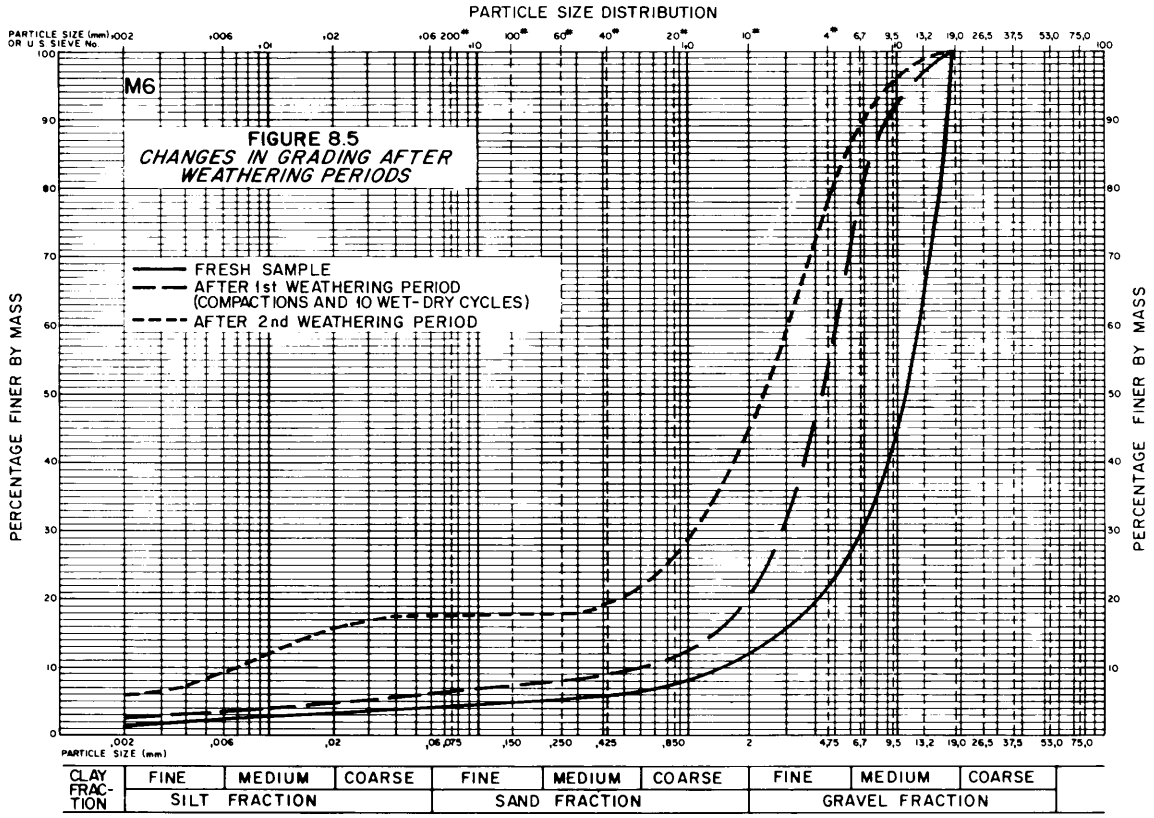


FIGURE 8.5
CHANGES IN GRADING AFTER WEATHERING PERIODS

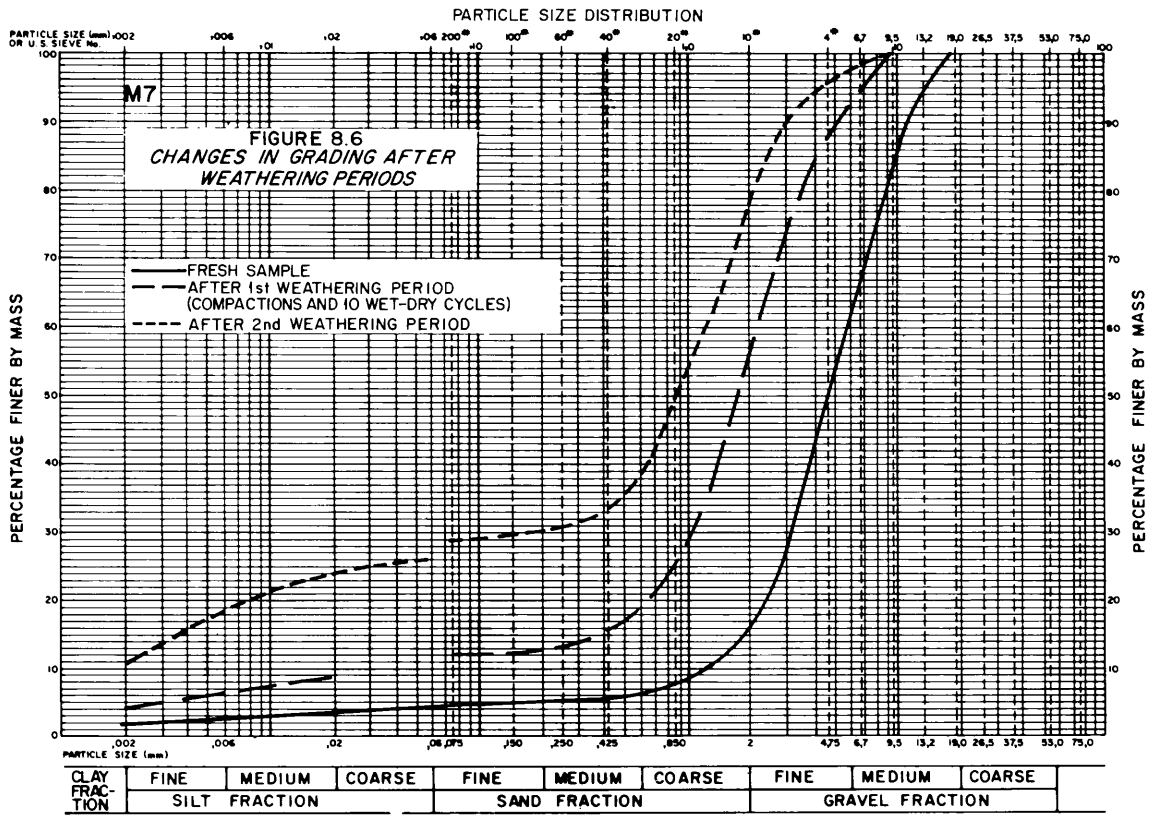


FIGURE 8.6
CHANGES IN GRADING AFTER WEATHERING PERIODS

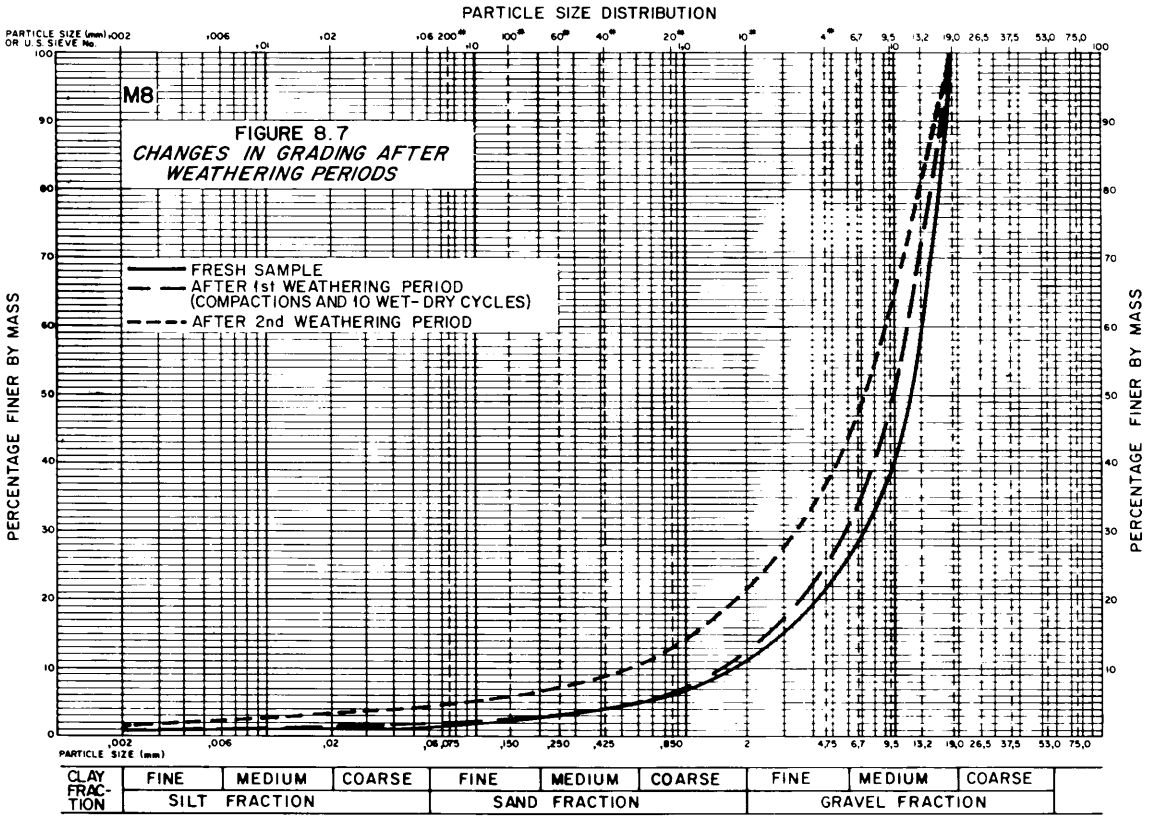


FIGURE 8.7
CHANGES IN GRADING AFTER WEATHERING PERIODS

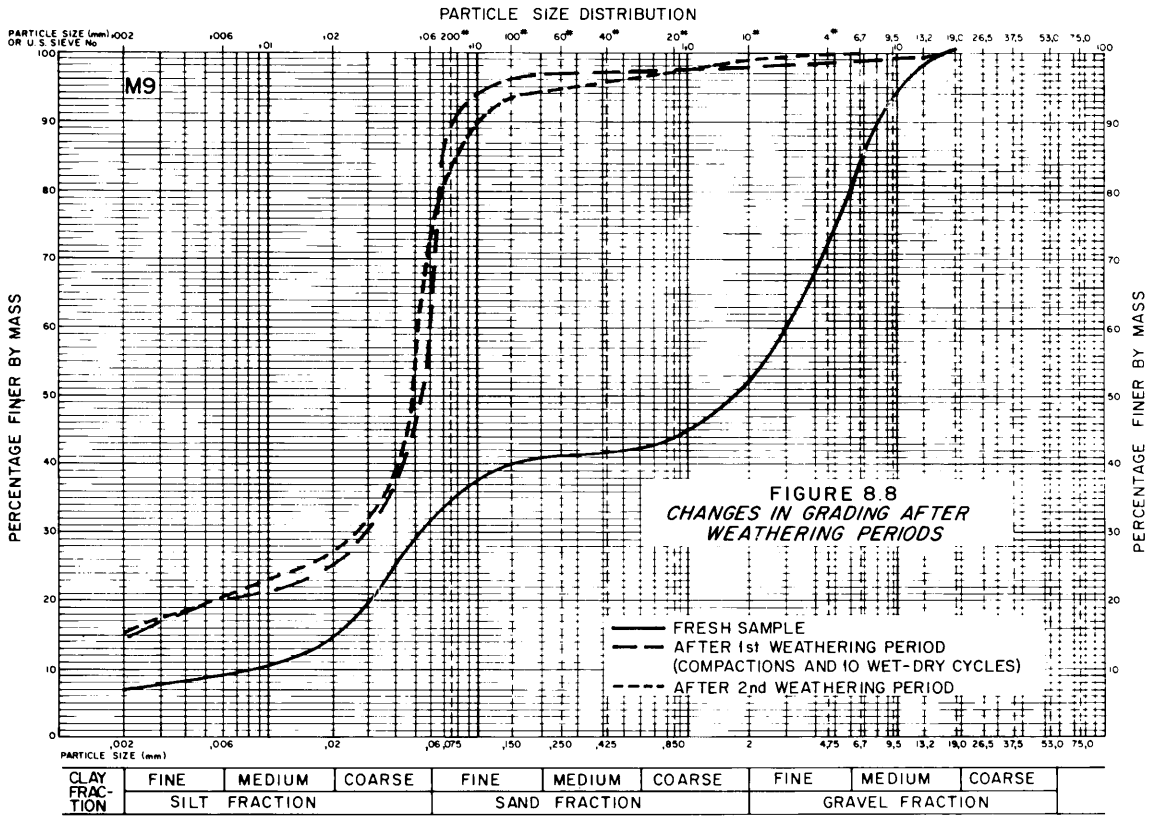
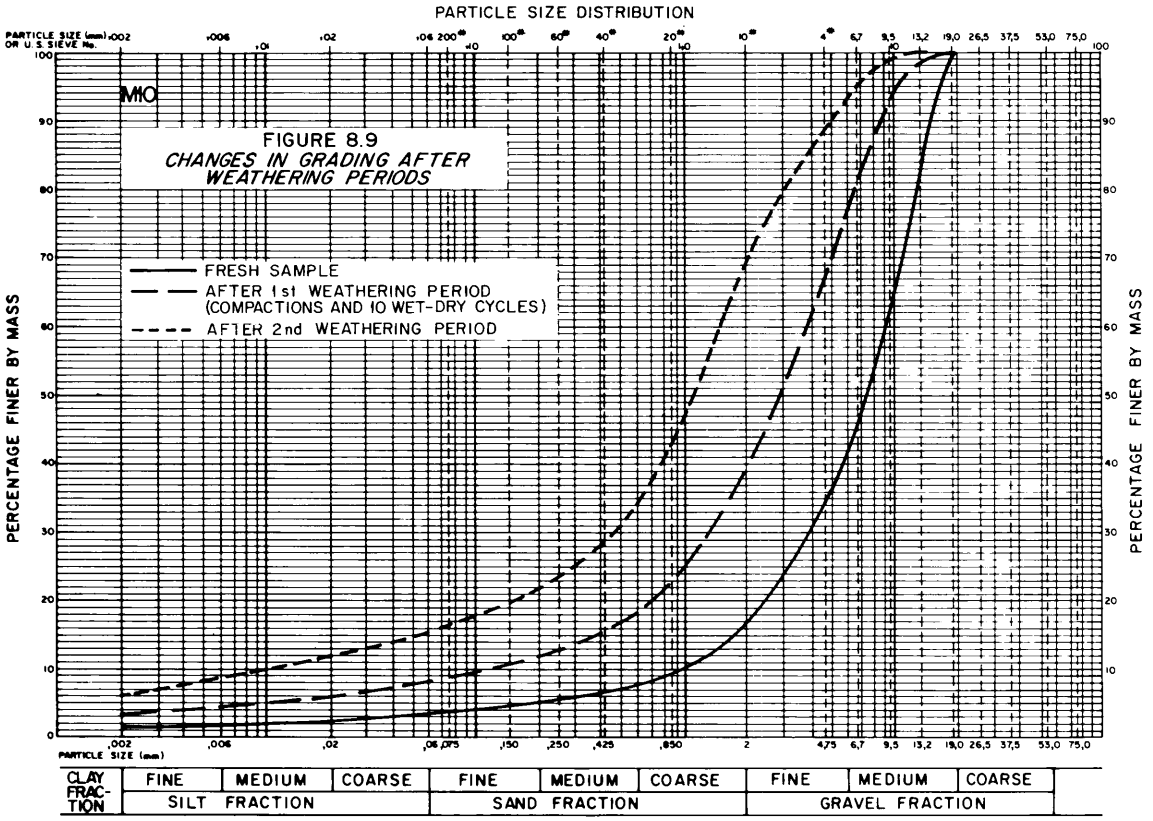
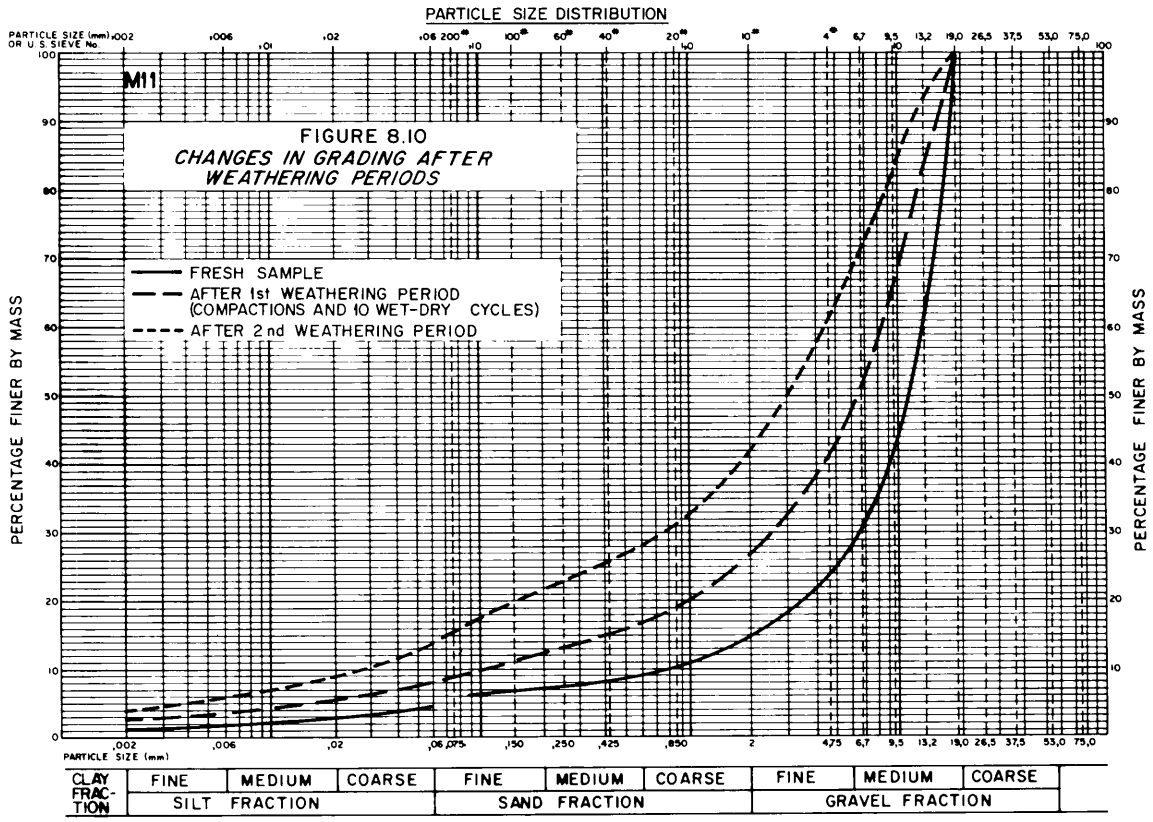
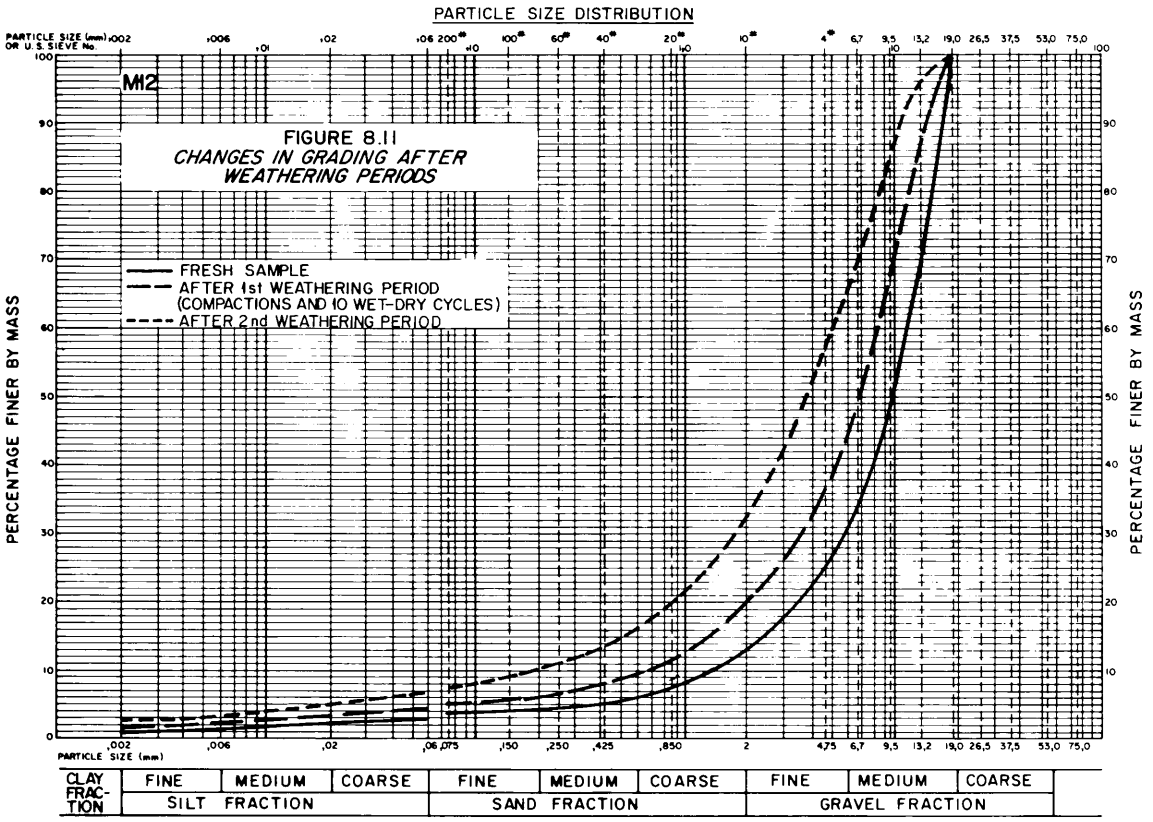
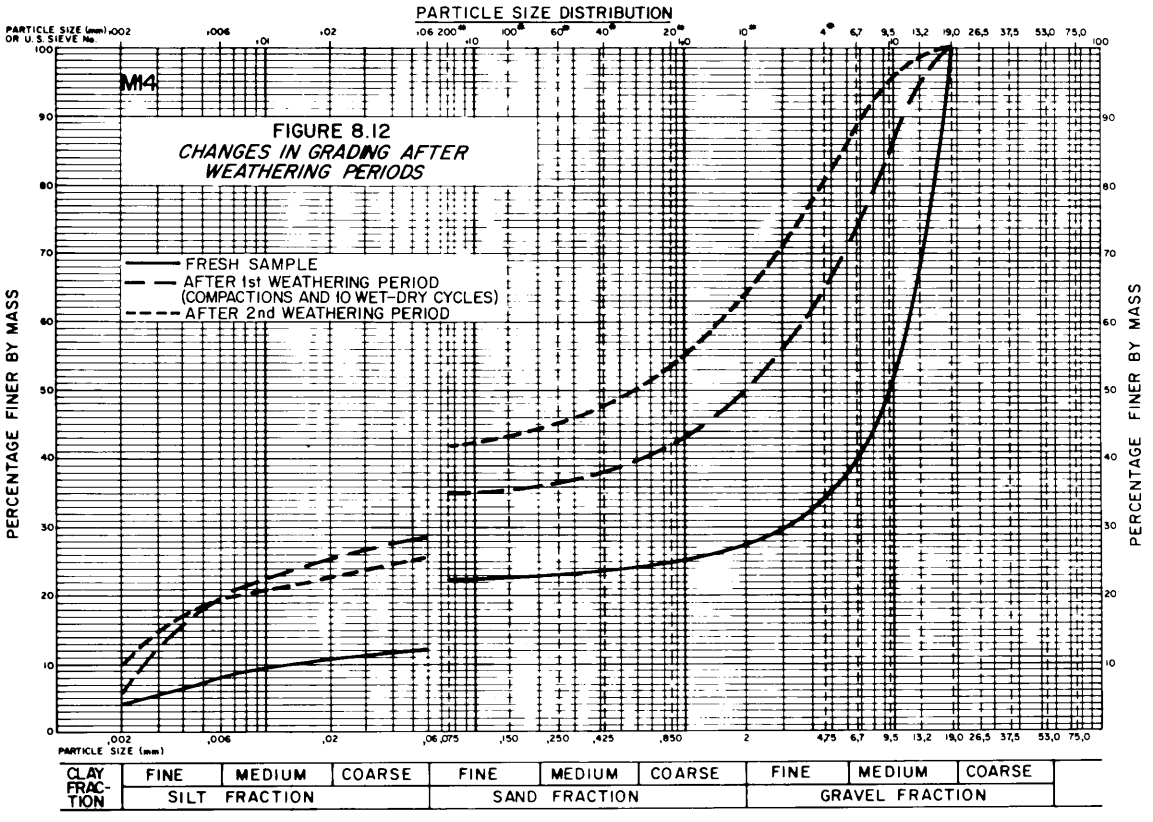


FIGURE 8.8
CHANGES IN GRADING AFTER WEATHERING PERIODS









break-down in the finer fractions. In the same way M3 and M12 broke down more in the coarser fractions. Samples M2 and M8 showed little break-down. Plates 13 and 14 show some samples during various stages of the experiment.

8.3 California bearing ratios

The changes in Modified AASHTO CBRs during the weathering experiment are shown in Figures 8.13 to 8.15. It should be noticed that the OMCs determined for the fresh material were used throughout the experiment although they probably changed for some samples due to the generation of more fines.

No single trend is shown by all the samples. M4, M6, M9 and M14 showed definite decreases in CBRs from the fresh to the "weathered" state; while the values for M2, M5 and M7 decreased slightly. Samples M3 and M8 gave similar values throughout. Slight increases in CBR values were shown by samples M10, M11 and M12. Sample M1 which was treated slightly differently in the pilot study also exhibited an increasing trend.

The tests indicate therefore that although the strength properties of some mudrocks decrease with weathering, this is not always the case. Almost half the mudrocks tested did not weaken under the repeated wetting and drying and compaction but remained the same or even increased in strength.

8.4 Atterberg limits and linear shrinkages

Atterberg limits and linear shrinkage results are shown in Table 8.1. The general trend for the liquid and plastic limits is to decrease during the weathering cycles. There are, however, exceptions to this trend. Trends for the PIs and linear shrinkages are somewhat erratic. Some values increased slightly or decreased slightly but never in a linear way. In many cases a peak or a low is reached after the first weathering period. The highest PI reached, even after weathering, was 10,4 although most values were much lower.

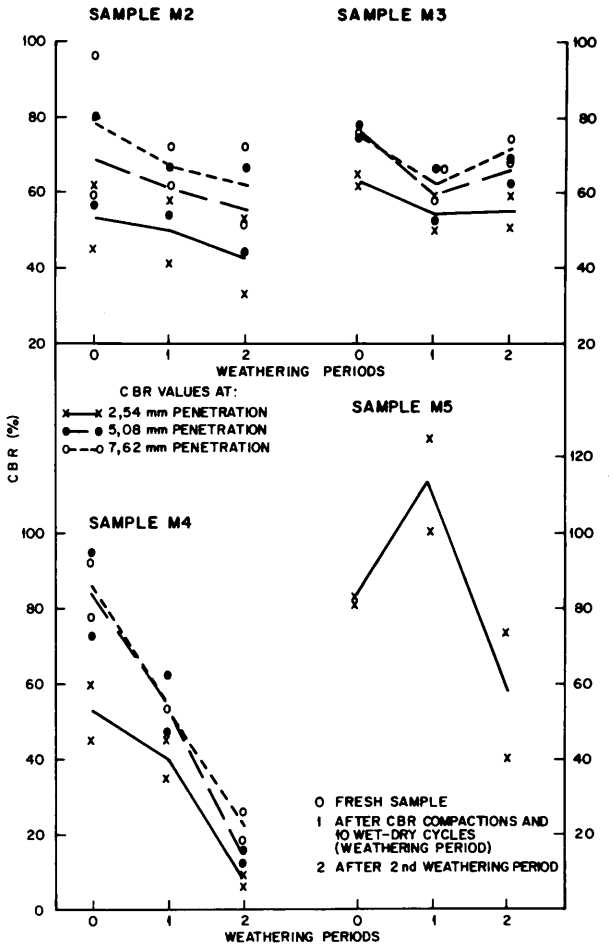


FIGURE 8.13
CHANGES IN CBR (MOD. AASHTO COMPACTION) AFTER WEATHERING PERIODS

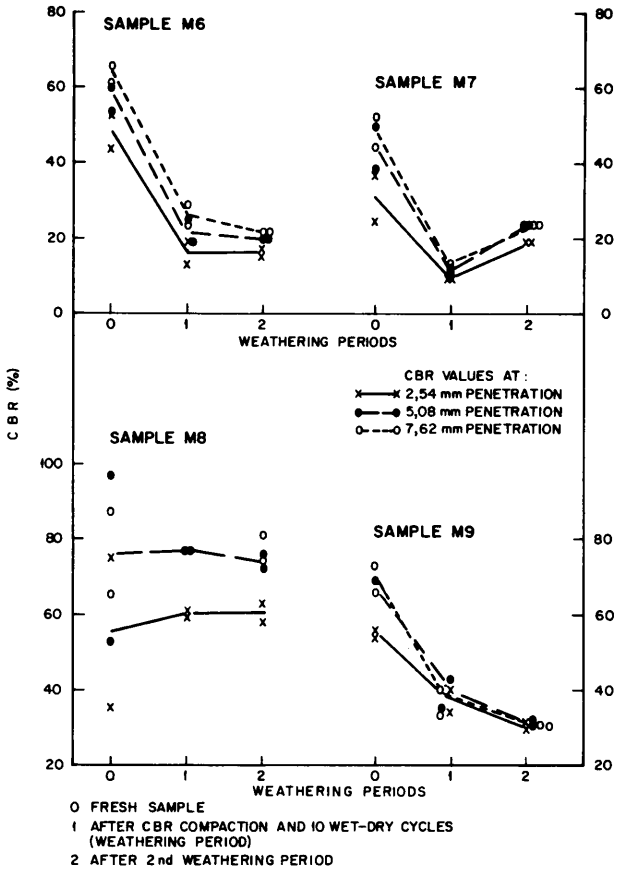


FIGURE 8.14
CHANGES IN CBR (MOD. AASHTO COMPACTION) AFTER WEATHERING PERIODS

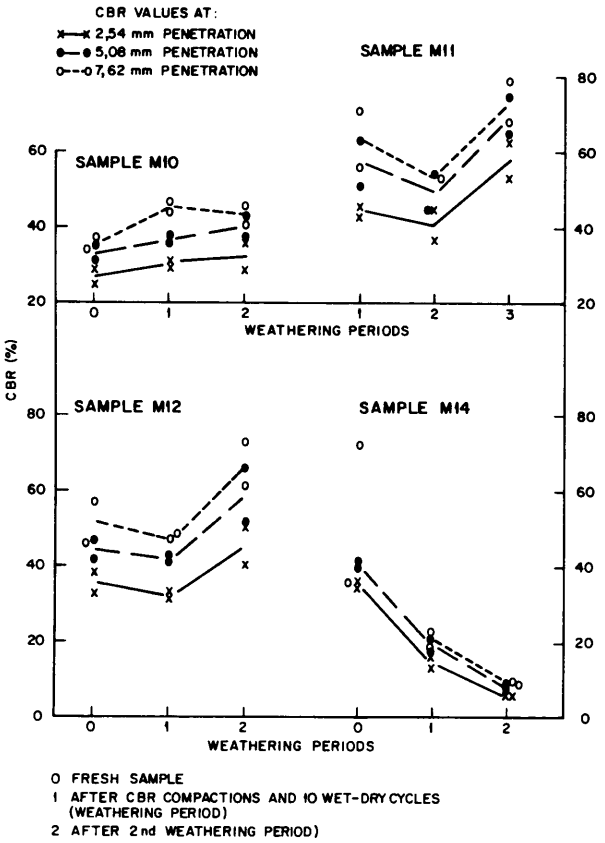


FIGURE 8.15
CHANGES IN CBR (MOD. AASHTO COMPACTION) AFTER WEATHERING PERIODS

TABLE 8.1: ATTERBERG LIMITS AND LINEAR SHRINKAGES DURING THE ACCELERATED WEATHERING TESTS

Sample number	Liquid limit %	Plastic limit %	Plasticity index	Linear shrinkage %
M2 (0)	22,4	n.d.	NP	1,0
M2 (1)	n.d.	n.d.	NP	1,3
M2 (2)	19,6	13,8	5,8	1,3
M3 (0)	21,5	n.d.	NP	1,7
M3 (1)	n.d.	n.d.	NP	2,7
M3 (2)	21,1	14,0	7,1	1,3
M4 (0)	23,1	n.d.	NP	2,0
M4 (1)	20,0	16,1	3,9	1,3
M4 (2)	24,0	16,0	8,0	3,3
M5 (0)	23,1	19,3	3,8	1,3
M5 (1)	20,7	16,9	3,8	0,1
M5 (2)	21,0	16,8	4,2	2,0
M6 (0)	29,5	22,5	7,0	4,7
M6 (1)	28,4	18,2	10,2	5,3
M6 (2)	26,6	18,2	8,4	6,7
M7 (0)	28,9	23,0	5,9	5,3
M7 (1)	27,0	18,0	9,0	4,0
M7 (2)	26,9	18,0	8,9	3,3
M8 (0)	n.d.	n.d.	NP	
M8 (1)	18,0	13,9	4,1	0,7
M8 (2)	n.d.	n.d.	NP	1,3
M9 (0)	22,7	17,9	4,8	2,3
M9 (1)	23,1	20,3	2,8	1,3
M9 (2)	22,5	17,1	5,4	2,0
M10 (0)	23,8	15,9	7,9	3,5
M10 (1)	22,5	18,4	4,1	2,7
M10 (2)	24,4	16,8	7,6	3,5
M11 (0)	22,3	17,9	4,4	1,7
M11 (1)	22,0	17,8	4,2	1,5
M11 (2)	21,8	17,7	4,1	1,3
M12 (0)	18,9	17,7	1,2	1,0
M12 (1)	19,3	16,4	2,9	1,9
M12 (2)	17,8	16,1	1,7	1,3
M14 (0)	38,2	29,0	9,2	3,0
M14 (1)	39,0	28,6	10,4	2,7
M14 (2)	36,9	29,8	7,1	3,0

Note: NP = Non-plastic

n.d. = Not done on account of low plasticity

8.5 X-ray analysis of salts appearing during wet-dry cycles

When the crushed mudrock samples were subjected to wetting and drying cycles fine white crystals of salt appeared on the upper surfaces of pieces of certain samples (M1, M10, M11 and M12) during the oven-drying period. These are visible on Plate 14.

The salts were collected by washing them into a glass beaker and filtering the material through fine filter paper with the aid of a vacuum pump. The liquid was filtered until a relatively clear solution was obtained and then evaporated to dryness. Some of the salts were powdery while others formed aggregations. The latter were crushed with an agate mortar and pestle until fine enough to be mounted in the X-ray holder. Diffractograms were run from $\theta = 35°$ to $\theta = 1°$. The following results were obtained: (It should be noted that due to the 30 cycles of wetting and drying, the state of hydration of the salts is not necessarily the original state.)

M1 - Gypsum $CaSO_4.2H_2O$
- Hemihydrite $2CaSO_4.H_2O$
- Gypsum:Hemihydrite ratio approximately 15:1

M11 - Hemihydrite $2CaSO_4.H_2O$
small amount of Halite NaCl

M12 - Hemihydrite $2CaSO_4.H_2O$
- Thenardite Na_2SO_4

M10 - Hemihydrite $2CaSO_4.H_2O$
Small amounts of halite NaCl and possibly thenardite Na_2SO_4.
An unidentified salt is also present in M10.

8.6 Summary

(a) The disintegration and slaking of mudrocks, especially during construction, is one of the properties most worrying to users. The "weathering periods" exposed the different rates of break-down exhibited by the different mudrocks (Figures 8.1 to 8.12) and it is clear that a quick test is required to establish in advance the extent

Plate 12: Equipment used for compaction and volume change measurements during the compaction and CBR tests

Plate 13: Slaked material of sample M9 after the 1st weathering period (container 320 x 500 mm)

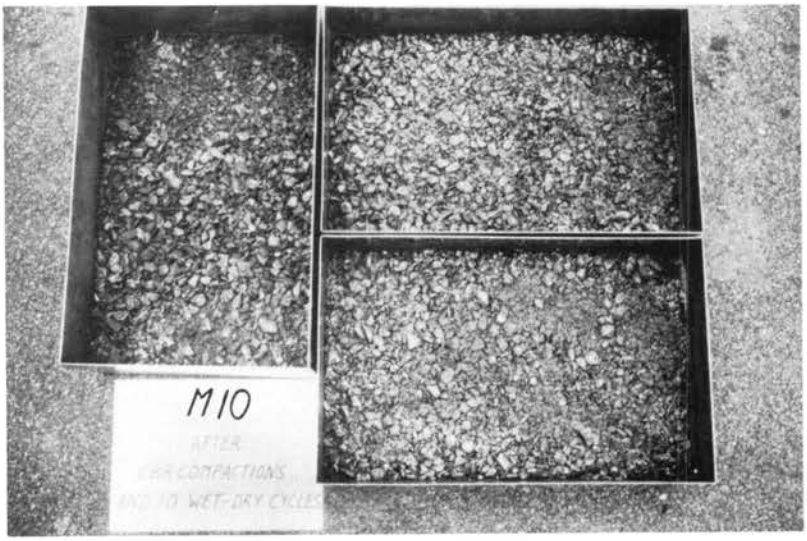


Plate 14: Disintegrated material of sample M10 after the 1st weathering period — note white salts on surface

of this property. It is also recommended that compaction tests be carried out on crushed material which has been oven-dried and soaked once. This will produce more practical results, especially on rapidly-disintegrating and slaking samples.

(b) The CBR values did not change according to single trends during the "weathering periods". Some decreased in value while others increased or remained unchanged. Liquid limits and plastic limits tended to decrease, probably due to the effect of the oven-drying, while the PIs and linear shrinkages did not show any conclusive trends. The highest PI reached, even after the "weathering periods", was still less than 11.

(c) Salts which appeared on the surface of four of the crushed mudrocks during wet-dry cycles were analysed, using X-ray diffraction. They were shown to be mainly hydrates of calcium sulphate, such as gypsum and hemihydrite although sodium sulphate (thenardite) and sodium chloride (halite) were also found in some.

CHAPTER 9

SWELL PROPERTIES

9.1 Introduction

The development of the free swell test has been discussed in the pilot study (Section 5.2.11) and this method was followed for all the other samples. The apparatuses used for the uniaxial and triaxial tests are shown on Plates 15 and 16. Notes about the behaviour of the samples were made during the experiments, i.e. problems experienced during sawing, the development of cracks or discontinuities in the freshly sawn cubes and after immersion or drying, etc. Some samples were cut up easily, requiring about two to three hours for the preparation of about ten cubes while others such as M2, M8 and especially M13 presented many problems. For M13 only five of the 12 cubes planned could be prepared successfully. Sketches were made of all the sample blocks showing the bedding direction and the arbitrarily chosen a and b axes. All the samples, except M13, were orientated, M3, M4, M6 and M9 having been marked at the sampling point. For most of the samples the cubes were sawn from a single slab orientated parallel to the bedding, but in some irregularly shaped blocks this could not be achieved. Vertical displacements were, however, minimal. If duplicate cubes were available for a certain treatment, they were chosen from cubes spaced somewhat apart laterally or from two adjoining slabs. This ability to obtain all the cubes for testing from a limited thickness (maximum about 110 mm) and area holds clear advantages as far as free swell investigations are concerned. It is usually impossible to obtain "duplicates" from field drilling as the core has to be split up along bedding planes. Olivier (1976a) showed that there are marked variations in the swell behaviour of mudrocks within short distances perpendicular to bedding.

A number of cyclic swell determinations (up to four) were done on single cubes for the first samples. The purpose of this was to determine if the percentage swell and swell behaviour, e.g. rate of swell, changes. Fewer swell determinations were done for the last samples but repetitions were still carried out as the wetting and drying process simulates exposure

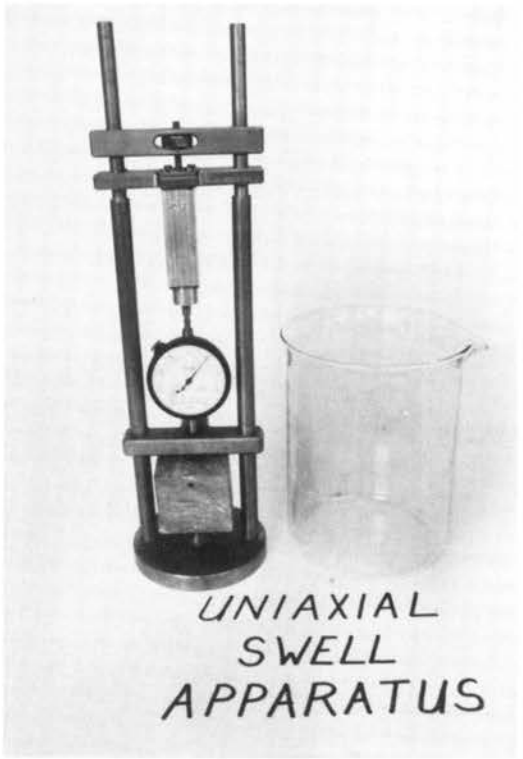


Plate 15: Uniaxial free swell apparatus (without recorder)

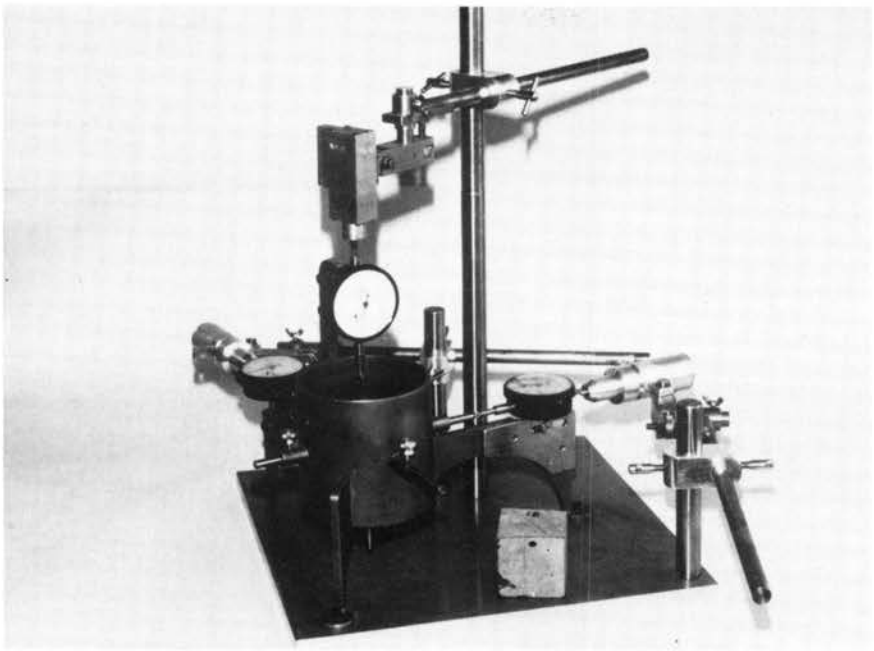


Plate 16: Triaxial free swell apparatus (without recorder)

to the elements and wetting and drying in a pavement. The cracking or breaking down and expansion during these repetitions contributed to better insight into the behaviour of the samples. Repetitions could not be done on some samples as they broke down during immersion.

Examples of swell cubes after some free swell determinations are shown on Plate 17.

9.2 Measurements and calculations

The time-dependent swell behaviour and water absorption were measured during each immersion. The dimensions of each cube were determined after sawing and all the samples were weighed. Cubes were re-weighed just before installation or just after they have been taken out of the oven. After immersion the cubes were surface-dried to remove all shiny or free water and weighed. Problems were encountered with some samples because of chips breaking off during the swell test. Others could not be weighed afterwards because they disintegrated or slaked during immersion.

The results are listed under the following headings in the swell tables in the Appendix:-

(i) Maximum swell percentages (along a, b and c axes)

These were calculated as follows:

$$\frac{\text{Maximum swell (mm)}}{\text{Dimension along axis (mm)}} \times 100$$

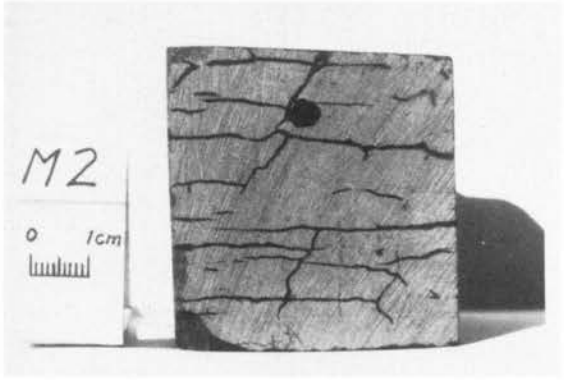
and designated $S_{max(a)}$, $S_{max(b)}$ and $S_{max(c)}$

(ii) Total swell time

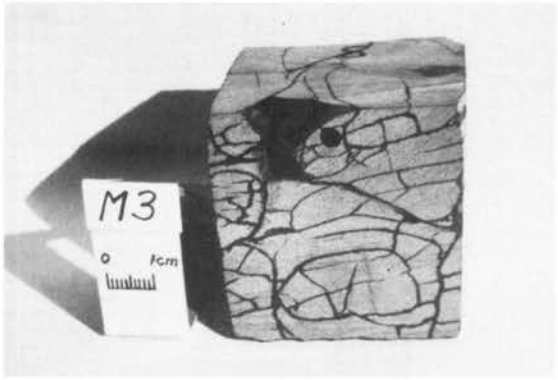
Most of the cubes were immersed for a 21 to 24-hour period but some were immersed for 68 to 72 hours to determine whether the one day immersions were sufficient for measuring swell.

(iii) Time to reach half of the maximum swell

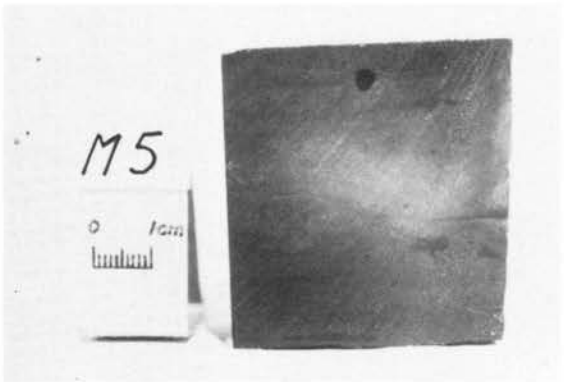
These were calculated using the readings taken manually during the experiment and interpolating when required. After normal working hours analogue recordings were used. There is some inexactitude in these values but they give an idea about the shape of the swell versus time curve.



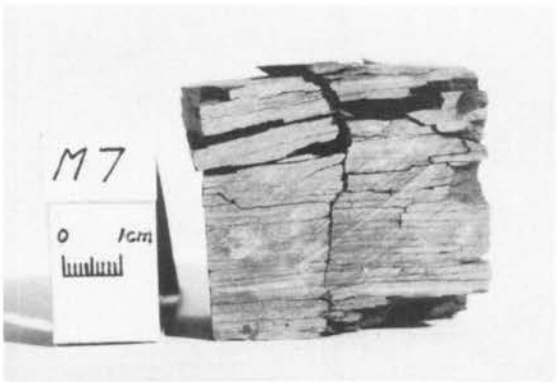
M 2 — after 4 immersions (cracks accentuated by water)



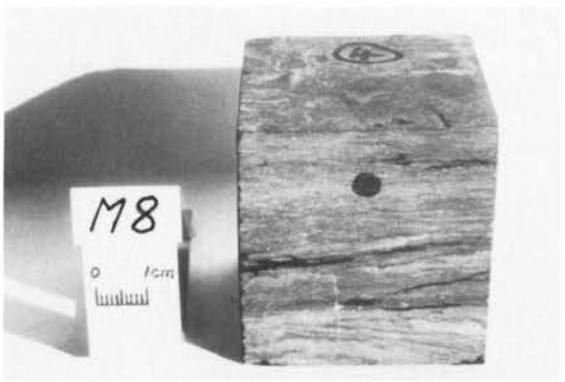
M 3 — after 3 immersions (cracks accentuated by water)



M5 — after 3 immersions — no cracking



M7 — after 1 immersion



M8 — after 3 immersions (cracks accentuated by water)

M11(a) — after 1 immersion

M12 — after 1 immersion

M14 — after 2 immersions

Plate 17: Examples of cubes after various numbers of free swell determinations

(iv) Percentage of total swell which takes place after 6 hours of immersion

This was calculated to determine to what extent swells are completed after 6 hours' immersion.

(v) Percentage of total swell which takes place during the last 2 hours

This was done to find out whether only negligible swell takes place during the last 2 hours of a 24-hour immersion. The analogue recordings were used. For samples M1 and M2 where swells were only recorded manually and therefore not after working hours, a rough estimate of the last 2 hours' swell was obtained by using the formula:

$$\text{Last 2-hour swell} = \frac{\text{Swell during night}}{\text{Time (hours)}} \times 2$$

which is just the average hourly value for the night multiplied by two.

(vi) Moisture lost or gained during the immersion in water or during the time when the cubes were exposed to the atmosphere (air drying)

To determine these values the following mass measurements were taken:

Natural mass (M_n) - mass of cubes just after they had been sawn from the sample blocks.
Air-dried mass (M_{ad}) - mass of cube which had been exposed to the atmosphere for a certain number of days.
Dried mass (M_d) - mass of cube after drying in the oven at 50 or 105 °C.
Saturated mass (M_s) - mass of surface-dried cube after immersion.

From these masses the following were calculated:

Natural moisture content (W_n)

$$W_n = \frac{M_n - M_d}{M_d} \times 100$$

Saturated moisture content or moisture content after swell (W_s)

$$W_s = \frac{M_s - M_d}{M_d} \times 100$$

Moisture lost during air drying (W_{ad})

$$W_{ad} = \frac{M_n - M_{ad}}{M_d} \times 100$$

In some cases obviously erratic values were obtained due to the unnoticed loss of a small chip or chips during immersion. In these cases a "corrected" value was calculated by using e.g. the average moisture content of all the available results for that particular sample. Values calculated in this way are given in italics in the tables.

9.3 Discussion

The large quantity of swell data presented problems as to how they should be interpreted. The points of interest for this study are discussed below but further important information can also be obtained from the tables. It should be noted that two sample blocks from sample M11 (M11 and M11a) were used. This was done because of a slight difference in colour between some of the blocks sampled. These blocks behaved markedly differently as far as free swell was concerned. Relevant figures are given at the end of the Chapter.

9.3.1 Maximum percentage swell perpendicular to bedding ($S_{max(c)}$) for samples dried at 105 °C

The results are plotted in Figure 9.1. These are probably the most important values as they are usually given as representing the "free swell" of a sample. The mudrocks did not give an even spread of values; eight samples swelled less than 1,0 per cent, four more than 3,5 per cent and three samples yielded intermediate values. This meant that eight samples expanded less than 0,5 mm along the 50 mm axes.

9.3.2 Maximum percentage swell perpendicular to bedding ($S_{max(c)}$) for samples immersed at natural moisture content

The results are illustrated in Figure 9.2. Twelve of the 15 samples expanded less than 0,8 per cent and ten 0,4 per cent or less. Volume changes of these rocks from the state as sampled in the field were, therefore, generally low.

A graph comparing swells from oven-dried and natural moisture conditions

is given in Figure 9.3 and Table 9.1 gives the factors by which the average oven-dried values are greater than the average natural values.

TABLE 9.1: FACTOR BY WHICH SWELLS OF OVEN-DRIED SAMPLES ARE GREATER THAN SWELLS OF NATURAL SAMPLES

Sample number	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M11a	M12	M13	M14
Factor greater than natural swell value	3,4	4,6	1,8	0,9	5,6	1,6	5,3	1,1	7,1	1,9	1,1	6,6	2,4	1,1	8,0

Figure 9.3 and Table 9.1 show that $S_{max(c)}$ did not change proportionately. The increase in $S_{max(c)}$ of oven-dried samples is also not related to the additional percentage moisture absorbed by the cubes as is shown in Figure 9.4 where the increase in $S_{max(c)}$ (maximum oven-dried swell minus maximum natural swell) is plotted against the additional moisture absorbed during soaking (from natural to soaked condition). The average natural moisture and saturated moisture contents (after 24 hour immersion) are given in Figures 9.5 and 9.6 respectively.

9.3.3 Comparison of the amount of moisture absorbed and $S_{max(c)}$ for oven-dried samples

These parameters are compared in Figure 9.7 and the distribution of the points show that the relationship is very poor. Samples which absorbed little water usually expanded less and vice versa but the variations were wide. Samples M1 and M3 absorbed about the same amount of water (1,5 and 1,6 per cent) and swelled 1,3 and 0,5 per cent respectively. Sample M12 absorbed 2,9 per cent and swelled 2,7 per cent while M14 absorbed 14,0 per cent and swelled only 1,6 per cent.

9.3.4 Change of $S_{max(c)}$ due to the effect of different pre-treatments

In addition to determining $S_{max(c)}$ from the natural and oven-dried states, some cubes were also subjected to exposure to the atmosphere (air drying) for periods ranging from one day to two months before they were tested.

The results for the axes perpendicular to bedding for all the treatments are shown in Figures 9.8 to 9.12.

For most samples there is a definite increase in $S_{max(c)}$ with an increase in time of air-drying. This is shown in samples M1, M2, M3, M5, M6, M7, M9, M10, M12 and M14 and is also very likely in M11. Samples M4, M8 and M13 did not exhibit much change due to the air-drying but these are all very low swelling samples with a low moisture content.

The effect of air drying as far as free swell is concerned is similar to that of oven-drying. Table 9.2 lists the average swells after drying in the oven at 105 °C and the average swells ($S_{max(c)}$) of the air-dried samples after the maximum levels of swell have been reached.

For most of the samples the effect of air-drying is the same as oven-drying. Seven samples gave slightly lower swells after air-drying while four samples gave slightly higher values after air-drying. The average air-dried $S_{max(c)}$ values for M11 and M9 are somewhat higher than the oven-dried values while the reverse is the case with M7. From the limited results available for the first couple of days of air-drying it is difficult to determine when the maximum effect of air-drying on swell has been attained, but it seems to range between one and seven days and is usually close to its maximum after two to three days.

9.3.5 Moisture changes during air-drying and oven-drying

The moisture changes which resulted from exposing cubes to the atmosphere for various periods and from oven-drying at various temperatures are illustrated in Figures 9.13 to 9.20. All the samples lost moisture on exposure to the atmosphere. This is an important observation as some people are of the opinion that mudrocks absorb moisture after excavation and that this causes the break-down of some mudrocks. The influence of intermittent periods of such "intensive" air-drying, followed by moisture absorption, is considered to be of particular importance in the air-breakage of the rock material as they contribute to the build-up of residual strain and eventually to the complete break-down of the rock fabric (Olivier, 1979b).

While all the curves show a definite loss of moisture with increased time of exposure there are some discrepancies. M1 has a spurious duplicate result for the 2 days exposure value. M3 gave an inconsistent curve with almost no losses up to 10 days and an increased loss at 29 days. M4 shows

TABLE 9.2: COMPARISON OF EFFECT OF AIR-DRYING AND OVEN-DRYING ON $S_{max(c)}$

Sample number	Average percentage swell after air-drying	Average percentage swell after oven-drying (105 °C)	Air-dried values used to calculate average percentage swell (days)
M1	1,13	1,30	7, 14, 30, 63
M2	0,28	0,32	2, 6, 20, 30
M3	0,51	0,54	1, 3, 10
M4	0,26	0,21	0, 1, 6, 13, 30, 63
M5	0,32	0,28	3, 8, 14, 30, 60
M6	0,61	0,62	3, 10
M7	3,26	4,22	2, 3, 7, 14, 30
M8	0,18	0,24	2, 3, 7, 10, 14
M9	4,54	3,86	9, 30
M10	4,30	4,43	22, 35
M11	0,57	0,40	7, 14, 30, 68, 97
M12	2,14	2,70	7, 38
M13	0,13	0,12	0, 2, 14
M14	1,72	1,60	15, 35

a smaller loss at 30 and 63 days than at 6 and 13 days.

Fairly good curves can usually be drawn to show the loss of moisture with time but a lack of points makes this somewhat subjective. Samples M1, M2, M5, M8, M11, M13 and M14 reached a relatively stable maximum loss value after a couple of days while the values for M3, M4 and M6 cannot be interpreted with accuracy; M3 because of an inconsistent curve, M4 because of two low values following two higher ones and M6 because of a lack of results. The following samples were still losing moisture after some weeks of air-drying: M7 (probably) and M9, M10 and M12 (definitely). These samples all exhibited high maximum percentage swells ($S_{max(c)}$) and they slaked or disintegrated when immersed in water. Table 9.3 gives an estimate of the time taken to lose 80 per cent of the maximum percentage moisture lost during air-drying. For samples still losing moisture at the end of the experiment, the maximum was taken as the last point on the curve.

The table indicates a wide range of rates of moisture losses. A sample with a high moisture content, such as M14, loses 80 per cent within 1 day while samples with a moderately high moisture content, such as M10 and M12,

TABLE 9.3: ESTIMATES OF DAYS TAKEN TO LOSE 80 PER CENT OF MAXIMUM AMOUNT OF MOISTURE LOST DURING EXPOSURE TO ATMOSPHERE

Sample number	Maximum moisture lost (%)	Time to lose 80 % (days)	Estimate of accuracy
M1	0,66	5	Fair
M2	0,50	6	Good
M3	-	-	No estimate possible
M4	0,60	4	Good estimate if later points disregarded
M5	1,48	2½	Good
M6	1,35	5	Good estimate if maximum value is correct
M7	3,04	3	Good
M8	0,23	2	Good
M9	2,72	7	Good
M10	1,37	17	Good
M11	0,68	?	No points up to 7 days
M12	1,18	12	Good
M13	0,13	3 - 4	Good estimate but long range of values possible
M14	11,30	1	Good

take much longer. Eighty per cent loss is, however, usually attained within one week.

Table 9.4 shows the percentage of the natural moisture content (NMC) (determined by drying at 105 °C) lost during air-drying. As in the case of Table 9.3, the last available value was taken for samples still showing loss of moisture towards the end.

There is a wide variation in the percentages lost. M14, a weathered sample with a high moisture content, lost 92 per cent of the natural moisture content within a very short time whereas M7 and M9, also with appreciable moisture contents, only lost 49 and 51 per cent respectively and took a much longer time. The samples with lower moisture contents tend to lose a lower percentage of their natural moisture content during the air-drying period, e.g. M3, M4, M8 and M13.

TABLE 9.4: PERCENTAGE OF NATURAL MOISTURE CONTENT LOST DURING AIR-DRYING

Sample number	Moisture loss - values taken at days	Average maximum moisture lost (%)	Natural moisture content (NMC) (Dried at 105 °C) %	Air-dried loss / NMC x 100	Remarks
M1	14, 30, 63	0,66	1,13	58	
M2	20, 30, 60	0,52	1,12	46	
M3	29	0,37	1,59	23	Value at 10 days too low
M4	6, 13, 30, 63	0,47	1,62	29	Values at 30 and 63 days bring down average
M5	8, 14, 60	1,44	2,12	68	
M6	10	1,35	3,80	36	Not sure if value at 10 days is maximum
M7	7, 14, 30	2,91	5,93	49	
M8	7, 10, 14	0,23	0,97	24	2 and 3 days can be taken as well
M9	16, 30	2,65	5,15	51	Some loss of moisture between 16 and 30 days
M10	22, 35	1,28	2,71	47	Samples still losing moisture at 35 days
M11	14, 30, 68, 97	0,68	1,34	51	
M12	38	1,17	1,89	62	Samples still losing moisture at 38 days
M13	14	0,13	0,62	21	
M14	7, 15, 35	11,31	12,28	92	

The moisture contents obtained for the samples after oven-drying at various temperatures and for various periods indicate, as shown on the figures, that one day's drying of a 50 mm cube in a 105 °C oven is generally not enough for a sample to reach constant mass. This is borne out by the results for most of the samples. If drying is done at 50 °C, one day is completely inadequate. Four or even seven days of drying at 50 °C do not remove as much moisture as one or two days' drying at 105 °C. This is indicated on Figure 9.13 (samples M1 and M2) where both 50 and 105 °C drying temperatures were used.

9.3.6 Comparison of $S_{max(c)}$ over period of 20 to 24 hours to period of 68 to 72 hours

One cube of each sample, excluding samples M1, M2, M5, M9 and M11a, were oven-dried and immersed for a 68 to 72-hour period in contrast to the generally used 20 to 24 hour period for the other cubes. (M9 and M11a would in any case have shown no additional swell during the extended time as they expanded fully within a matter of minutes.) The results for the swell axes perpendicular to the bedding are shown in Figure 9.21. The majority of the samples expanded during the extended immersion period. Samples M3 and M14 expanded slightly less during the longer period but this must be ascribed to experimental errors. Table 9.5 lists the percentage increases in swell during the extended immersions.

Samples M4, M6, M10 and M12 show definite indications of expanding more during the extended soaking time. M11 and M13 probably also increased slightly while M3, M7 and M14 showed no change. The $S_{max(c)}$ remained in the same category, i.e. there were no major changes in the amounts of maximum swell. Only in the case of sample M8, a low swelling sample, was the expansion doubled during the longer period, but others, such as M10 and M12, also showed notable increases. For M12, however, one of the duplicate 24-hour values was somewhat low and this influenced the results.

In general then, samples over the whole range of expansions were affected but the values remained in the same category. If an immersion time of 20 to 24 hours is specified, the larger part of swell will take place within this period. Extended periods of immersion will cause more expansion in some samples but the amounts, quantity-wise, do not warrant this.

TABLE 9.5: PERCENTAGE INCREASE OF $S_{max(c)}$ DUE TO LONGER IMMERSION PERIOD

Sample number	24 hr average $S_{max(c)}$	72 hr average* $S_{max(c)}$	Swell difference (72 hr average - 24 hr average)	% of $S_{max(c)}$ taking place after 24 hours (24 hr taken as 100 %)
M3	0,55	0,39	-0,16	(-29)
M4	0,21	0,29	0,08	38
M6	0,62	0,79	0,17	27
M7	4,23	4,28	0,05	1
M8	0,24	0,49	0,25	104
M10	4,43	5,19	0,76	17
M11	0,40	0,42	0,02	5
M12	2,70	3,84	1,14	42
M13	0,12	0,14	0,02	17
M14	1,61	1,43	-0,18	(-11)

* Cubes usually dried over a longer period than cubes immersed for 24 hours

A fact which may have influenced the results is the oven-drying time. Most of the 24-hour duration swells were conducted on samples dried for one or two days while the 72-hour swells were done on samples dried for three or four days. Figures 9.13 to 9.20 and Figure 9.5, where the cubes dried for a longer period are indicated with a dash, showed that generally a small percentage of extra water is driven off during the longer periods of drying. It is, therefore, uncertain whether the increases in $S_{max(c)}$ exhibited by some samples, are solely due to the longer period of immersion.

9.3.7 Rate of swell

The expansion with time was monitored by reading the dial gauges and recording the swell curves throughout the experiments. An idea of the rate of swell can be obtained by calculating the time taken to reach half of the eventual $S_{max(c)}$.

The results for the first immersion of the oven-dried samples are given in Figure 9.22. The more expansive rocks swelled at a faster rate than the less expansive ones. Comparison with Figure 9.1 shows that the

samples which expanded more than 1,0 per cent (M1, M7, M9, M10, M12 and M14) needed less than 100 minutes to reach half their maximum amount of swell while the other samples all needed more. Fairly repeatable results were obtained for the more expansive rocks but values for the others varied widely because of the low values and flat curves. When the cubes were dried again and immersed for a second time, all the samples needed less time to reach half the maximum swell, probably because the water had easier access to all parts of the cubes through visible, as well as micro-cracks. Results along the other two axes of the cubes were similar to those perpendicular to the bedding but more scattered because of lower expansions in that plane.

9.3.8 Percentage of $S_{max(c)}$ taking place after six hours

The swell curves were used to calculate the percentage of $S_{max(c)}$ which occurred after the samples had been immersed for six hours. The results for the first swells of the oven-dried samples are given in Figure 9.23. As with the times to reach half $S_{max(c)}$ (Section 9.3.7) there is a relationship between $S_{max(c)}$ and the percentage of this which took place after six hours. For samples M2, M3, M4, M5, M6, M8, M11 and M13, large percentages of $S_{max(c)}$ took place after six hours, while the samples which expanded more than 1,0 per cent (M1, M7, M9, M10, M12 and M14), swelled little, if any, during this time.

When the cubes were immersed for second or third determinations, the most common occurrence was a decrease in the percentages. The decreasing steps (or increasing steps) were, however, not constant and no general rule can be applied.

9.3.9 Percentage of $S_{max(c)}$ taking place in last two hours

The percentages are shown in Figure 9.24. Only the low-swelling samples experienced more than two per cent of their $S_{max(c)}$ during this time. These values are not very accurate as a minute difference increases the percentage markedly due to the small total swell values. Samples M7, M9, M10 and M12 exhibited practically no swells during the last two hours while M1, M3 and M14 showed very small percentages. These include all the samples showing appreciable swells and show, therefore, that expansion

virtually ceases after 20 to 24 hours of immersion.

9.3.10 Comparison of maximum percentage swells along three axes ($S_{max(a)}$, $S_{max(b)}$, and $S_{max(c)}$)

Murayama and Yagi (1966) found that a claystone sample and a mudstone sample expanded about twice as much perpendicular to the bedding than along an axis parallel to it. For the mudrock samples maximum swell percentages were measured along three axes in most of the tests. The a and b directions are parallel to the bedding (except for M13 which was not orientated) and were arbitrarily chosen for the particular sample block from which the swell cubes were sawn.

The maximum percentage swells along the c-axes ($S_{max(c)}$) were taken as 100 and the percentages which $S_{max(a)}$ and $S_{max(b)}$ constitute of this value were calculated for all the samples. To determine whether these ratios exhibit any changes because of different treatments, they were calculated for:

(a) the swells during the first immersions of the cubes oven-dried at 105 °C;

(b) the swells during the first immersions of all the cubes irrespective of whether they were at natural moisture content, air-dried for various periods or oven-dried at 105 °C; and

(c) the swells when all the cubes were immersed for a second and third time, again irrespective of treatment.

The only results excluded from (b) and (c) were those where long immersions were used or where the cubes were dried at 50 °C. The results are tabulated in Table 9.6.

The following conclusions were made:

(a) The relation between $S_{max(c)}$, $S_{max(b)}$ and $S_{max(a)}$ did not change much from the first to second or third immersions or because of different treatments.

(b) The samples which exhibited the higher expansions, such as M1, M7, M10, M12 and M14, had low and similar expansions in the a and b directions. M9 was an exception to this rule, having a swell equal

to the swell perpendicular to the bedding along the a-axis. This sample, however, differs from the others mentioned in that it has no distinct bedding.

(c) In general the less expansive samples exhibited higher proportional swells along the other axes relative to the c-axes, than the more expansive samples. The differences are not marked in samples showing clear bedding, such as M5, M8 and M11 - M8 giving ratios similar to those of the more expansive samples - but obvious in the more massive samples (M2, M3, M4, M6 and M13). Sample M4 swelled more along an axis in the bedding plane than perpendicular to it, while M13 behaved isotropically, swelling almost equally along all three axes. It is obvious that the orientation of the clay minerals in samples where the bedding is more visible caused a relatively higher swell perpendicular to the bedding than parallel to it.

TABLE 9.6: RELATIVE EXPANSIONS ALONG THE SWELL CUBE AXES

Sample number	Relationship between swells along cube axes*											
	Cubes - oven-dried 105 °C - 1st swells				Cubes - various treatments - 1st swells				Cubes - various treatments - 2nd and 3rd swells			
	Axes			Number of results	Axes			Number of results	Axes			Number of results
	a	b	c		a	b	c		a	b	c	
M1	10	16	100	2	13	16	100	14	17	22	100	12
M2	59	29	100	1	78	52	100	9	84	51	100	18
M3	21	47	100	2	22	45	100	8	24	46	100	16
M4	44	132	100	2	45	121	100	9	46	117	100	18
M5	14	26	100	3	12	25	100	12	14	26	100	24
M6	22	42	100	2	30	42	100	6	45	45	100	11
M7	13	12	100	2	13	13	100	10				
M8	11	16	100	2	16	16	100	8	13	15	100	18
M9	99	51	100	1	96	54	100	5				
M10	18	18	100	2	17	17	100	8				
M11	24	9	100	2	27	21	100	9	34	33	100	12
M12	7	6	100	2	8	8	100	7	8	9	100	6
M13	80	45	100	1	109	96	100	3	93	107	100	3
M14	15	13	100	2	18	14	100	9	12	12	100	4

* c-axes: perpendicular to bedding (M13 unorientated)
a and b axes: in bedding plane

9.3.11 Changes in $S_{max(c)}$ during repeated swells

The swells of most cubes were measured for a second or third time to establish the effect of the wetting and drying cycles on their swell behaviour. This could not be done for samples M7, M9, M10 and M14 because the samples broke down to various degrees during the first immersion. For the other samples, dried at 105 °C, the first swells were usually the highest (Figure 9.25), although most values were fairly close together for the less expansive samples. The differences between the first and subsequent swells were larger for the more expansive samples which could be tested (M1 and M12). This could have been due to the cracks which developed parallel to bedding i.e. the cube had already expanded to a certain degree when the dial gauges were zeroed before the water was poured in.

The cubes pre-treated in different ways expanded most after they had been dried for the first time. It did not matter whether the cube was subjected to a few days of air-drying or to oven-drying. A cube immersed in water at its natural moisture content expanded most during its second immersion, i.e. at the first immersion after it had been dried completely. The air-dried cubes which had been exposed to the atmosphere for only a few days also swelled less during the first immersion but with an increase in time (additional air-drying), a change in the swell behaviour became evident and the value of the first swell became the highest. This is best illustrated by the more expansive samples. Sample M8 is an exception to these observations as almost all the first swells, independent of pre-treatment, were lower than the second swells with the third maximum swell inbetween these values.

9.3.12 Change in percentage water absorbed during repeated swells

The percentages of water absorbed during the first and subsequent swell determinations are shown in Figure 9.26. The swell cubes generally absorbed more water during the second cycle than during the first. There was often a slight increase in the third swell but for some samples the absorptions during the second and third swells were similar. The wetting and drying must have influenced the texture of the rock to a certain extent to allow more voids for water as the cubes absorbed more water during the second swell cycle but expanded less. Olivier (1979b) states that alternating cycles of wetting and drying result in the build-up of residual strain in the rock material and this eventually contributes to the complete break-down of the rock.

9.4 Summary

(a) The samples yielded free swells after oven drying ranging from very little (0,1 per cent) to 9,1 per cent with the majority of swells below 1,0 per cent. Swells of samples with natural (field) moisture content were much lower and not directly related to the amount of swell after oven-drying. There was very little correlation between the amount of water absorbed during the swell period and the maximum percentage swell.

(b) All the mudrock cubes exposed to the atmosphere lost moisture during the time of exposure as a result of air-drying. The percentage moisture lost during this process was generally much less than that driven off during oven-drying but the maximum swell percentages were usually similar after these two processes.

(c) The rate of expansion when immersed in water was related to the degree of expansiveness of the sample. Some highly expansive samples expanded fully within a few minutes while other expansive samples took longer. The less expansive samples sometimes continued to swell slowly even after 24 hours immersion. A 24-hour immersion period is, however, considered ample for a routine free swell test.

(d) Well-stratified samples expanded much more in a direction perpendicular to the bedding than in a direction parallel to the bedding while structurally more isotropic samples often yielded higher percentages (relative to the axis perpendicular to the bedding) in the bedding plane. In a few cases swells of similar magnitudes were recorded along one axis in a direction parallel to the bedding.

(e) The samples expanded most after a few days of air-drying or after oven-drying. Expansions during subsequent immersions were generally lower although more water was absorbed.

(f) An important practical observation during the test programme was that cubes immersed at their natural moisture content did not disintegrate or slake to the same extent as cubes which had been exposed to the atmosphere or which had been dried in an oven. It is therefore clear that if such a sample is kept wet or at its natural moisture content without being allowed to lose moisture at any time, the deterioration after exposure would be significantly reduced. This is illustrated in some road cuttings in mudrock where the side which is mostly in the shade and is

kept wet as a result of seepage of ground-water, deteriorates much less than the side exposed to the sun where air-drying occurs.

(g) The free swell test proposed by the ISRM (1972b) and modified as described previously, is a viable test but the range of values obtained were perhaps too limited for general engineering classification purposes. Samples which slaked completely also exhibited swells similar to samples which disintegrated into flakes or cracked parallel to the direction of the bedding.

(h) The work carried out indicates that cooling water may be used when cutting the hard samples, provided that the samples are sawn within a couple of days after sampling and provided that the samples were sealed in plastic bags immediately after excavation. A single day of air-drying will cause some mudrocks to disintegrate immediately when they come into contact with water. The soft samples should be sawn without the use of water. The maximum free swell during 24 hours' immersion after drying at 105 °C should be determined. Drying at 105 °C provides both a constant reference level and exclusion of most of the natural water (Olivier, 1976a).

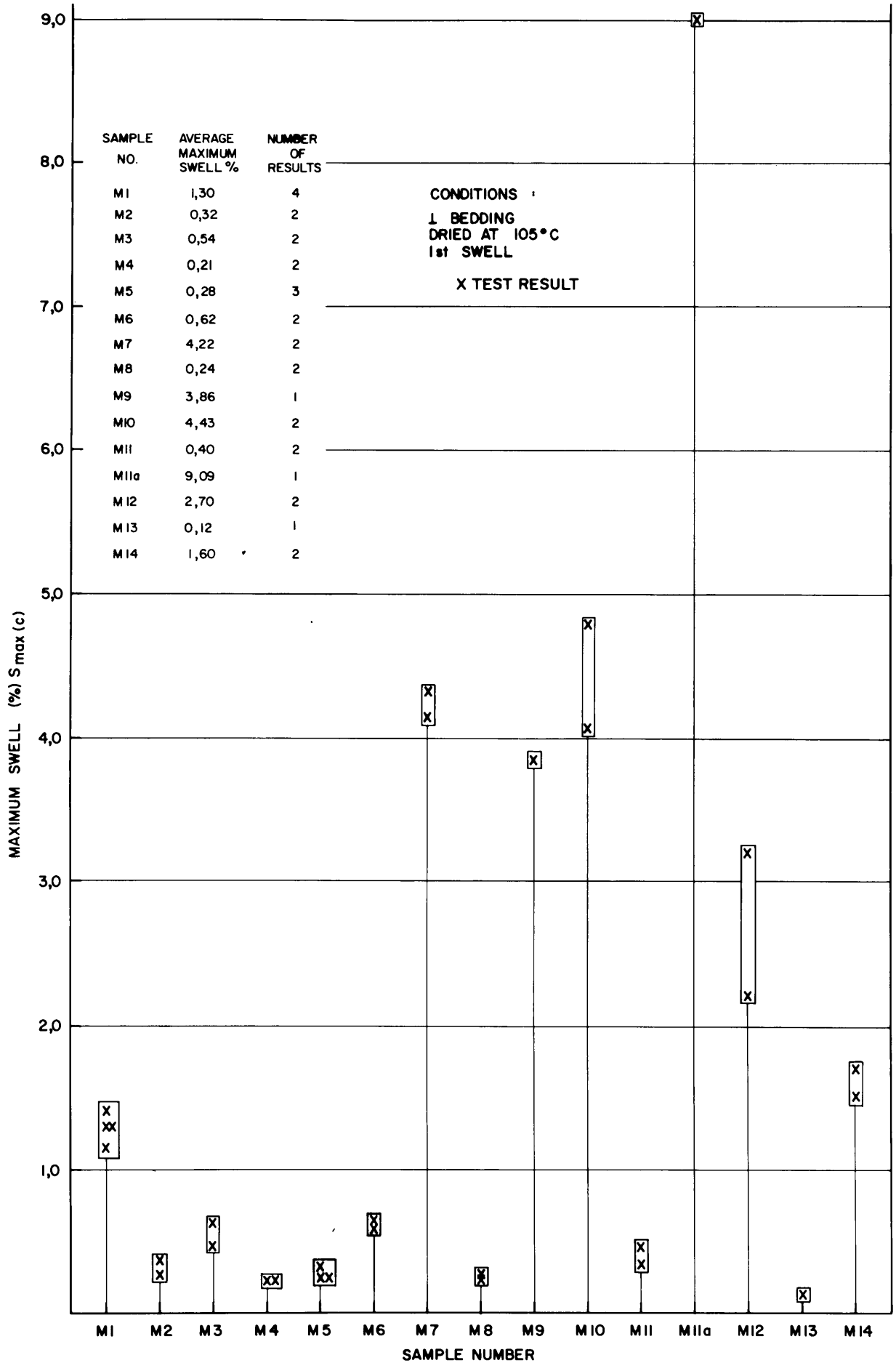


FIGURE 9.1

MAXIMUM SWELL OF OVEN-DRIED SAMPLES .

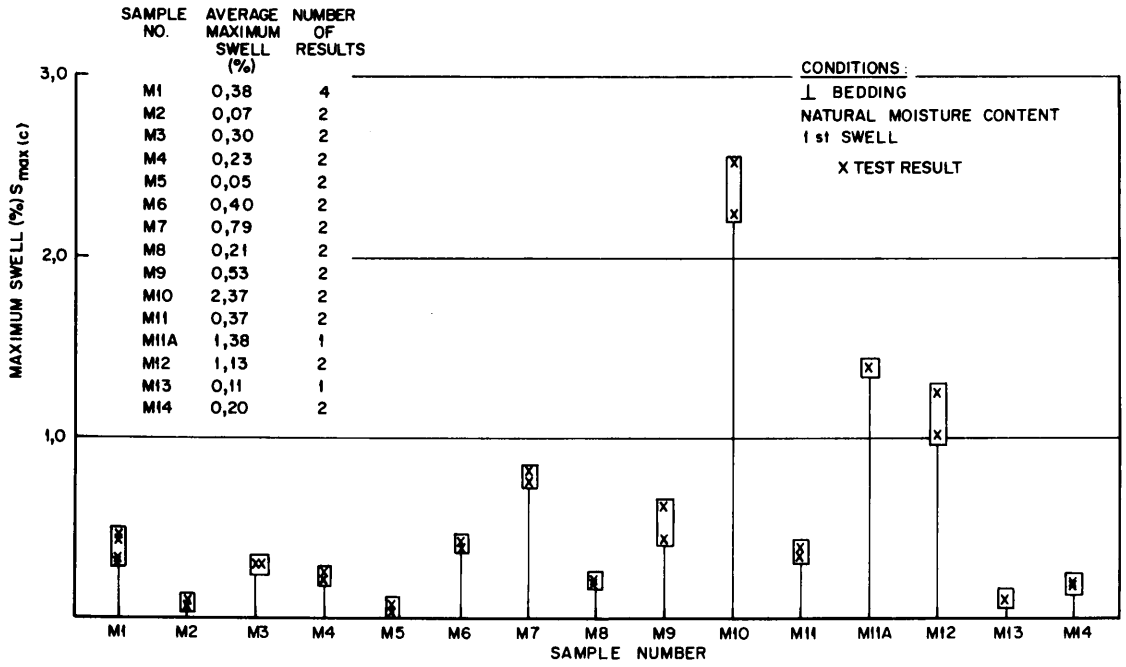


FIGURE 9.2

MAXIMUM SWELL OF NATURAL SAMPLES

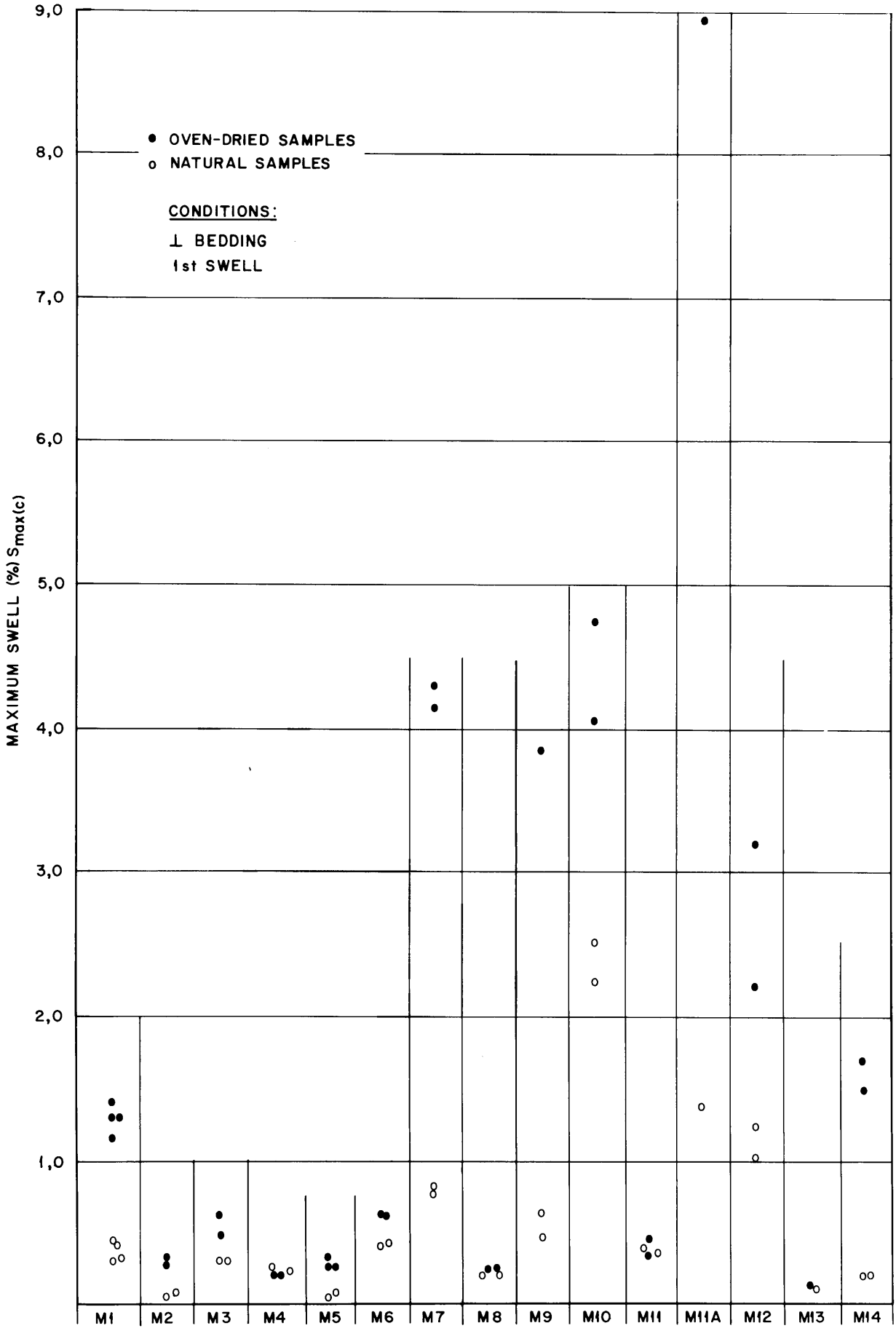


FIGURE 9.3

COMPARISON OF MAXIMUM SWELLS FOR NATURAL AND OVEN-DRIED SAMPLES

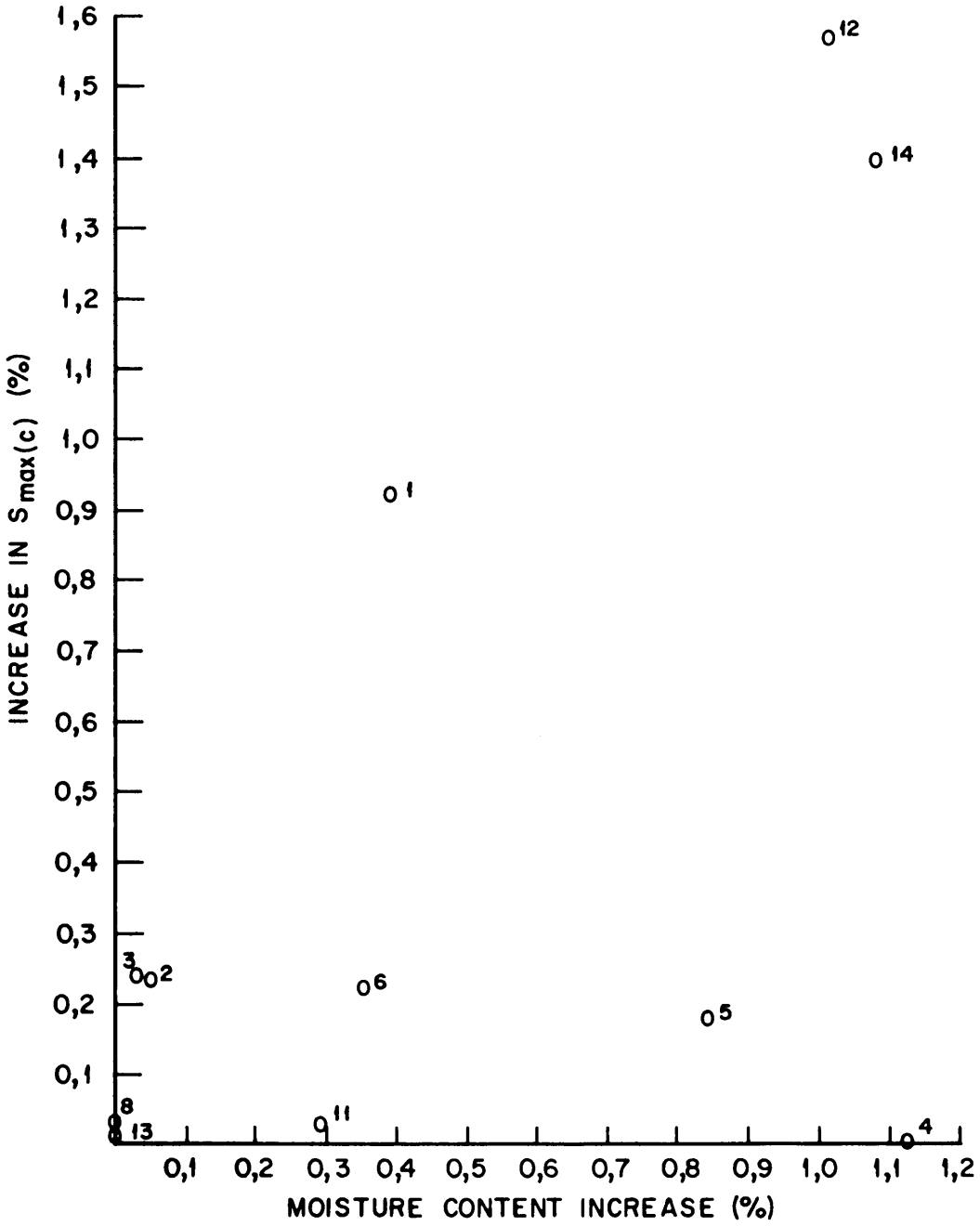


FIGURE 9.4

RELATION BETWEEN INCREASE IN MAXIMUM PERCENTAGE SWELL AND ADDITIONAL MOISTURE ABSORBED FROM NATURAL TO SOAKED STATE

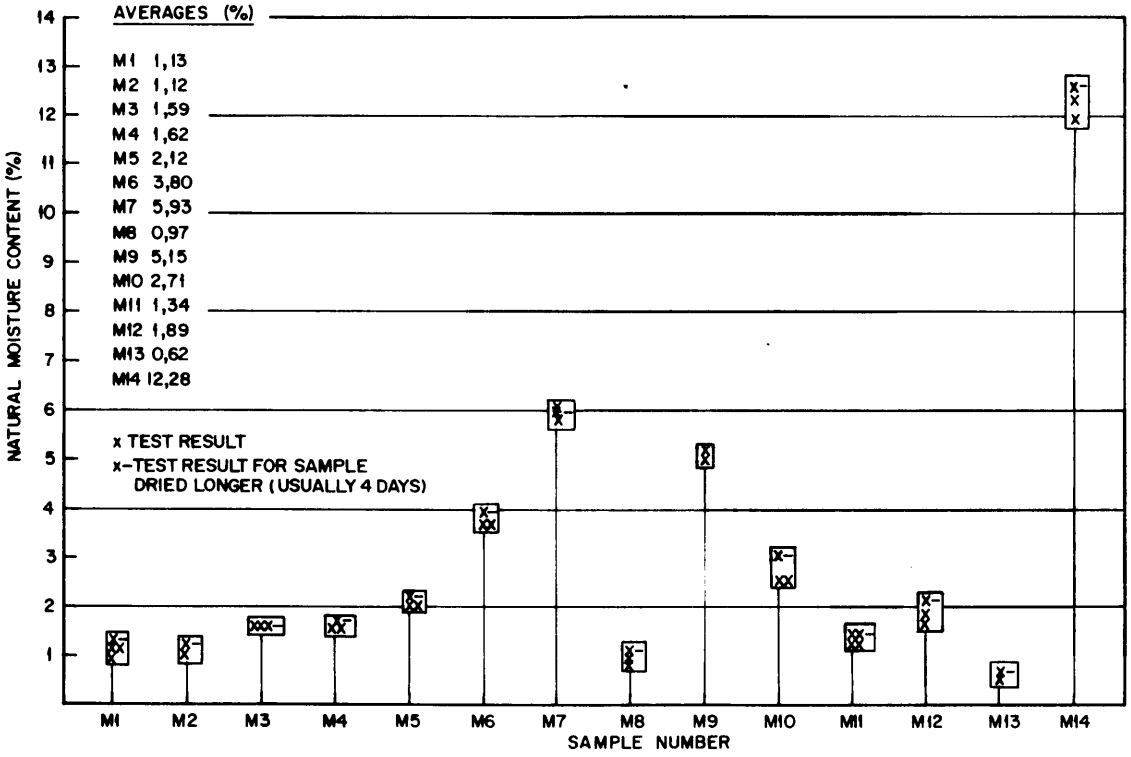


FIGURE 9.5
NATURAL MOISTURE CONTENT OF SAMPLES

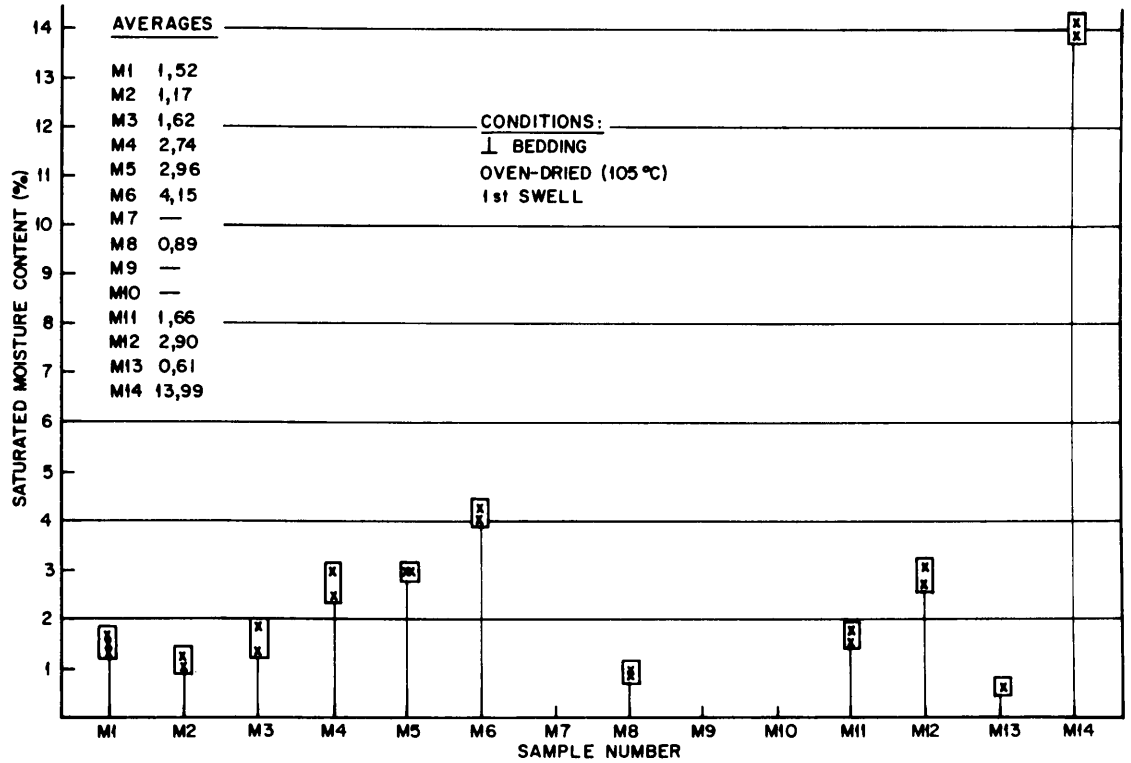


FIGURE 9.6
SATURATED MOISTURE CONTENT AFTER 24 HOUR IMMERSION

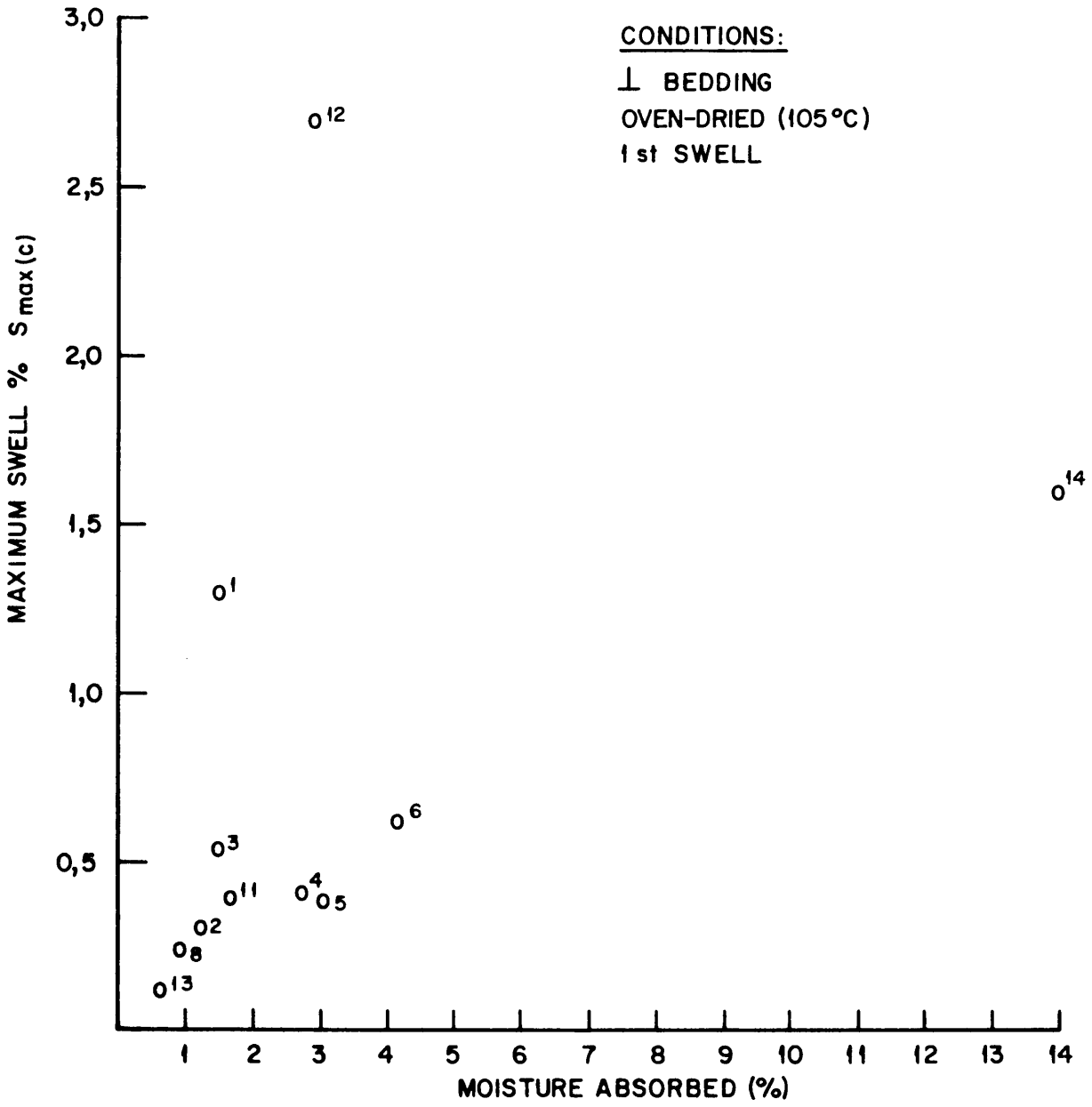


FIGURE 9.7

COMPARISON BETWEEN MAXIMUM SWELL PERCENTAGE AND AMOUNT OF MOISTURE ABSORBED

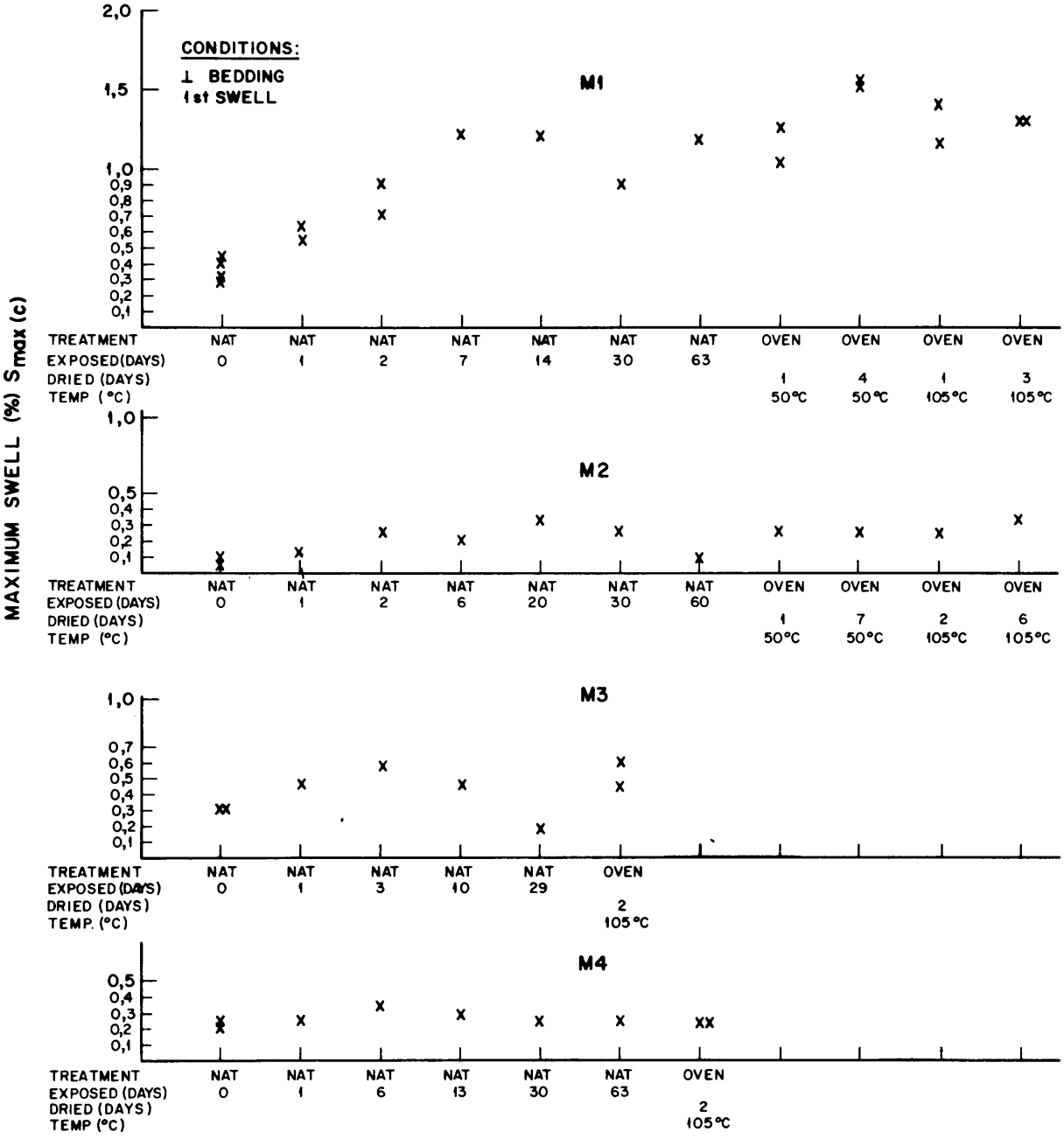


FIGURE 9.8

MAXIMUM SWELL OF SAMPLES AFTER DIFFERENT TREATMENTS

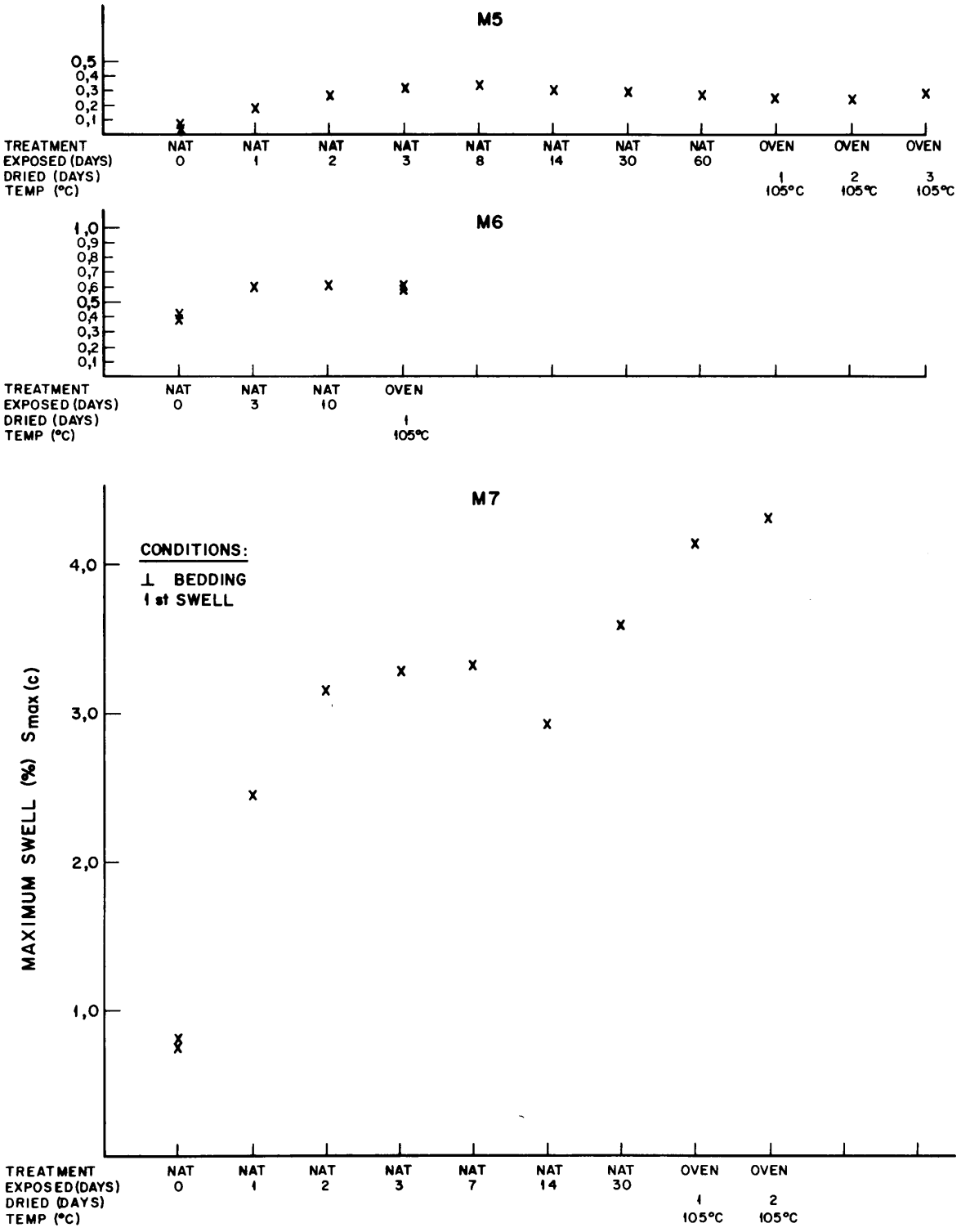


FIGURE 9.9

MAXIMUM SWELL OF SAMPLES AFTER DIFFERENT TREATMENTS

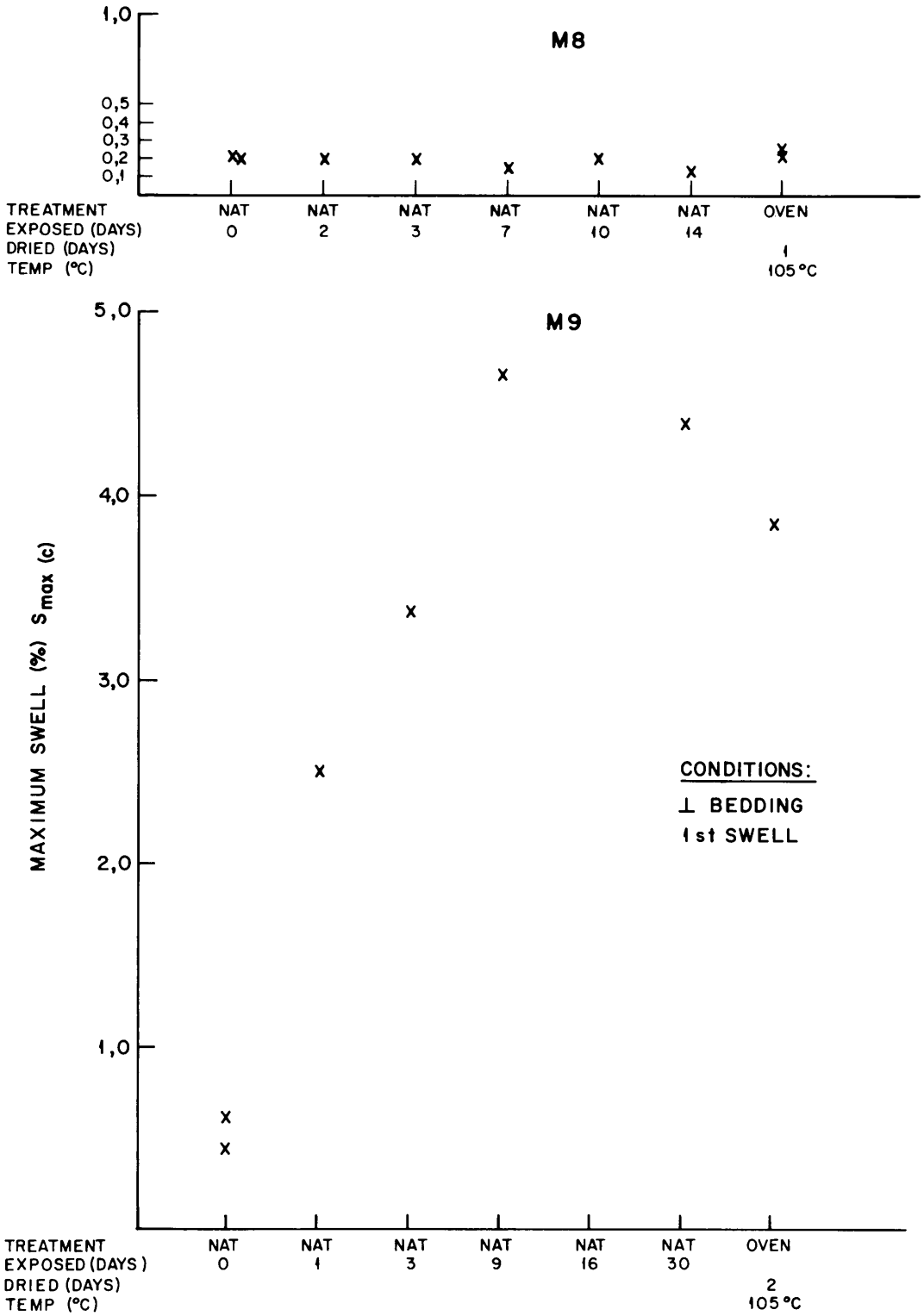


FIGURE 9.10

MAXIMUM SWELL OF SAMPLES AFTER DIFFERENT TREATMENTS

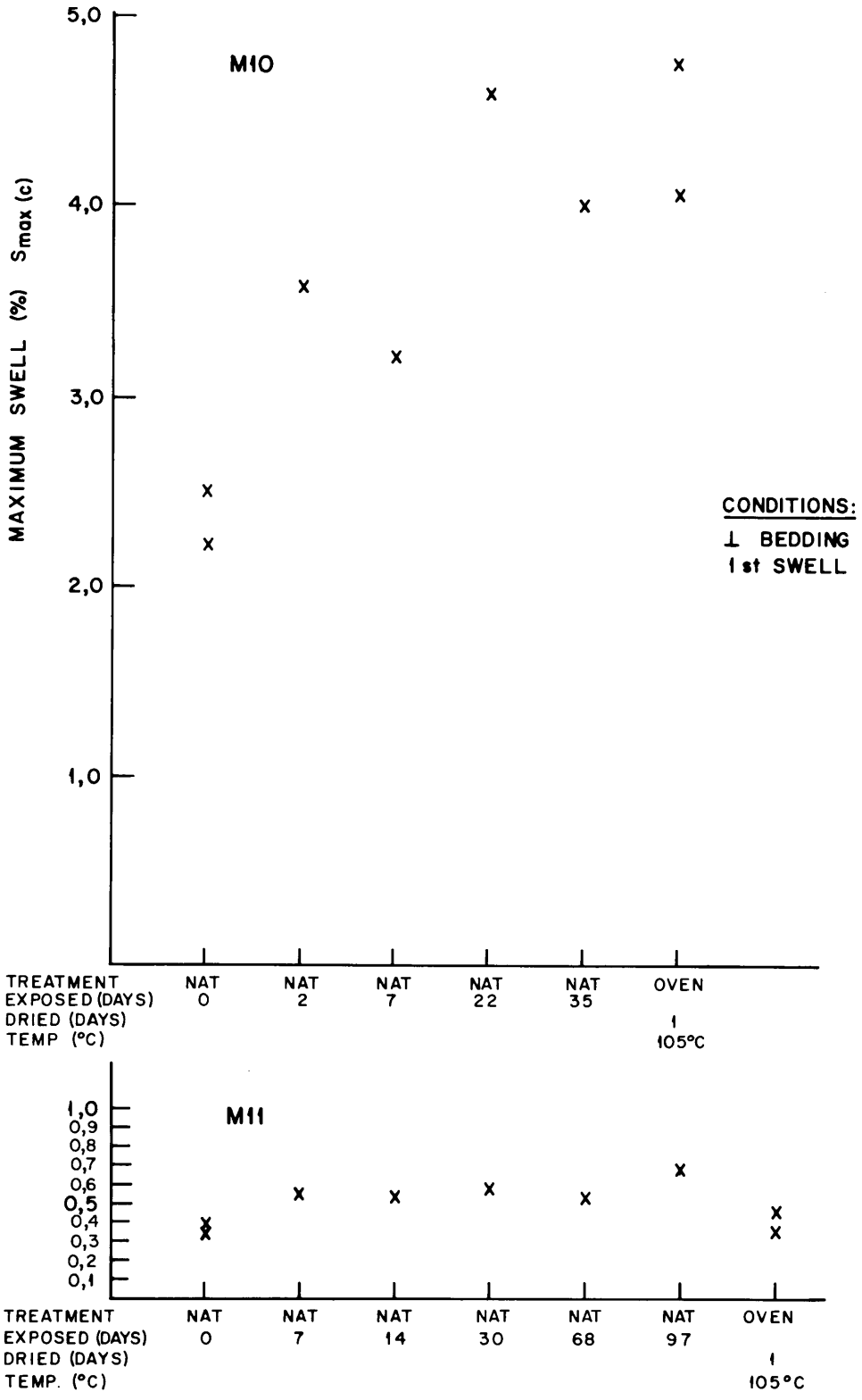


FIGURE 9.11

MAXIMUM SWELL OF SAMPLES AFTER DIFFERENT TREATMENTS

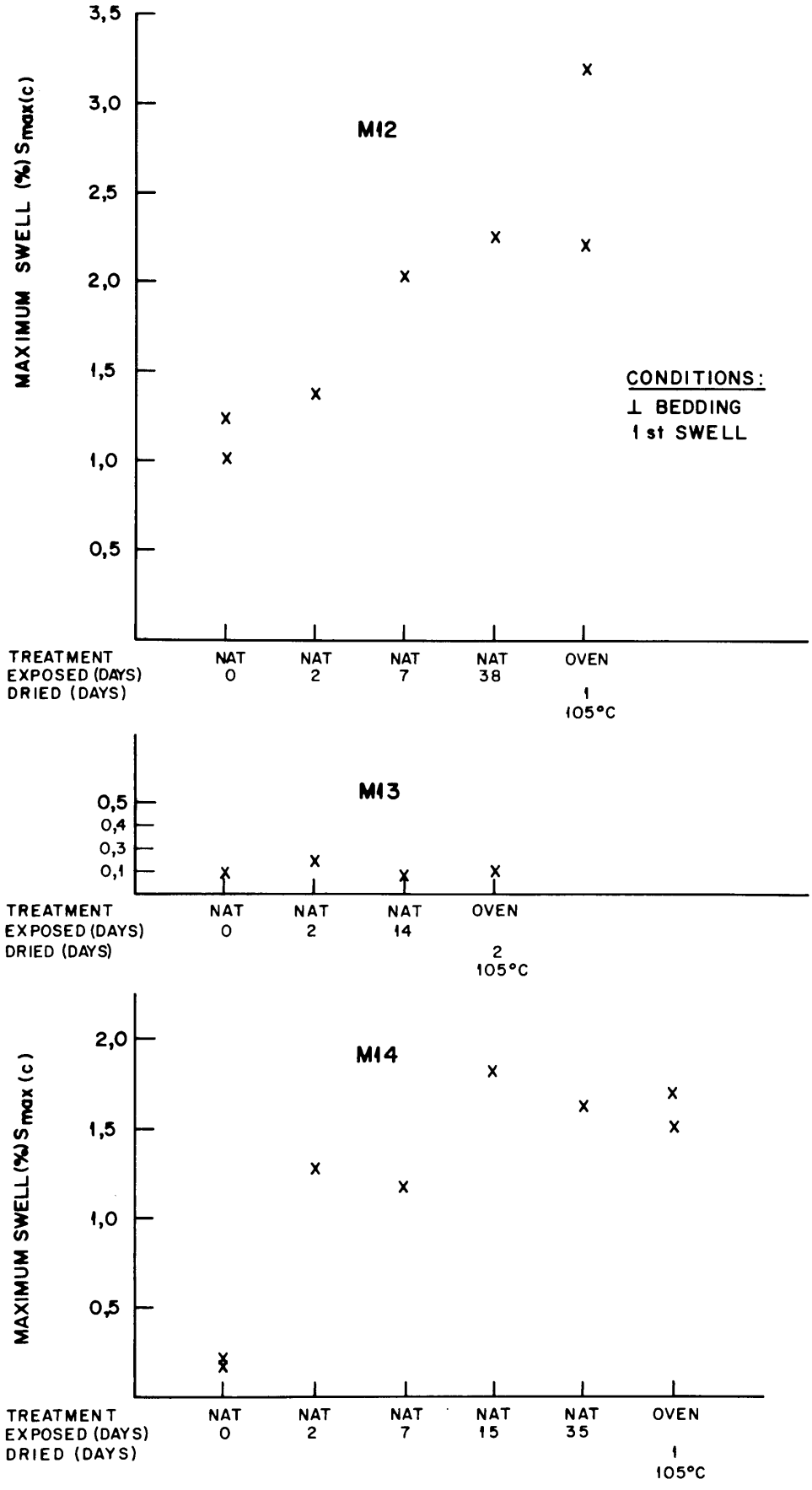


FIGURE 9.12

MAXIMUM SWELL OF SAMPLES AFTER DIFFERENT TREATMENTS

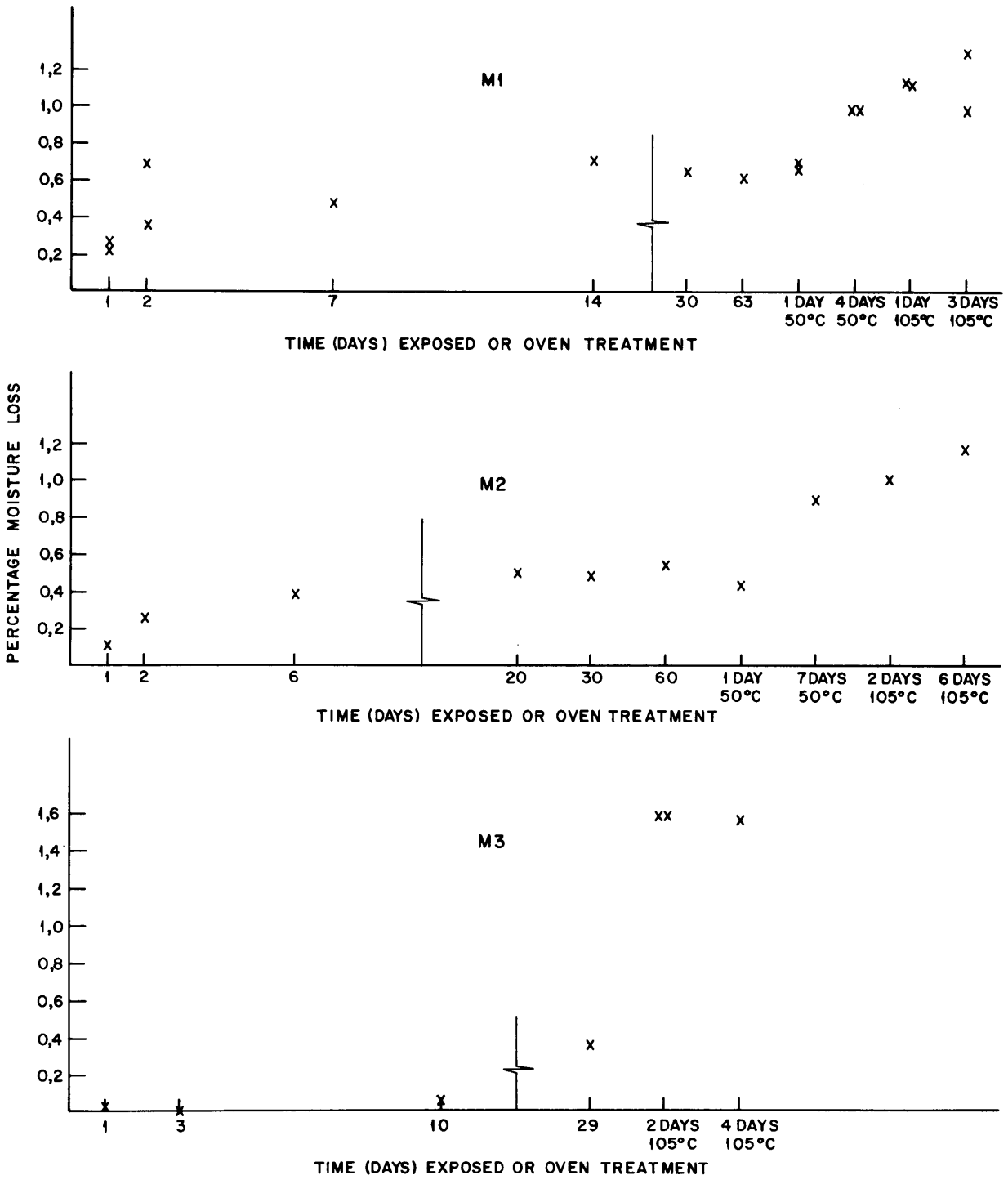


FIGURE 9.13

LOSS OF MOISTURE ON AIR-DRYING AND OVEN-DRYING

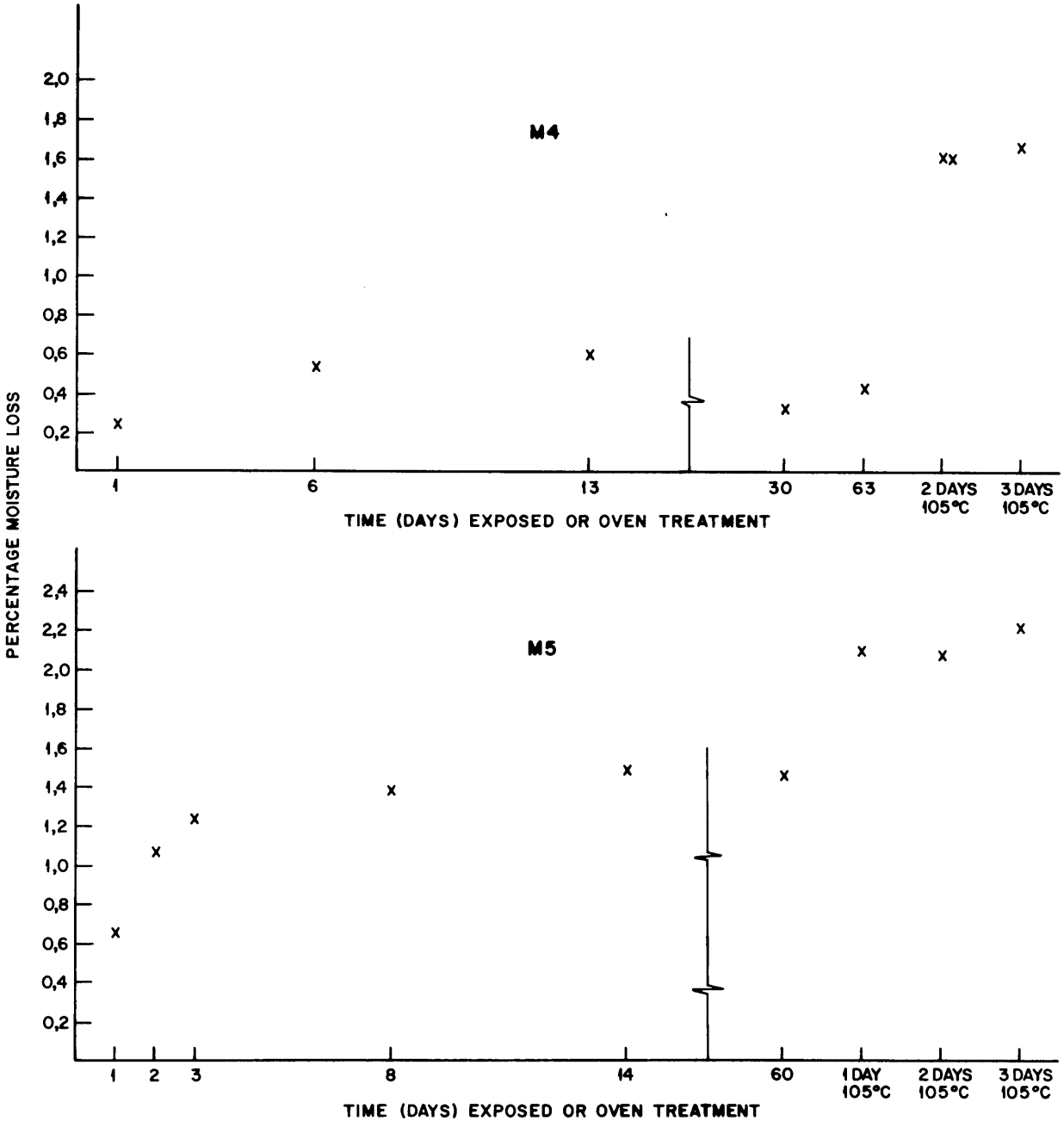


FIGURE 9.14

LOSS OF MOISTURE ON AIR - DRYING AND OVEN - DRYING

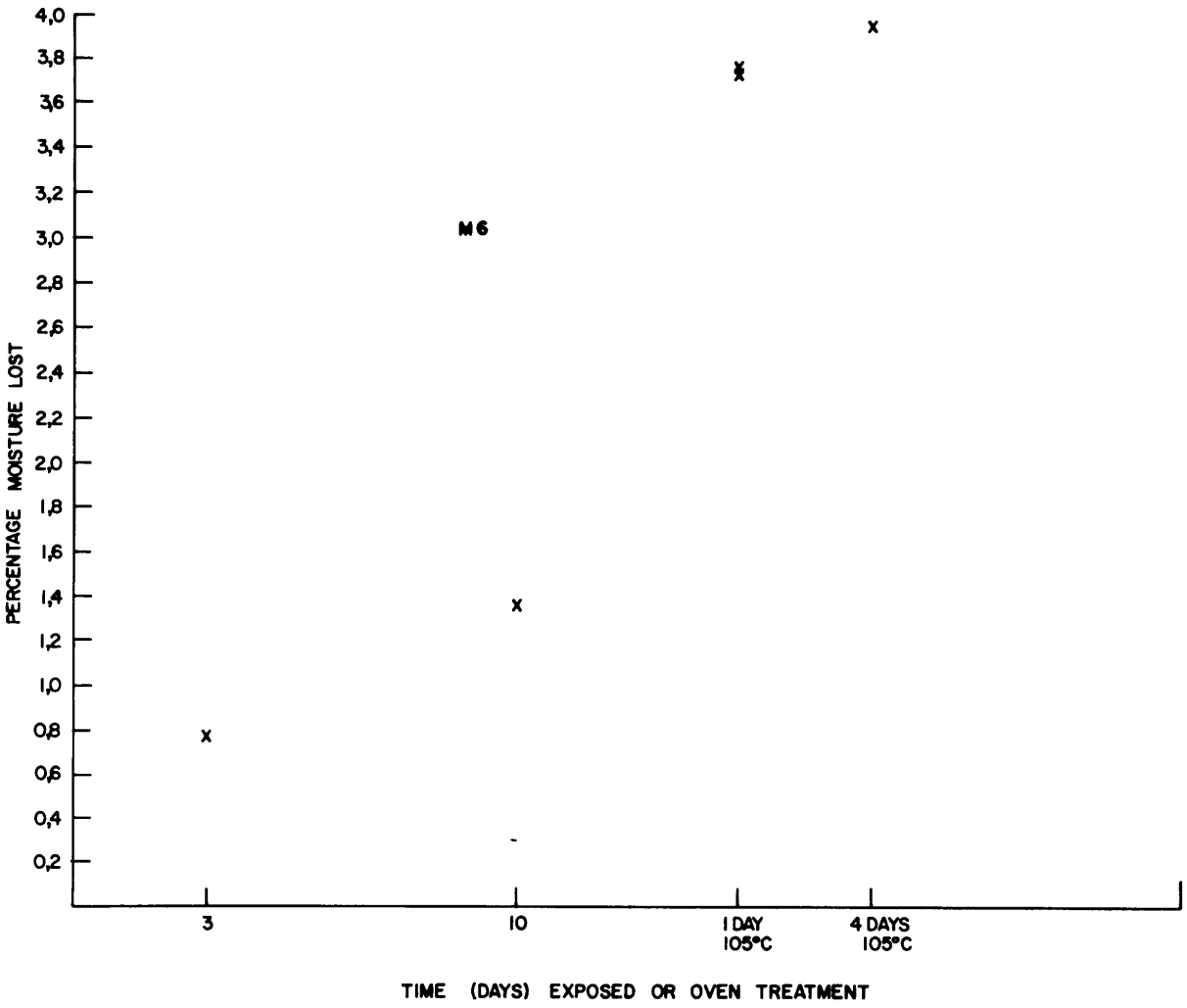


FIGURE 9.15

LOSS OF MOISTURE ON AIR - DRYING AND OVEN DRYING

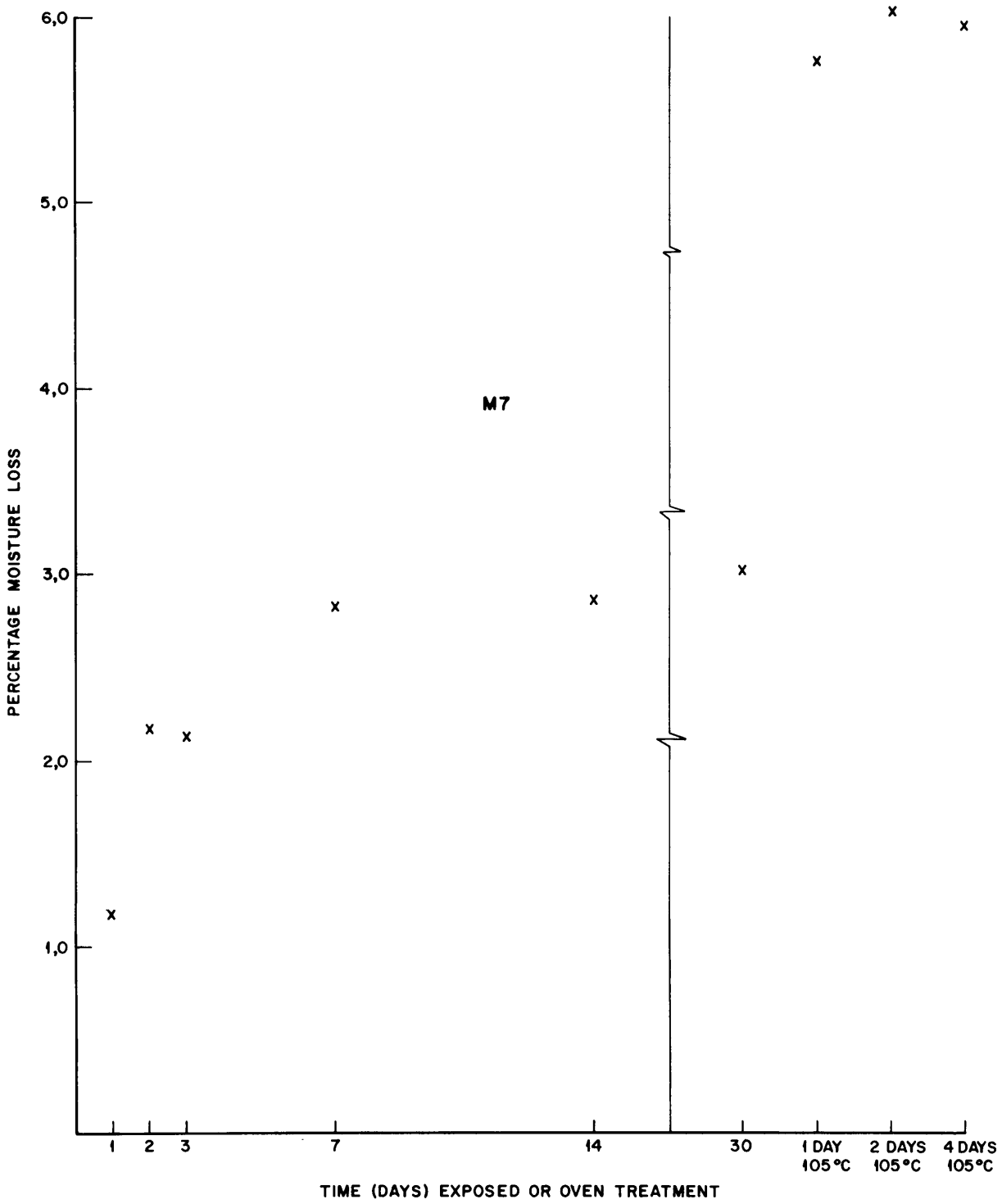


FIGURE 9.16

LOSS OF MOISTURE ON AIR-DRYING AND OVEN-DRYING

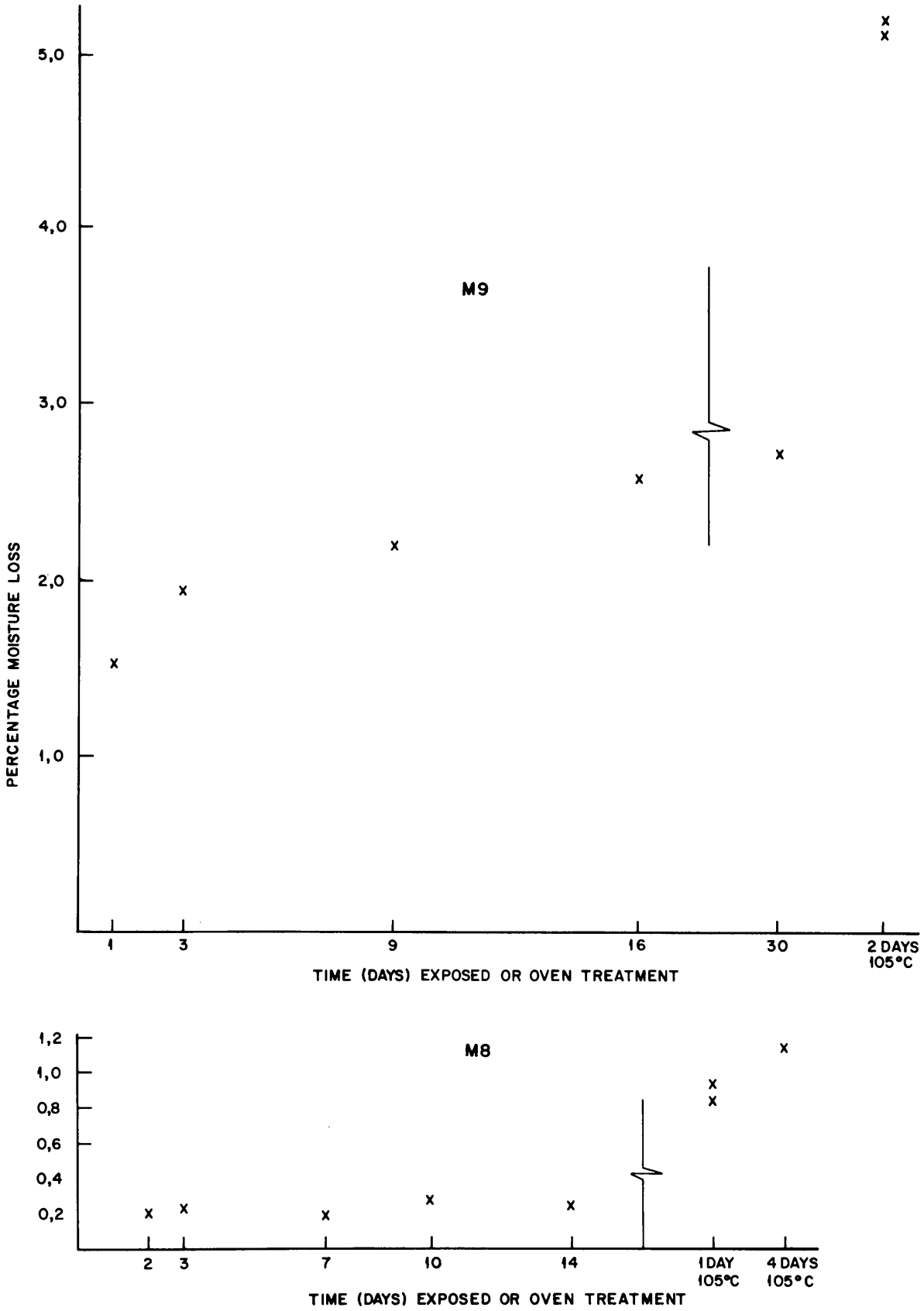


FIGURE 9.17

LOSS OF MOISTURE ON AIR - DRYING AND OVEN - DRYING

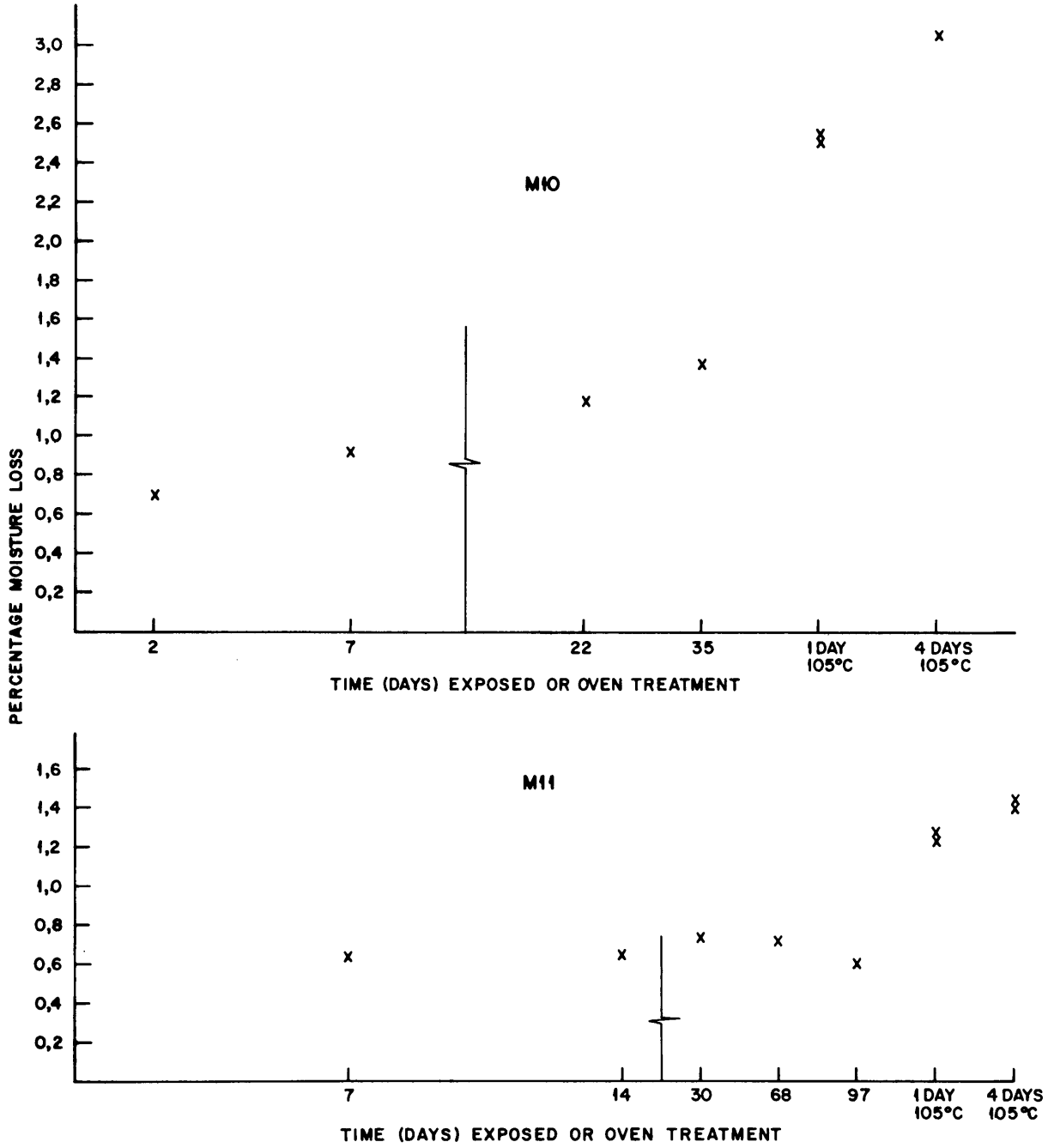


FIGURE 9.18

LOSS OF MOISTURE ON AIR - DRYING AND OVEN - DRYING

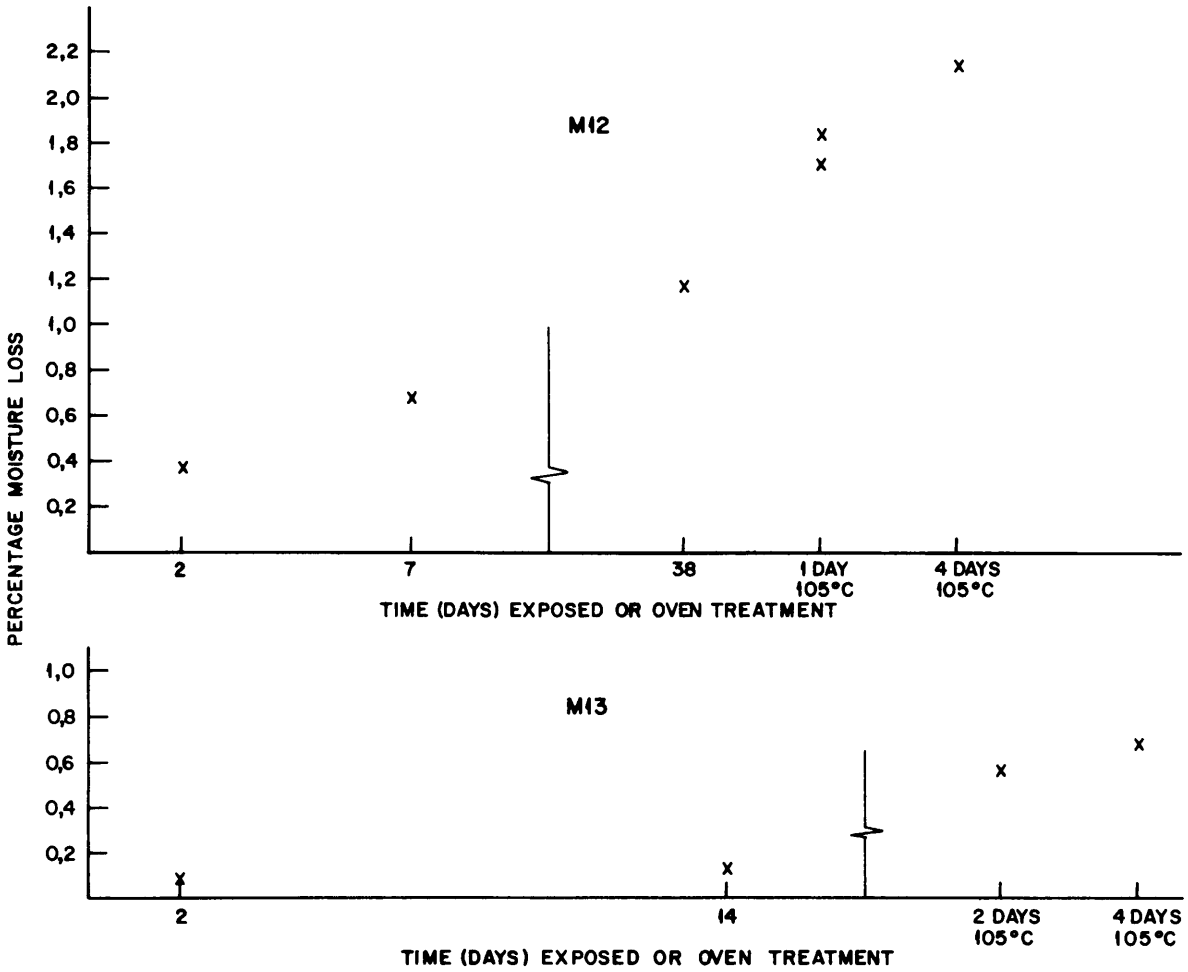


FIGURE 9.19

LOSS OF MOISTURE ON AIR - DRYING AND OVEN -DRYING

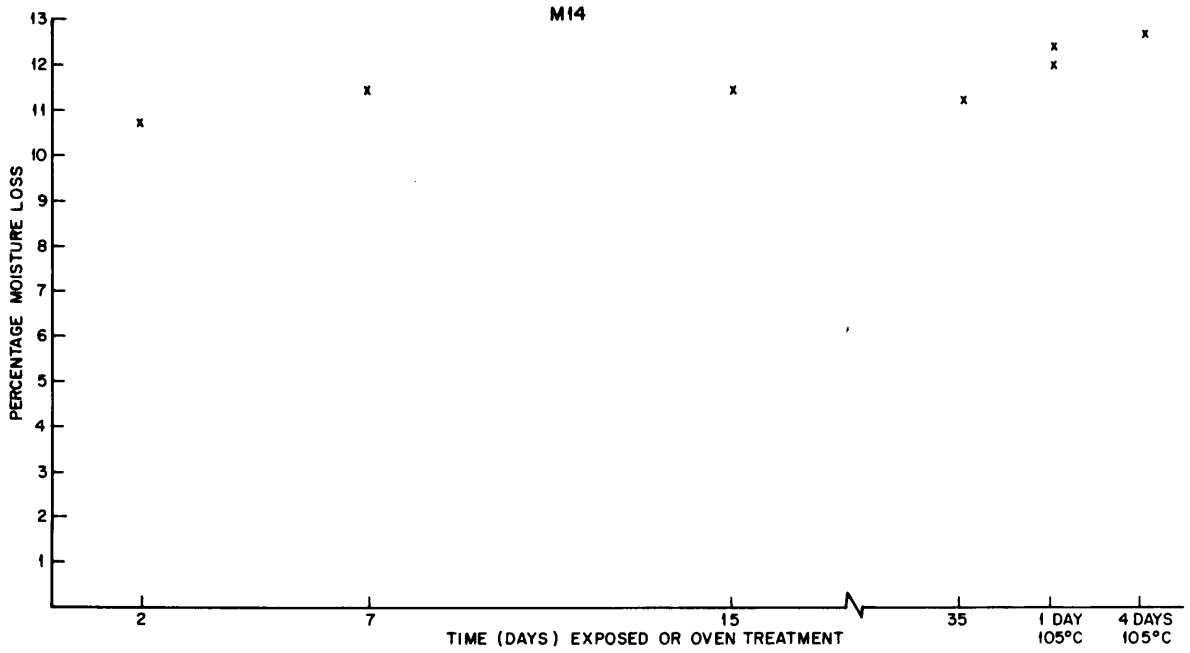


FIGURE 9.20

LOSS OF MOISTURE ON AIR - DRYING AND OVEN - DRYING

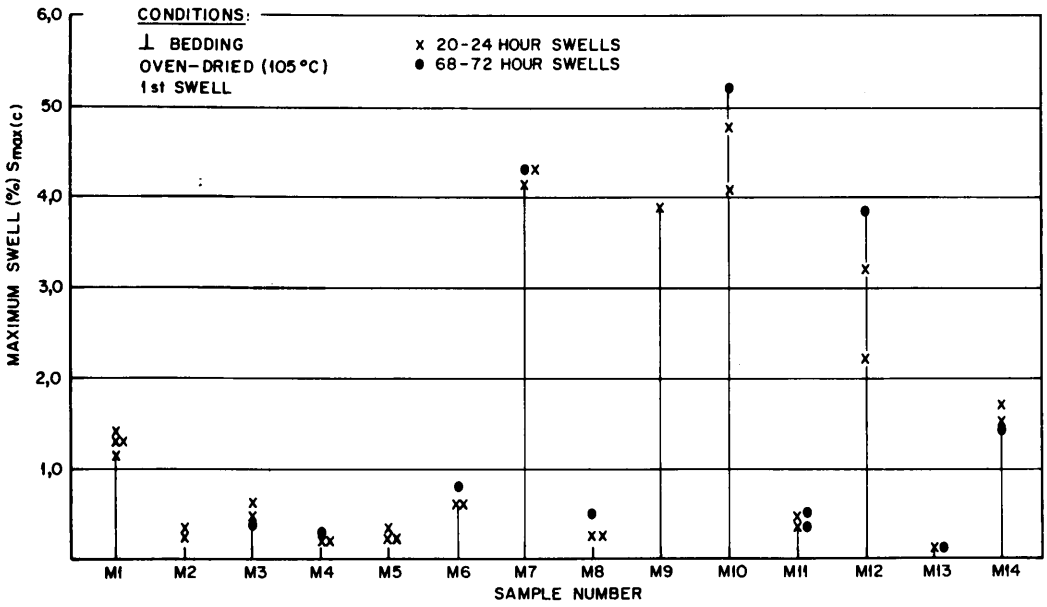


FIGURE 9.21

COMPARISON OF MAXIMUM SWELL OVER PERIODS OF 20 - 24 hrs AND PERIODS OF 68 - 72 hrs

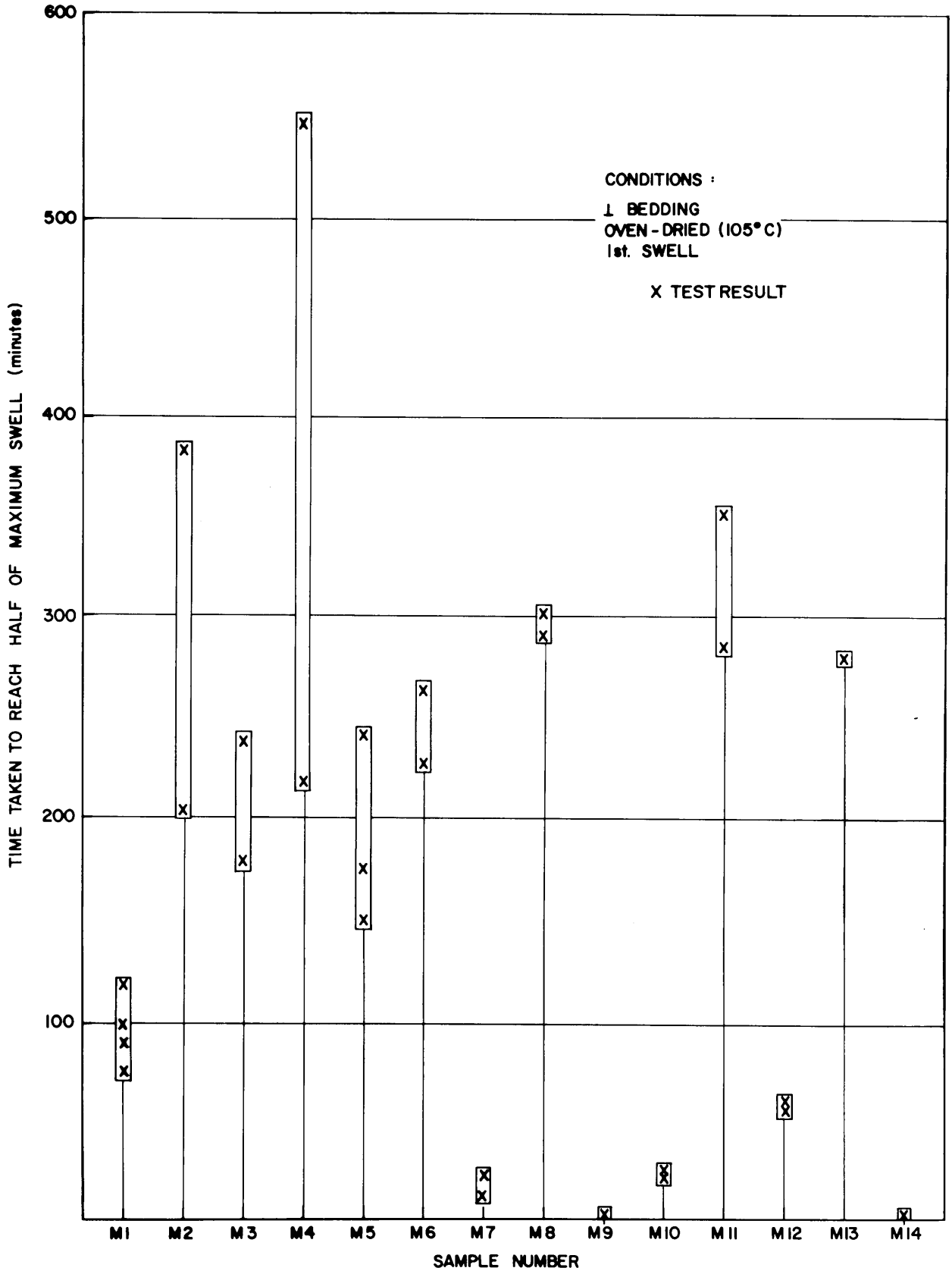


FIGURE 9.22

TIME TAKEN TO REACH HALF OF THE MAXIMUM SWELL .

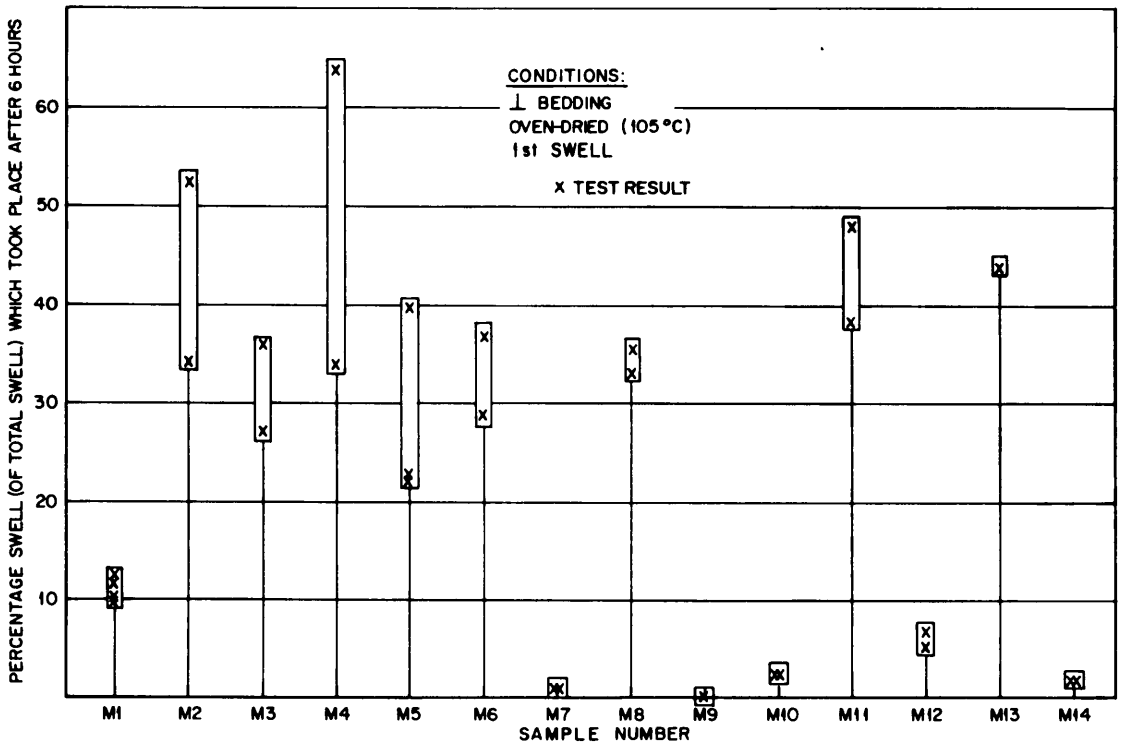


FIGURE 9.23
PERCENTAGE SWELL AFTER 6 HOURS

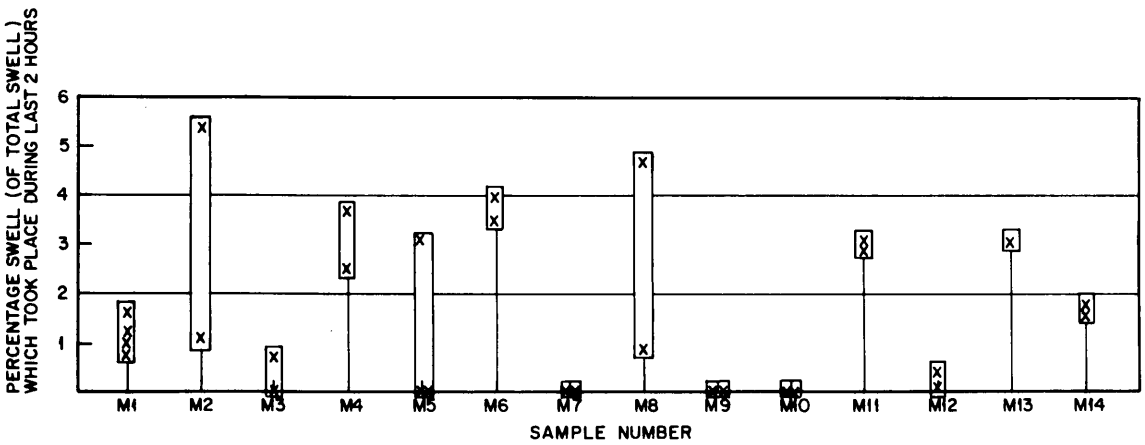


FIGURE 9.24
PERCENTAGE SWELL DURING LAST 2 HOURS

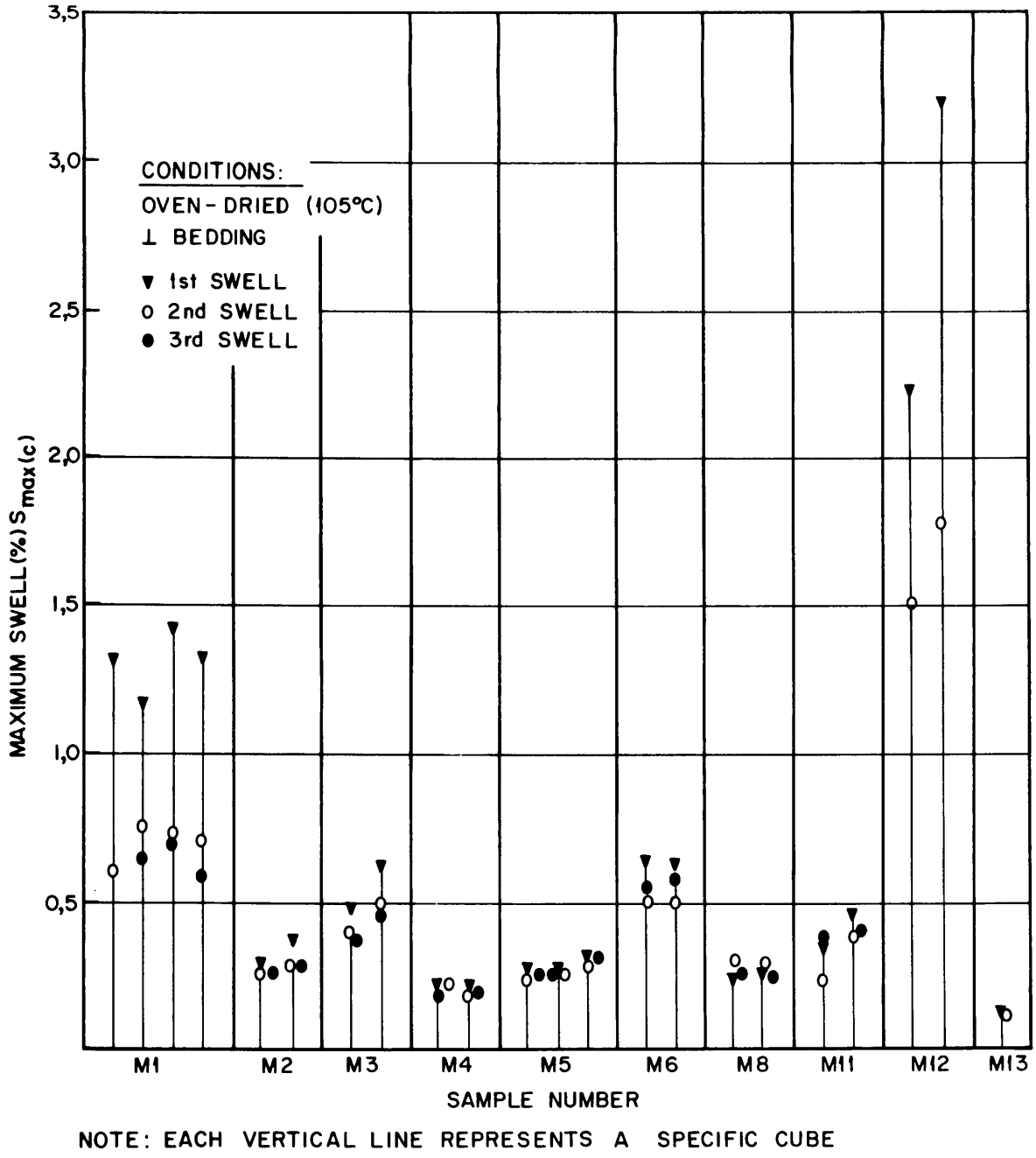


FIGURE 9.25

COMPARISON OF MAGNITUDES OF 1st, 2nd AND 3rd SWELLS

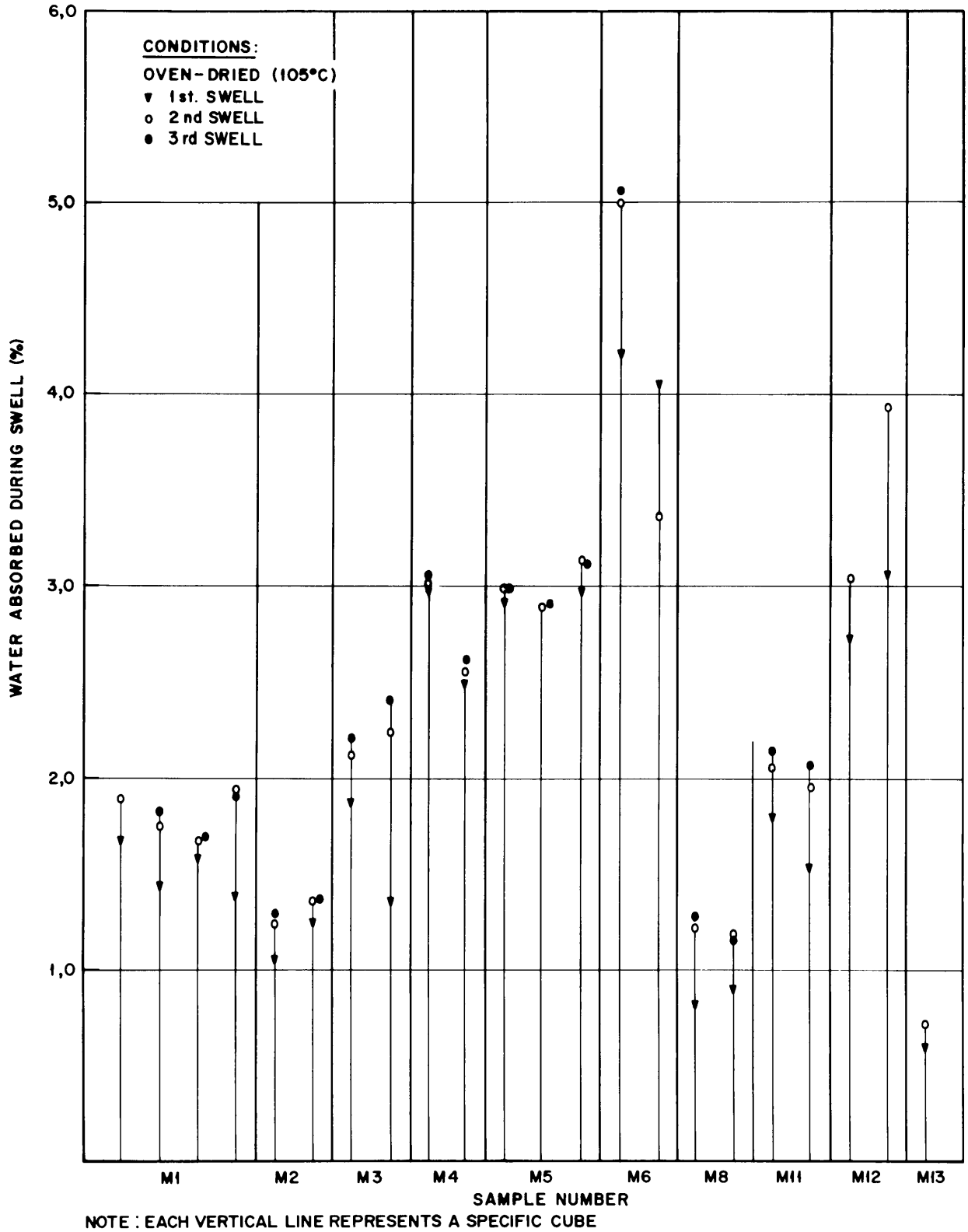


FIGURE 9.26

COMPARISON OF WATER ABSORPTION DURING 1st., 2nd. AND 3rd. SWELLS

CHAPTER 10

ABSORPTION CHARACTERISTICS

10.1 Natural absorption and absorption of samples left in a vacuum

10.1.1 Introduction

Absorption tests were done for the following reasons:

(a) To determine the general absorption characteristics of mudrocks.

(b) To see if absorption increases if samples are left under vacuum before soaking.

(c) To check the hypothesis of "air breakage" (Badger et al, 1956) which is sometimes used to explain the slaking or disintegration of mudrocks.

According to this hypothesis air is compressed inside the rock by the water absorbed and this induces stresses which break up the rock. Taylor and Spears (1970) state: "During dry periods evaporation from the surfaces of rock fragments promotes high suctions, which in turn result in increased shearing resistance (of individual fragments) by virtue of high contact pressures. With extreme desiccation the bulk of the voids will be filled with air, which, on rapid immersion in water, becomes pressurized by the capillary pressures developed in the outer pores. Failure of the mineral skeleton along the weakest plane ensues and an increased surface area is then exposed to a further sequence of events". This hypothesis can be verified by comparing the behaviour of samples soaked naturally and samples soaked after being left under vacuum for a certain period. The latter samples should not break down to the same extent as the former ones.

Following the pilot study (Section 5.2.8) a special glass stopper was made for a large desiccator to determine the absorption of mudrock samples left under vacuum for a few days (vacuum saturated absorption).

10.1.2 Method

A minimum of four 30 mm cubes per sample were sawn from sample blocks which had been kept at their natural moisture content (NMC) since sampling. These four cubes were used to determine the absorption under natural and vacuum saturated conditions for oven-dried samples and samples at their natural moisture content.

After weighing, two of the four cubes were put into the oven for drying at 105 °C. Another cube was put into the desiccator and subjected to a vacuum while the remaining cube was immersed in water to determine the absorption at the natural moisture content. The way in which the cubes from each sample were treated can be summarized in the following way (Table 10.1).

TABLE 10.1: TREATMENT OF CUBES USED TO DETERMINE VARIOUS ABSORPTIONS

Treatment of cube	Dried for (days)	Under vacuum for (days)	Soaked for (days)
NMC - soaked	0	0	4
NMC - under vacuum - soaked	0	8	4
Oven-dried - cooled - soaked	4	0	4
Oven-dried - under vacuum - soaked	4	4	4

The oven-dried samples soaked under normal conditions were allowed to cool in a desiccator for two hours before being immersed in water. The oven-dried cubes which had been subjected to a vacuum were transferred directly to the desiccator after weighing. After the period, during which the samples were kept under vacuum, de-aired distilled water was sucked into the desiccator under vacuum to cover the cubes. Paper tissues were used to surface dry the cubes following the four-day soaking periods. The desiccator used is shown on Plate 18 and the results are listed in Table 10.2 and illustrated graphically in Figure 10.1.

TABLE 10.2: RESULTS FROM NATURAL AND VACUUM-SATURATED ABSORPTION TESTS

Sample number	Natural moisture content	Absorption under natural conditions %		Absorption under vacuum %		Comparison of values for natural and vacuum saturated absorption		Natural moisture content as percentage of saturated moisture content	
		From natural to saturated a	From oven-dried to saturated b	From natural to saturated c	From oven-dried to saturated d	$\frac{c}{a} \times 100$ %	$\frac{d}{b} \times 100$ %	Under natural conditions	Under vacuum
M1	0,97 0,97 0,96	0,68	1,88	0,86	1,75 1,67	126	91	51	57
M2	0,88 0,89 0,77	0,28	1,18	0,28	1,22 1,18	100	102	72	71
M3	1,02 0,95 1,00	1,05	2,30	1,15 1,05	2,03 1,83	105	84	43	51
M4	0,88 0,83 0,86	2,03	3,09	1,91	2,68 2,53	95	84	28	33
M5	0,74 0,78 0,43	2,03	2,82	2,59	3,20 3,41	128	117	23	20
M6	3,16 3,18 2,80	2,58	5,13	2,02 1,62	5,15 7,36	71	122	59	49
M7	2,19								
M8	0,73 0,64 0,55	1,21	1,97	1,48	1,79 1,95	122	95	32	34
M10	2,16 2,04 1,78				4,67				43
M11	2,02 1,96	2,08	4,82	1,73	4,56	83	95	41	44
M11A	1,12 1,13	4,18		4,48	5,62 5,60	107			20
M12	1,89 1,96 1,68	1,51	3,46	1,67	5,60 4,01	111	110	53	40
M13	0,48 0,40	0,41	0,84	0,47	0,82	115	98	52	50
M14	8,75 11,91	3,42	13,94	4,30	16,55 16,46	126	118	74	63

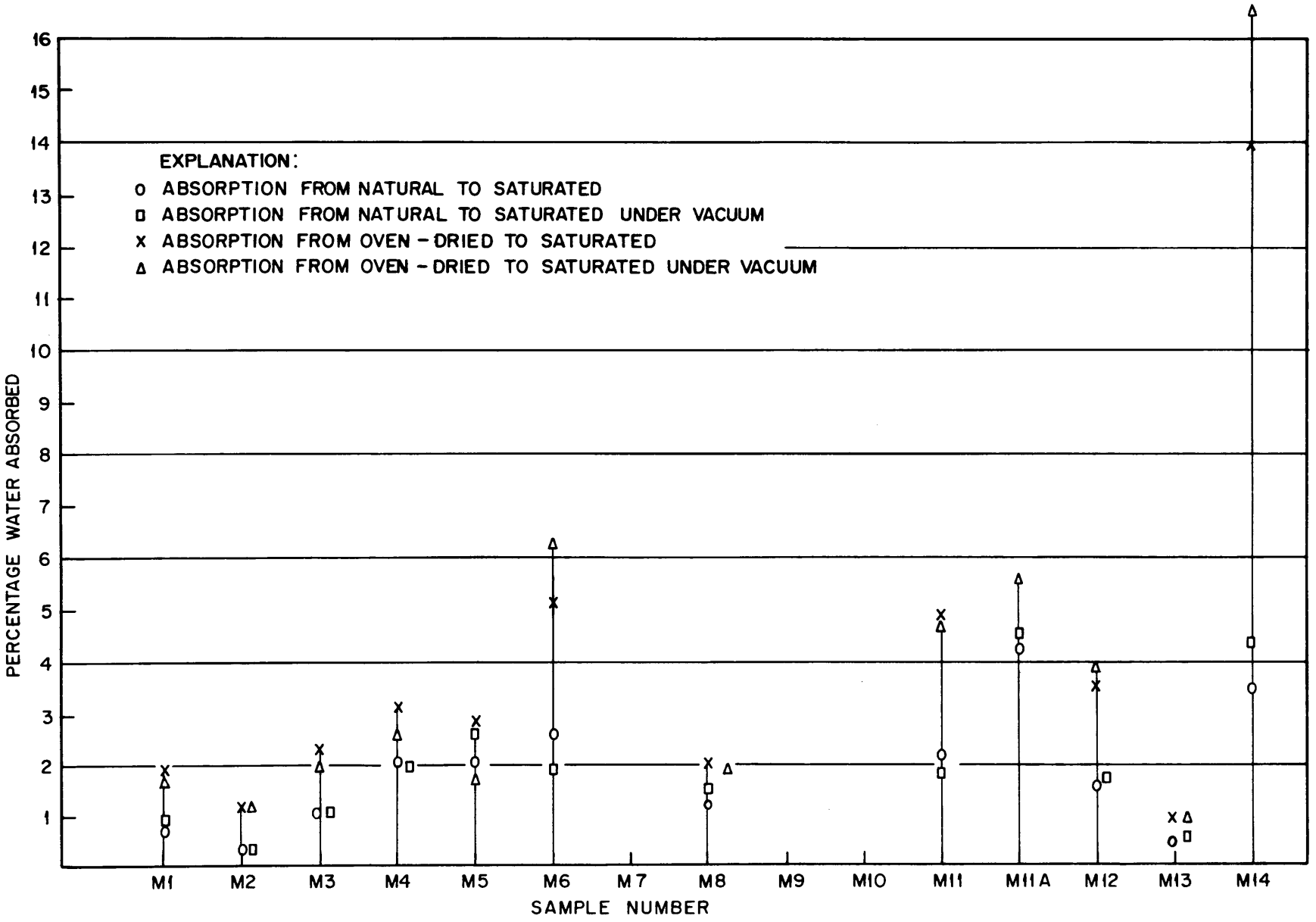


FIGURE 10.1

WATER ABSORBED BY NATURAL AND OVEN-DRIED SAMPLES UNDER ATMOSPHERIC AND VACUUM CONDITIONS

10.1.3 Discussion

Very consistent results were obtained from the samples which were less affected by water, such as M2, M3, M4, M5, M11 and M13. The only problem here was the loss of some dust from the cube surfaces during soaking and drying. Samples M1, M8 and M12 exhibited thin cracks parallel to the bedding which could harbour free water. Samples M6 and M11a broke down to a certain degree or formed many open cracks which complicated the drying process. Sample M14 became slightly clayey on the outside during the soaking and this led to some losses during drying. Samples M7, M9 and M10 were impossible to test because they disintegrated or slaked when immersed in water.

When the natural samples were soaked they absorbed between 0,3 and 4,5 per cent water. Most of the absorptions were in the 1 to 3 per cent range. The oven-dried samples absorbed more - between 0,8 and 16,5 per cent - but only one sample absorbed in excess of 6,0 per cent water. It must be noted that the absorptions of the natural and oven-dried samples cannot be compared directly. The absorptions of the natural samples have been calculated as a percentage of the natural masses while that of the oven-dried samples have been calculated as percentages of the oven-dried masses.

From a comparison between similar absorptions under normal and vacuum saturated conditions it can be seen that for the cubes immersed at natural moisture content there was generally more absorption when the cubes had been subjected to a vacuum prior to soaking. Table 10.2 shows that eight of the twelve samples absorbed more water when treated in this way. For the oven-dried samples there was no clear difference as some samples absorbed more water during the one treatment and others less. It may be due partly to the fact that the samples immersed at natural moisture content had been subjected to a vacuum for a longer period.

The hypotheses of air-breakage could not be substantiated as there were no visual differences between the behaviour of cubes treated in the two different ways. This is illustrated in Plate 19 where examples of two samples treated in the normal way (N) and under vacuum (V) are shown. Nakano (1967) came to the same conclusion after conducting the test on duplicate mudstones. It is, however, possible that dial gauges may indicate some differences in behaviour which are not visible to the eye (Olivier, 1976b).

10.2 Rate of absorption

10.2.1 Introduction

The rate at which rocks absorb water is an important engineering property and it is especially important when tests involving water are studied. A test similar to that of Deo (1972) was investigated during the pilot study (Section 5.2.7) and found to be applicable.

10.2.2 Method

Two 30 mm cubes were sawn for each sample from sample blocks which had been stored at natural moisture content. After sawing, the cubes were blown clean of dust, using compressed air. They were then weighed and placed in an oven to dry at 105 °C. The cubes were taken out individually after four days, weighed and put into a desiccator to cool. After two hours they were reweighed and the duplicate cubes from each sample were placed in crystallizing dishes and covered with distilled water at one-minute intervals. Surface drying and weighing took place after exactly 15, 40 and 90 minutes. For the later mass determinations the exact weighing times were not adhered to as strictly, as the readings were by then out of the high rate of absorption part of the curve. Readings were taken up to 16 days on the samples which did not break down too much. All the drying was done by the same person as it was important to follow standardized procedures. The results are given in Table 10.3. The percentages listed were calculated as the mass increases due to absorption of water given as percentages of the dried masses of the samples before immersion. The absorption with time curves are shown in Figure 10.2. The curve for M14 was not plotted in order to avoid reducing the scale for all the other samples.

10.2.3 Discussion

As with the absorptions discussed in Section 10.1, the test was easy to perform on mudrocks which did not slake or disintegrate during immersion, such as M2, M3, M4, M5, M11 and M13. The cubes from samples M1, M8 and M12 developed fractures parallel to the bedding and thin flakes came away. This presented problems in that these flakes were difficult to dry individually and difficult

TABLE 10.3: RESULTS OF RATE OF ABSORPTION TESTS

Sample number	Oven dried mass (g) (cold)	Initial natural moisture content (%)	Percentage moisture absorbed after (hours)										Remarks
			0,25	0,67	1,5	4,5	21	45,5	70	99	217	386	
M1	48,29	0,87	0,27	0,60	0,91	1,37	1,68	1,66	1,68	too many flakes			Sample cracked - broke in two
	43,89	0,96	0,36	0,71	1,05	1,53	1,80	1,75	1,73	1,85	1,85	1,87	Sample cracked
M2	87,81	0,96	0,16	0,23	0,35	0,56	1,07	1,21	1,24	1,23	1,24	1,24	No cracks
	75,20	0,97	0,17	0,23	0,32	0,47	0,92	1,17	1,22	1,25	1,24	1,25	
M3	65,37	0,92	0,20	0,28	0,37	0,57	1,06	1,42	1,56	1,58	1,62	1,62	No cracks
	68,52	0,98	0,23	0,31	0,41	0,70	1,30	1,58	1,72	1,75	1,82	1,82	
M4	56,72	0,85	0,67	1,02	1,41	2,13	2,65	2,63	2,66	2,66	-	2,79	No cracks - some dust
	51,13	0,78	0,74	1,13	1,60	2,29	2,58	2,54	2,56	2,58	-	2,70	
M5	63,91	0,70	1,27	1,83	2,35	3,00	3,18	3,21	3,26	3,27	3,32	3,36	No cracks - some dust
	56,71	0,72	1,43	2,08	2,70	3,30	3,39	3,40	3,42	3,49	3,54	3,60	
M6	60,30	3,48	1,18	1,96	-	5,04	5,62	5,71	too much disintegration				Samples cracked - difficult to keep together
	60,08	3,53	0,78	sample disintegrating too much									
M8	55,60	0,77	0,32	0,58	0,99	1,62	1,80	1,98	1,89	1,98	1,89	1,92	Sample cracked
	97,29	0,79	0,22	0,49	-	1,83	1,95	2,11	too many small flakes				
M11	52,62	1,94	1,10	2,05	2,98	4,18	4,33	4,33	4,33	4,45	4,45	4,50	No cracks - some dust
	54,21	1,94	1,25	2,01	3,01	4,15	4,41	4,35	4,46	4,50	4,52	4,56	
M11A	60,88	1,35	0,56	1,35	-	3,94	4,42	Sample disintegrating					Open cracks
	76,09	1,38	0,83	2,23	-	-	4,60	4,28	4,18	too many flakes			
M12	65,11	1,40	0,37	0,78	1,18	1,90	2,56	2,75	2,60	2,72	2,63	2,66	Sample cracked
	58,20	1,41	0,40	0,77	1,22	1,84	2,37	2,41	2,41	too many flakes			
M13	52,75	0,51	0,17	0,23	0,30	0,44	0,68	0,76	0,78	0,80	0,80	0,76	No cracks
	65,54	0,52	0,18	0,24	0,35	0,49	0,73	0,75	0,76	0,79	0,78	0,76	
M14	68,47	10,3	12,90	12,91	-	13,29	13,77	14,04	14,17	14,30	14,46	14,50	Few cracks - clayey on outside
	49,62	9,8	13,10	13,12	13,22	13,52	14,11	14,37	14,45	14,57	14,53	14,49	

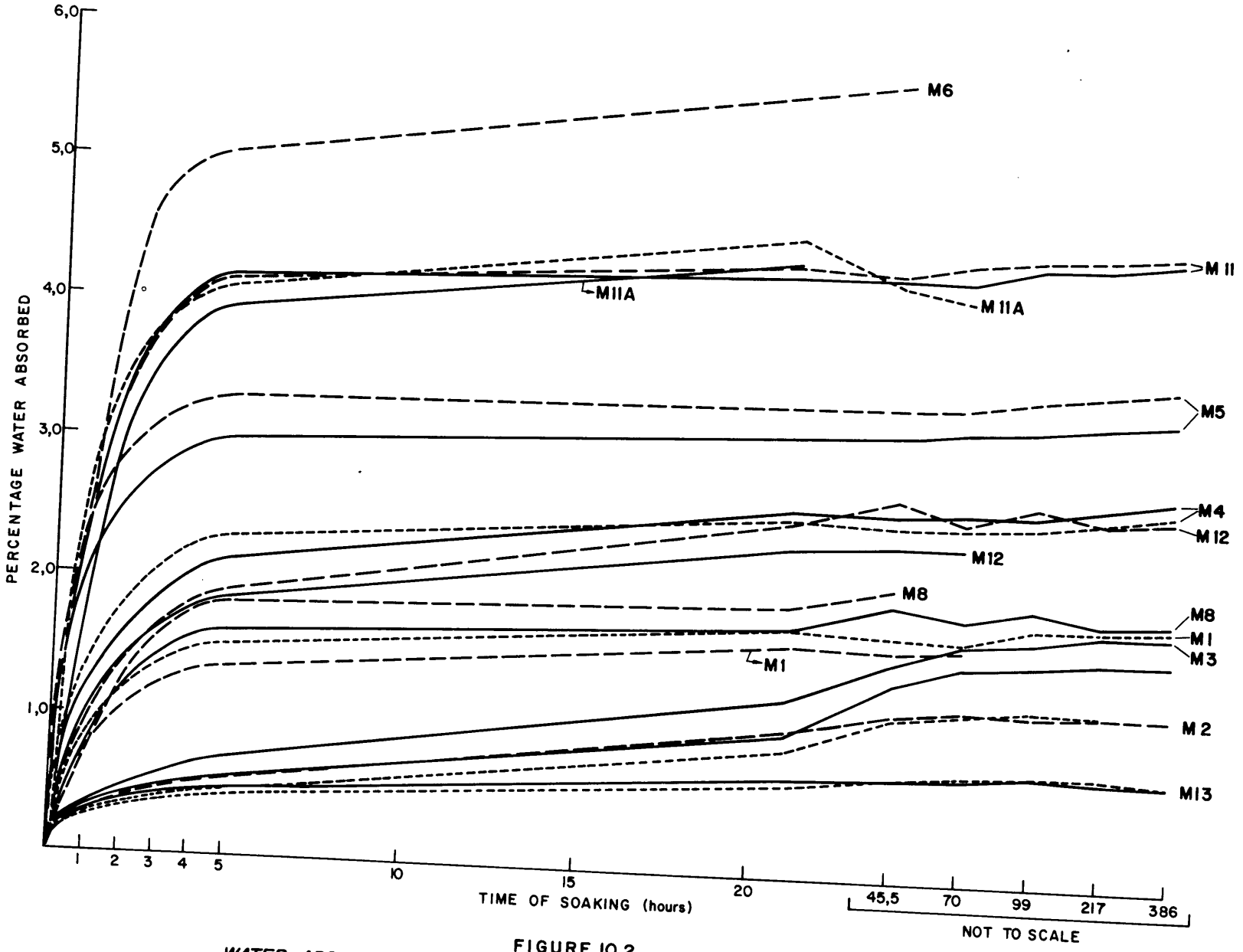


FIGURE 10.2
WATER ABSORPTION (PERCENTAGE) AGAINST TIME OF SOAKING

to keep with the sample throughout the test. The fractured samples also had to be handled with extreme care to keep them from splitting. Sample M6 fractured in random directions but furtunately one lump remained intact sufficiently to be used for weighing. Sample M11a also presented problems due to open fractures while M14, a weathered sample, became clayey on the outside. The results of this delicate test were, however, repeatable as is shown by the good agreement between the duplicate values. Plate 20 shows the cubes used.

In Table 10.4 the samples were arranged in order of increasing total absorption and the percentage of the total absorption (W_e) which had taken place at the time of some of the weighing intervals was calculated. Three arbitrary groups of low, medium and high absorption were chosen and average percentages for these groups were calculated. These clearly show that the percentages of W_e absorbed within the period shortly after immersion increased with the value of W_e. Samples M2, M3 and M13 (low W_e) absorbed an average of 31 per cent of W_e after 1,5 hours. In contrast, the medium absorbant samples absorbed an average of 58 per cent of W_e during the same period while M14, a highly absorbant mudrock, absorbed 90 per cent of W_e within 15 minutes. All the averages calculated confirm this trend.

10.3 Summary

(a) Absorption of water by mudrock cubes soaked at natural moisture content and after oven-drying were determined under atmospheric and vacuum conditions. No appreciable differences in absorption under these conditions were found, although the natural samples which were left under vacuum generally absorbed slightly more water than the samples soaked under atmospheric conditions. There were also no detectable visual differences in the breaking down behaviour of the samples soaked under the two different conditions. Absorptions after oven-drying ranged from 0,8 to 13,9 per cent but only one sample exceeded 5,1 per cent.

(b) The rate of absorption of water by mudrocks is important during construction when water is added for compaction and in the design of tests where soaking in water is involved. Tests performed on sawn cubes showed that the samples with higher total absorptions absorb higher percentages of this eventual total absorption during the early stages of immersion than the samples with lower total absorptions. Apart from specifying a very long period,

Plate 18: Apparatus used for determining vacuum saturated absorption

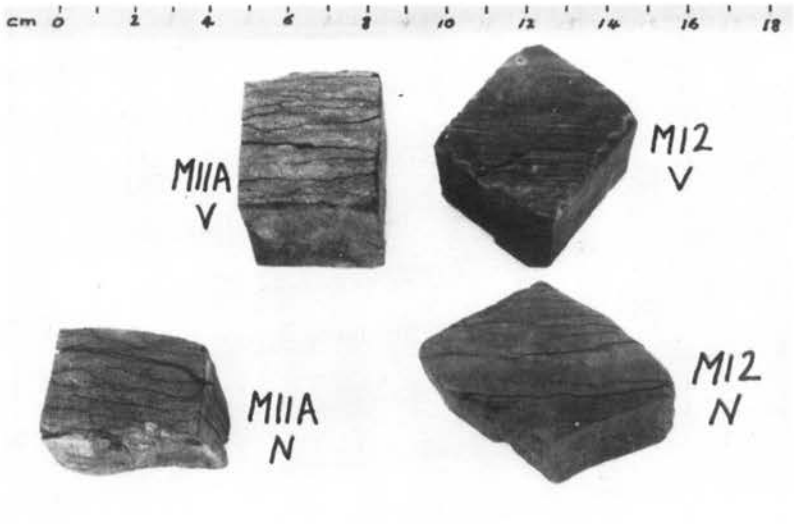


Plate 19: Comparison of cracking during normal and vacuum saturated absorption

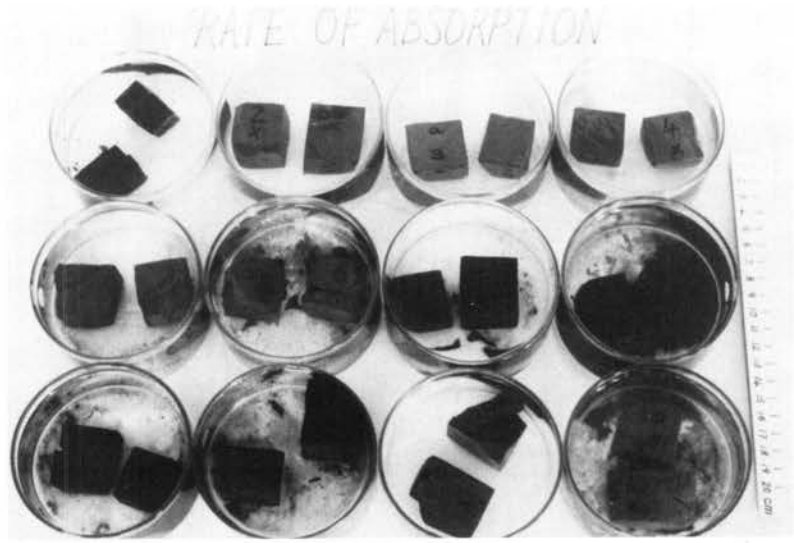


Plate 20: Samples used in rate of absorption test

TABLE 10.4: PERCENTAGE OF TOTAL ABSORPTION WHICH TOOK PLACE AFTER CERTAIN PERIODS

Sample number	Total moisture absorbed (W_e)* %	% of W_e after 0,25 h	% of W_e after 0,67 h	% of W_e after 1,5 h	% of W_e after 4,5 h	% of W_e after 21 h
M13	0,78	22	29	38	56	87
	0,78	23	31	45	63	94
M2	1,24	13	19	28	45	86
	1,25	14	18	26	38	74
M3	1,62	12	17	23	35	65
	1,82	13	17	23	38	71
Average		16	22	31	46	80
M1	1,82	15	33	50	75	92
	1,87	19	38	56	82	96
M8	1,98	16	29	50	82	91
	2,11	10	23		87	92
M12	2,75	13	28	43	69	93
	2,41	17	32	51	76	98
M4	2,79	24	37	51	76	95
	2,70	27	42	59	85	96
M5	3,36	38	54	70	89	95
	3,60	40	58	75	92	94
M11	4,50	24	46	66	93	96
	4,56	27	44	66	91	97
M11A	4,42	13	31		89	100
	4,60	18	48			100
M6	5,71	21	34		88	98
Average		21	38	58	84	96
M14	14,50	89	89		92	95
	14,57	90	90	91	93	97
Average		90	90	91	93	96

* W_e (total absorption) was chosen by studying the absorption with time curves and is therefore not necessarily equal to the last, possibly erratic, reading.

it is therefore impossible to give a definite period for which samples should be soaked before they are saturated. The cubes from most of these mudrocks are, however, more than 80 per cent saturated and beyond the high rate of absorption part of the curve after 4,5 hours. After 1,5 hours the average mudrock is approximately 50 per cent saturated.

CHAPTER 11

VOLUME CHANGE AND MOISTURE ADSORPTION WITH TEMPERATURE AND HUMIDITY CHANGES

11.1 Introduction

From field experience it is highly probable that humidity and temperature changes are two of the main agents responsible for mudrock disintegration and slaking. To test the effect of these two parameters, an experiment was designed in which temperature and humidity could be changed and volume and moisture changes monitored. Although various people have investigated the influence of humidity changes on various properties of mudrocks, studies along the lines envisaged have not been described previously.

Grice (1968) measured moisture adsorption of shale during an investigation of rock quality assessment. Samples were cycled between 100 per cent relative humidity (R.H.) in one bell-jar and 0 per cent R.H. in a bell-jar containing calcium chloride. He found that 75 per cent of the total adsorption took place within the first 24 hours of the cycles. In another experiment samples were cycled in the ranges of 20 to 30 °C and 60 to 90 per cent R.H. Most shales remained crack-free during nine months of these cycles.

Chenevert (1970) ground some mudrocks to between 2,38 and 2,0 mm and subjected the material to different humidities after drying in an oven. He found that the adsorption potential depended on the R.H. levels and that for most of the samples the increments in moisture adsorbed were larger in the higher ranges (90 to 98 per cent R.H.) than at lower humidities. Aughenbaugh et al (1975) investigated the penetration of moisture into mudrock. Small cores or cubes were subjected to different humidities. The samples lost or gained moisture according to the humidities and adsorbed moisture at a faster rate at higher humidities. Larger samples gained less moisture, percentage-wise, than smaller ones under the same conditions.

Van Eeckhout and Peng (1975) took some samples from coal mine shales and subjected them for long periods to stable zero and 100 per cent R.H. From the strength tests done it was clear that the moisture in the samples influenced the strength properties. From a further study Van Eeckhout (1976) concluded that mudrocks kept at a constant 60 per cent R.H. would

preserve a relatively high strength and keep contraction and expansion to a minimum. Fluctuations in humidity affected these properties and lowered the strength of the shales.

Olivier (1979b) recorded humidity variations between 65 and 100 per cent in the Orange-Fish Tunnel. The influence of these changes was studied experimentally by subjecting cores, instrumented to read expansion and contraction, to simulated conditions. He found, inter alia, that small humidity fluctuations could lead to volume changes and that irreversible changes (micro-cracks) in the fabric of non-durable samples occur during prolonged periods of air-drying at relative humidities below 60 per cent.

11.2 Experimental work

Apparatus

A Kotterman Type 2108 climate test box in which temperatures could be varied between minus 20 and plus 100 °C and humidities from 10 to 100 per cent R.H. was used (Plate 21). Because of some malfunctioning certain ranges of humidities could not be reached and the use of saturated salt solutions was investigated.

Saturated salt solutions

Experiments to obtain certain ranges of humidities envisaged for the test programme were conducted. Helpful information was obtained from publications by O'Brien (1948) and Wexler and Hasegawa (1954). The table given by O'Brien (1948) gave the impression that exact values would be obtained with saturated solutions at prescribed temperatures. This was not the case and the scatter of results from various tests was pointed out by Wexler and Hasegawa (1954). In some cases the required humidities could not be obtained, either because there were no salts listed to produce the required humidity or more often, even though a suitable salt was listed, it did not yield the listed humidity at the required temperature.

Humidity was measured using three hair-type hygrometers: a Lambrecht, a Thies and a Thies combined thermo- and hygrograph. The Kotterman cabinet was able to control the temperature to within 0,5 °C. Temperatures were recorded on the Thies thermograph and readings were taken on a thermometer installed at the inside of the cabinet window.

Experiments were also conducted to determine what surface areas and volumes of salt solutions were needed to maintain the humidities in the cabinet. Much moisture was lost during long cycles of high temperature. Seven half-filled crystallizing dishes, 125 mm (diameter) x 60 mm (depth) were found to be sufficient (Plate 22).

11.3 Preparation of samples

Small prisms measuring 30 x 30 x 50 mm, with the long axis perpendicular to the bedding, were sawn without the use of cooling water from sample blocks which had been stored in plastic bags since sampling. This small size was chosen as it would allow the samples to reach equilibrium sooner and still allow a reasonably long axis, the length of which could be monitored. Strain gauges were glued along the lengths of opposing sides of the long axes of the experimental prisms using strain gauge cement (Hottinger Baldwin Messtechnic GMBH X60 cement). To ensure that the two strain gauges adhered properly, soft rubber strips glued to perspex strips were pressed lightly against them in a clamp until the cement had set. Two strain gauges were glued loosely to the two remaining sides using Bostik and the wires were connected to measure strain (Consolidated Electrodynamics Corporation, Undated). The prisms were subjected to some temperature and humidity changes in the cabinet without the strain gauges being affected. This method was therefore applied to all the samples.

11.4 Benches for mounting

Tests proved that dial gauges could still perform at 50 °C and it was decided to check the volume changes measured by the strain gauges with these. Three benches, which could each hold five samples, were designed and manufactured from brass. (See Plate 23.) In addition grooved end caps for use on the top and the base of the prisms were made.

11.5 Preparation and mounting of samples

Three prisms were sawn from each of the mudrock samples (M3 excluded) and from a granite sample, which was to serve as an inactive check sample.

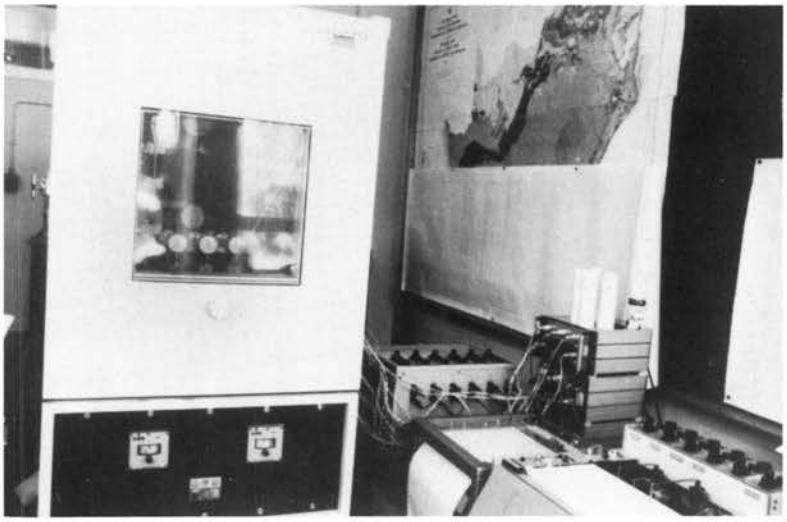


Plate 21: Temperature-humidity cabinet and recorders

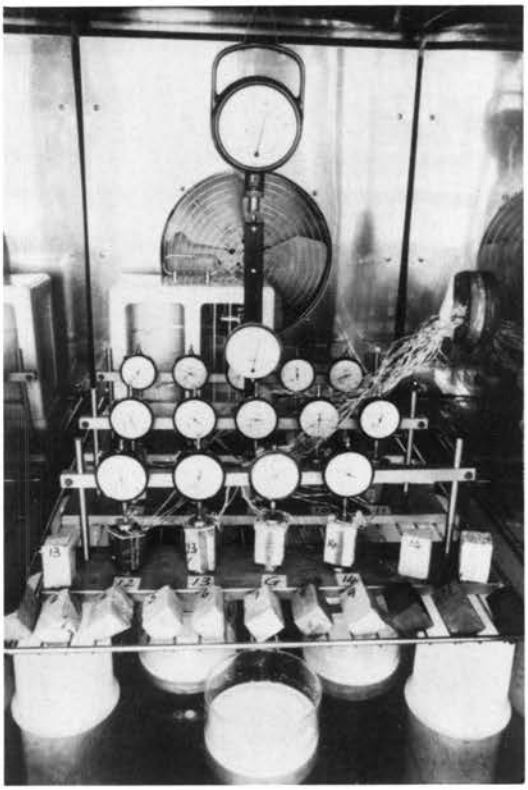


Plate 22: View of inside of cabinet showing saturated salt solutions, monitored sample prisms and humidity gauges

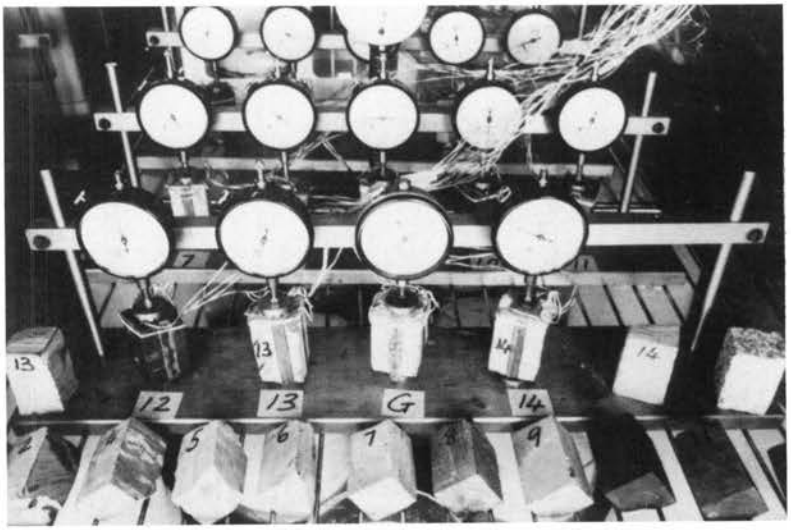


Plate 23: View of sample prisms monitored for volume changes and prisms used to measure changes in moisture content

The three prisms from each sample were to be used as follows:

(a) For volume change measurements along the axis perpendicular to the bedding (volume change prisms). These were fitted with strain gauges and mounted on the benches with dial gauges.

(b) For moisture change measurements (moisture change prisms). These were put into the cabinet with the above prisms and taken out at certain intervals for the determination of the change in mass on account of a change in moisture content.

(c) Samples to determine the moisture content of the prisms at the start of the experiment (moisture content prisms).

The volume change prisms were fitted with strain gauges. Leads were connected to them and an end cap attached using some Bostik to ensure that no short circuits would take place during the mounting. Throughout all the preparations the three prisms from any one sample were treated similarly to ensure that they would be in exactly the same condition at the start of the experiment. When no work was in progress the three prisms were stored in closed plastic bags.

After the volume change prisms had been mounted on the benches, the moisture change prisms were weighed and all of these were put into the cabinet (Plate 23). At the same time the moisture content prisms were put into an oven to dry at 105 °C. The leads from the strain gauges were taken through a hole in the wall of the cabinet and connected via power supplies to two Watanabe six-pen recorders and a two-pen Riken Denshi recorder.

Throughout the experiment the volume changes were monitored on the analogue recorders while output voltages were also measured regularly with a digital multimeter. The dial gauges, hygrometers and thermometer were read simultaneously. A continuous record of temperature and humidity was also obtained from the clockwork thermo- and hygrograph.

The loose moisture change prisms were weighed at the start of the experiment and thereafter just before each change in temperature and/or humidity. Opening the box during cycles was avoided as this would have affected the simulated climatic conditions unnecessarily.

11.6 Test programme

The test programme drawn up plus the reasons for each step are given in Table 11.1. It consists basically of a time during which all the prisms are brought into equilibrium under the same temperature and humidity conditions. This is followed by small temperature changes (20 °C) and then small humidity changes (about 25 %R.H.). This was done as it was uncertain how the prisms would behave i.e. it was possible that they would disintegrate. This was then followed by higher temperature changes (40 °C) and in turn higher humidity changes (about 63 %R.H.).

Towards the conclusion of the experiment some cycles simulating severe day and night conditions were used where temperature and humidity were changed simultaneously. At certain intervals throughout the experiment and at the end there were returns to the original conditions to establish whether irreversible changes had taken place in the prisms.

11.7 Discussion of measuring techniques

The test programme was carried out very successfully apart from the fact that the readings and recorded results from the strain gauges gave rise to uncertainty about their accuracy. A total of more than 2 000 readings were taken at regular intervals with the multimeter, and rolls of recording paper were used to record the expansion and contraction curves. All the readings were converted to percentage strain change and plotted, but it became clear that the values could not be trusted. During the experiment the recorder would indicate a positive change when e.g. the humidity was increased, but it then drifted back past the original level in a negative direction. The dial gauges did not indicate this but acted as expected i.e. they rose to a certain level and attained a condition of equilibrium. Another obvious discrepancy was that the granite dummy regularly showed higher changes under the same conditions than the mudrock samples which were the more active rock types. This inaccuracy was again verified by the dial gauges on the granite prism which indicated negligible movement. In the end it was decided to ignore all the strain gauge results and use only the dial gauge readings.

The dial gauge readings had to be corrected for temperature changes. This was necessary because both the brass frame of the bench on which the

TABLE 11.1: TEMPERATURE - HUMIDITY PROGRAMME

Step number	Duration of cycle hours	Cumulative time in days	Temp. or R.H. change or both	Temp. °C	% R.H. Lambrecht reading	Saturated salt solution used	Purpose of step
1	72	3	-	20	88	KCl	To bring all the prisms to equilibrium under similar temperature and R.H. conditions
2	24	4	Temp.	40	84	KNO_3	To determine the effect of small temperature changes with constant humidity
3	24	5		20	88	KCl	
4	24	6		40	84	KNO_3	
5	24	7		20	88	KCl	
6	48	9	Hum.	20	63	$Ca(NO_3)_2$	To determine the effect of small humidity changes with constant temperature - longer cycle as longer time needed for equilibrium
7	48	11		20	88	KCl	
8	48	13		20	63	$Ca(NO_3)_2$	
9	48	15		20	88	KCl	
10	24	16	Temp.	10	86	Cabinet setting	To determine the effect of larger temperature changes with constant humidity
11	24	17		50	80	KNO_3	
12	24	18		10	86	Cabinet setting	
13	24	19		50	80	KNO_3	
14	48	21		20	88	KCl	Back to original temperature and R.H. conditions
15	48	23	Hum.	20	25	$ZnCl_2$	To determine the effect of larger humidity changes with constant temperature
16	48	25		20	88	KCl	
17	48	27		20	25	$ZnCl_2$	
18	48	29		20	88	KCl	
19	24	30		40	84	KNO_3	Repeating small temperature and humidity changes to determine whether samples behave as at the beginning
20	24	31		20	88	KCl	
21	48	33		20	63	$Ca(NO_3)_2$	
22	48	35		20	88	KCl	
23	48	37	Both	5	92	$(NH_4)_2SO_4$	To determine behaviour of prisms during severe day and night climatic cycles. (Night - cold, with high humidity, and day - hot with low humidity)
24	48	39		50	21	$ZnCl_2$	
25	48	41		5	92	$(NH_4)_2SO_4$	
26	48	43		50	21	$ZnCl_2$	
27	48	45		5	92	$(NH_4)_2SO_4$	
28	48	47		50	21	$ZnCl_2$	
29	120	52		20	88	KCl	Back to original temperature and R.H. conditions

prisms were mounted and the brass end-caps expanded and contracted with temperature changes. Fifty mm INVAR steel rods were therefore inserted between the end-caps after the experiment when the prisms had been removed. A factor of expansion per degree temperature change was calculated after subjecting the benches to various temperature changes, e.g. from 5 to 50 °C and from 20 to 40 °C. The results were constant and the factor could, therefore, be used with confidence. All the readings taken at 20 °C were left unchanged but proportionate values were added to or subtracted from readings taken at higher or lower temperatures.

The moisture change prisms were taken out at the end of each cycle and weighed. Two of the prisms lost small chips during handling but these were collected and compensated for in the calculations of moisture changes. All the prisms were weighed within two or three minutes of being removed from the cabinet and replaced immediately after weighing.

The three hygrometers gave satisfactory, if not absolute results. They were set to correspond at about 50 %R.H. The hygrograph and Thies hygrometer, however, gave higher values than the Lambrecht hygrometer at high humidities. At lower humidities the Thies hygrograph gave slightly higher values than the Lambrecht hygrometer while the hygrograph registered lower values. The Lambrecht humidity readings were used on the figures and in the discussions.

The Kotterman cabinet and salt solutions gave very constant temperature and humidity conditions during the cycles. When a change was effected, the temperature stabilized at the new level within 20 minutes or less. Humidities also came within 10 per cent of the reguired value within 30 minutes.

The experiment continued for 52 days and readings were taken every day, including weekends.

11.8 Results and discussion

The results of the volume and moisture changes as well as the temperature and humidity readings are given in the Appendix. Volume change is given as percentage swell (+) or shrinkage (-) of the original length and was calculated as follows:

$$\frac{\text{Movement of dial gauge (mm)}}{\text{Length of prism (usually about 50 mm)}} \times 100$$

Moisture results were calculated as a percentage increase (+) or decrease (-) based on the mass of the samples at the time they were placed in the humidity cabinet at the start of the experiment e.g.

> Prism M1 weighed 121,17 g at the start and after three days at 20 °C and 88 %R.H. it weighed 121,49 g. The value listed in the table is $\frac{121,49 - 121,17}{121,17} \times 100 = +0,26\ \%$

The initial masses of the moisture change prisms, the lengths of the volume change prisms and the moisture contents of the mudrock samples at the start of the experiment are given in Table 11.2.

TABLE 11.2: MASSES, LENGTHS AND MOISTURE CONTENTS OF THE PRISMS USED IN THE TEMPERATURE-HUMIDITY EXPERIMENT

Sample number	Moisture change prism mass (g)	Volume change prism length (mm)	Initial moisture content (%)
M1	121,17	50,4	1,04
M2	119,39	50,6	0,92
M4	115,50	51,4	0,86
M5	106,02	49,5	0,66
M6	98,98	50,0	3,43
M7	97,60	54,1	3,23
M8	114,94	48,3	0,67
M9	112,48	52,0	3,36
M10	131,87	50,2	1,79
M11	125,33	49,5	1,46
M12	92,30	46,9	1,61
M13	108,20	50,0	0,47
M14	95,70	49,8	9,65
G	115,24	47,0	

The percentage change in volume and moisture during the experiment is illustrated in Figures 11.1 to 11.8. The temperatures and relative humidities are plotted at the top of each figure to facilitate interpretation. The behaviour of the prisms during the experiment is summarized in Tables 11.3 to 11.8 and is also shown graphically in Figures 11.9 to 11.12.

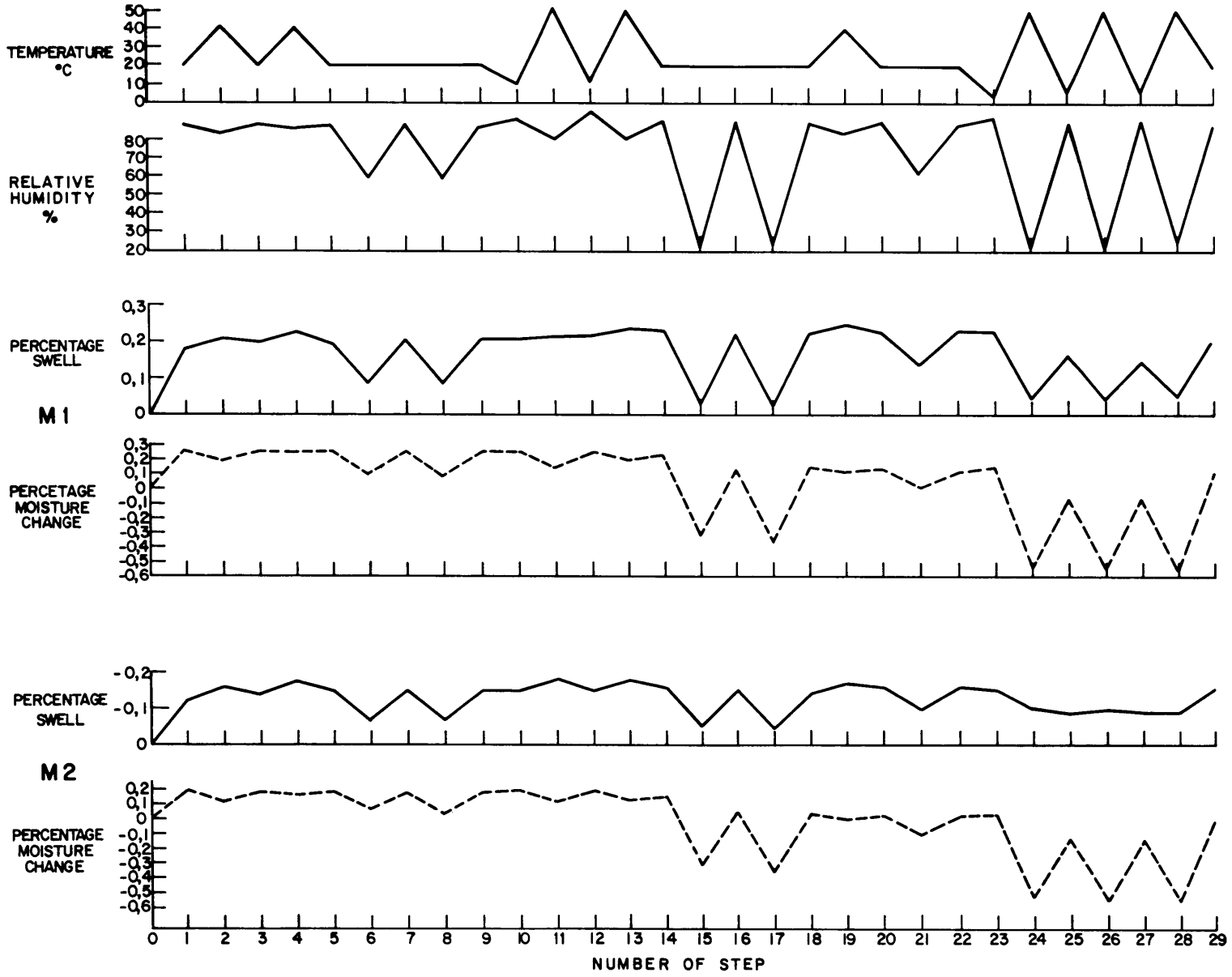


FIGURE II.I

SWELL AND MOISTURE CHANGES WITH CHANGES IN TEMPERATURE AND HUMIDITY

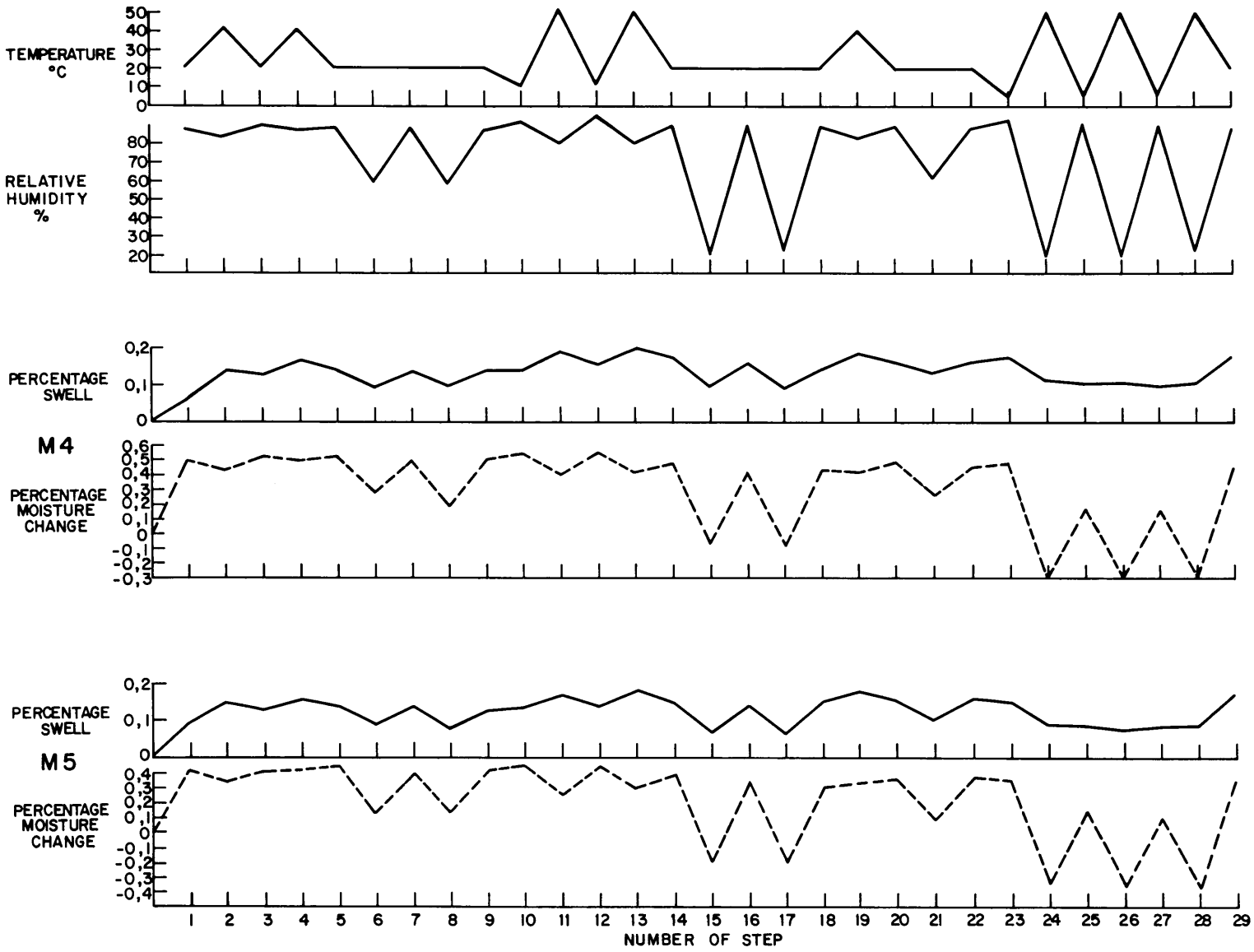


FIGURE II.2
SWELL AND MOISTURE CHANGES WITH CHANGES IN TEMPERATURE AND HUMIDITY

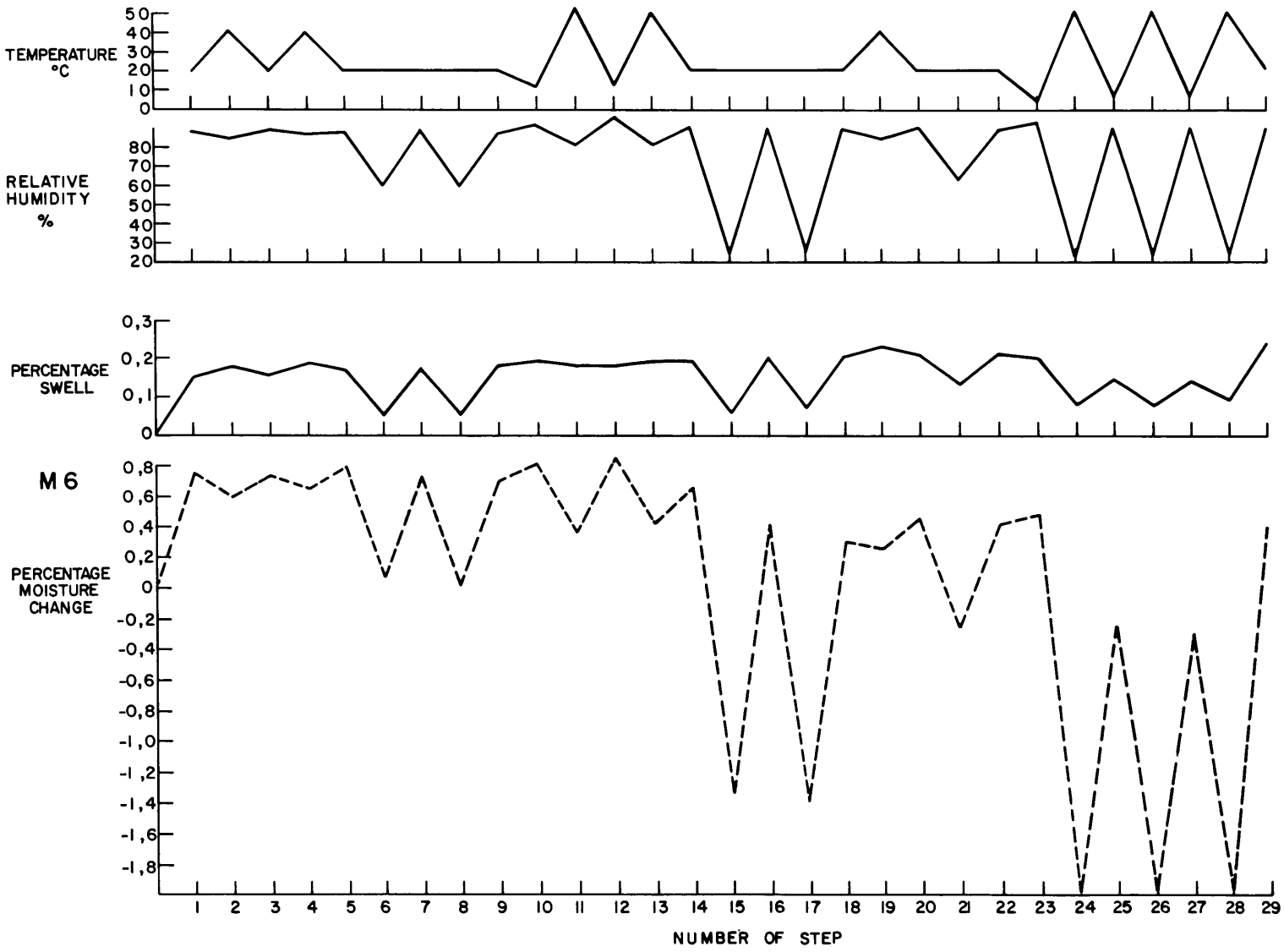


FIGURE 11.3
SWELL AND MOISTURE CHANGES WITH CHANGES IN TEMPERATURE AND HUMIDITY

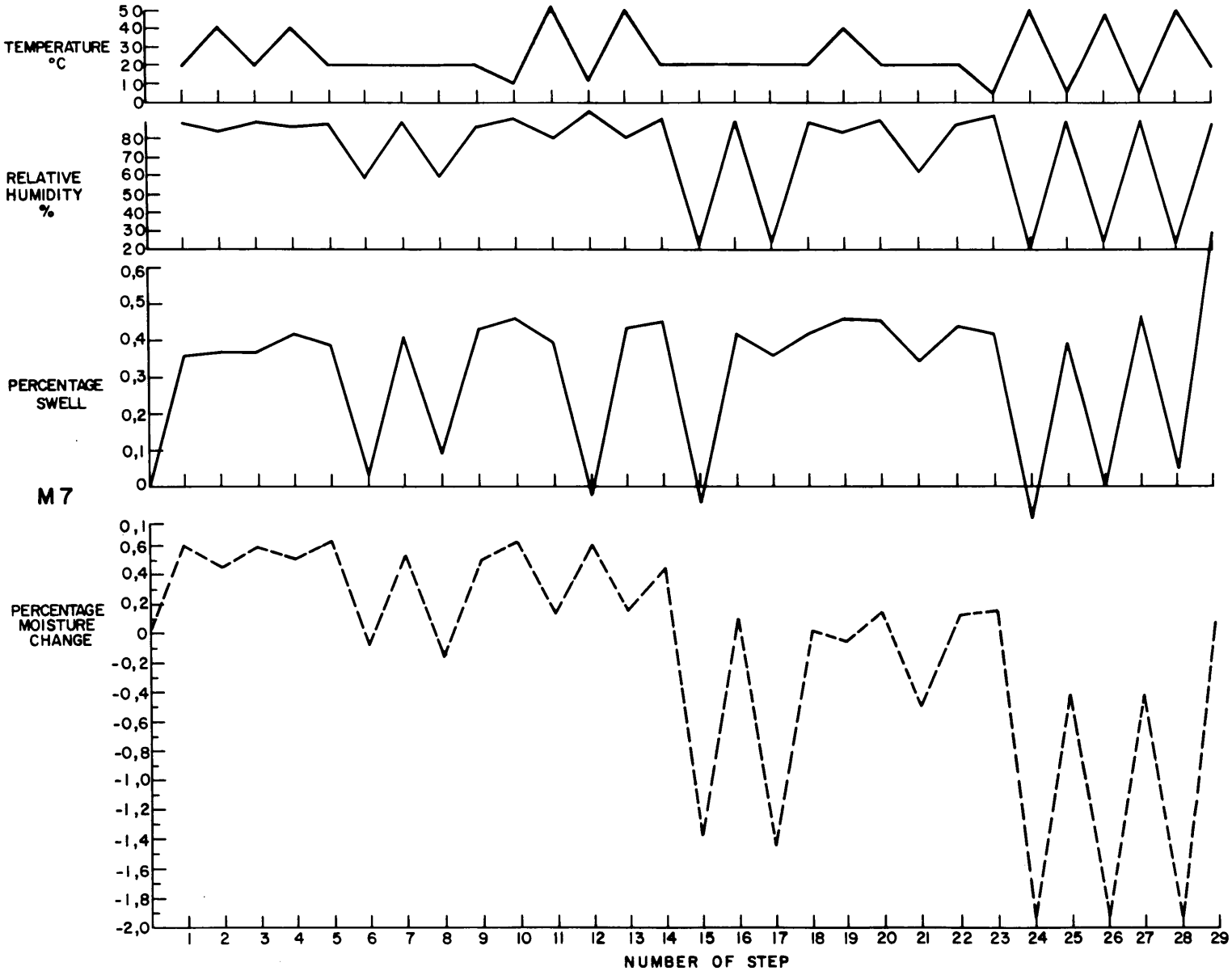


FIGURE 11.4

SWELL AND MOISTURE CHANGES WITH CHANGES IN TEMPERATURE AND HUMIDITY

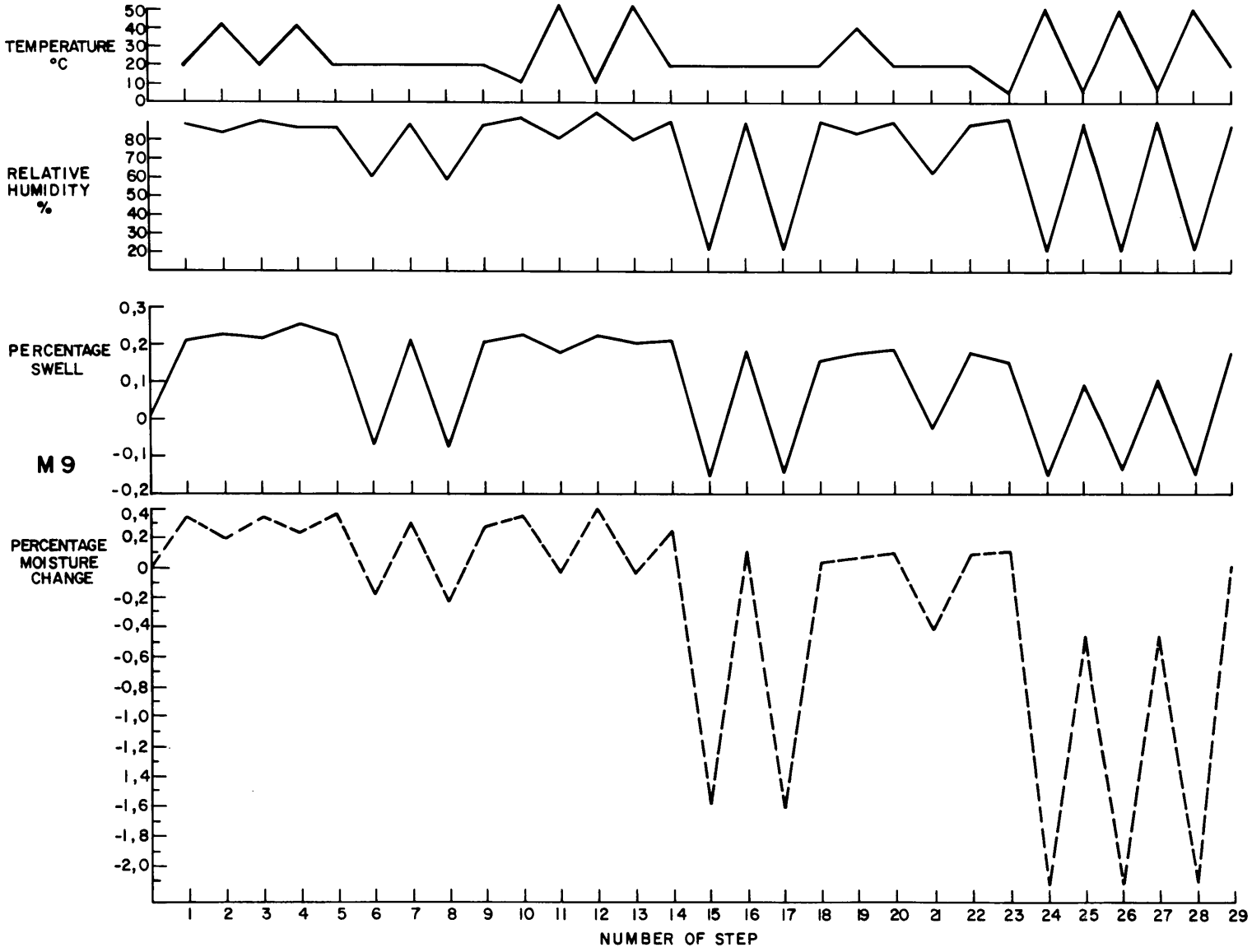


FIGURE 11.5

SWELL AND MOISTURE CHANGES WITH CHANGES IN TEMPERATURE AND HUMIDITY

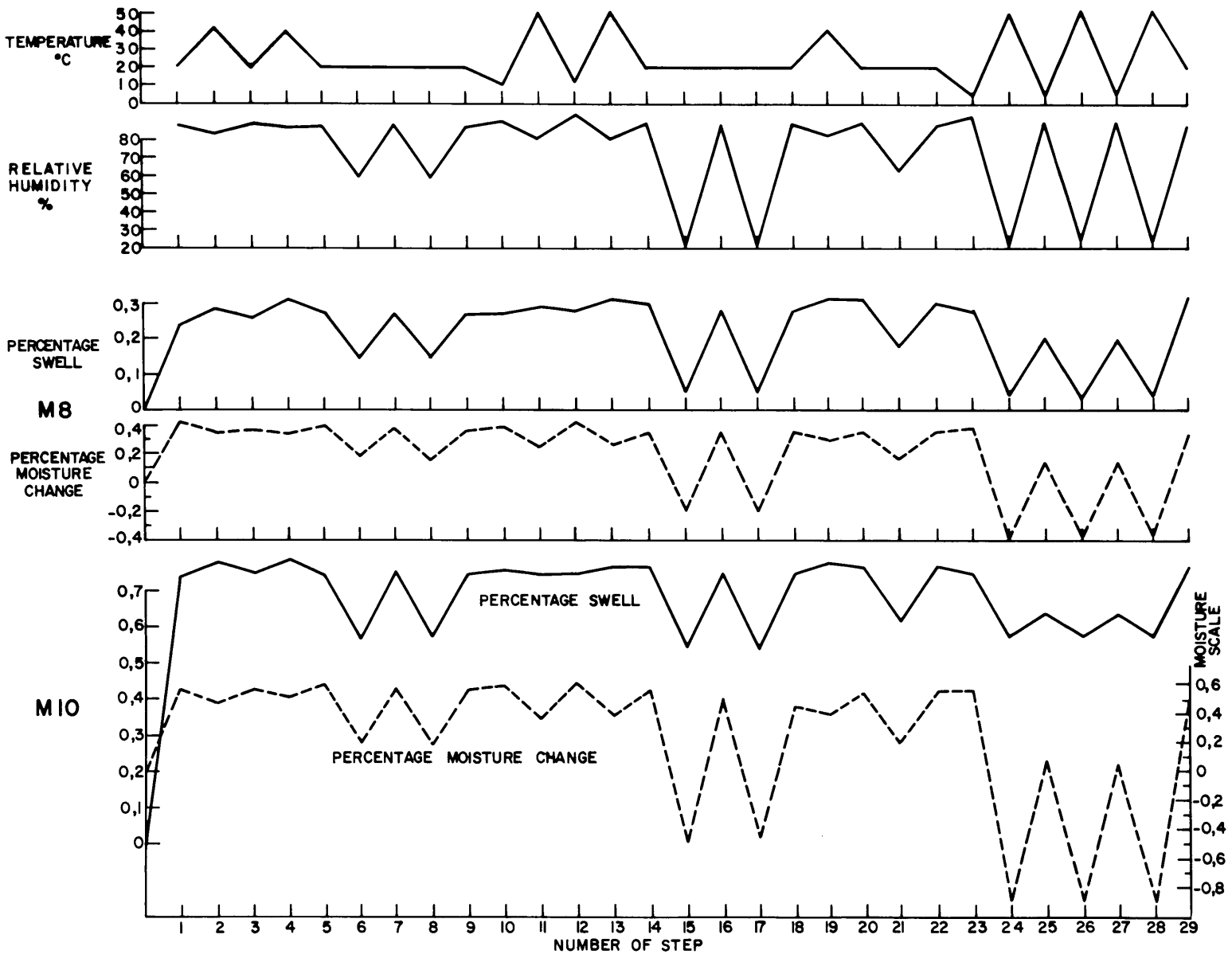


FIGURE 11.6

SWELL AND MOISTURE CHANGES WITH CHANGES IN TEMPERATURE AND HUMIDITY

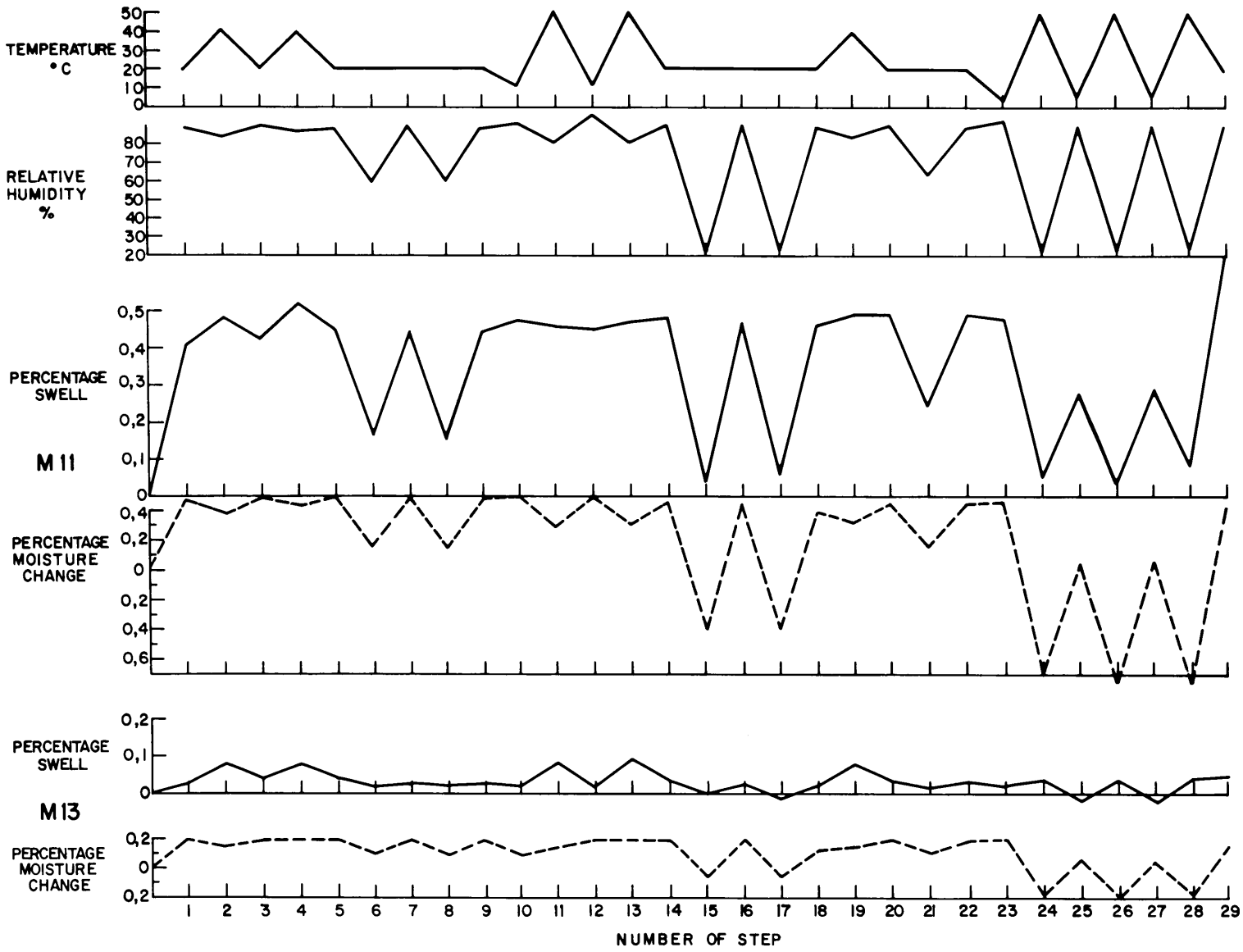


FIGURE 11.7

SWELL AND MOISTURE CHANGES WITH CHANGES IN TEMPERATURE AND HUMIDITY

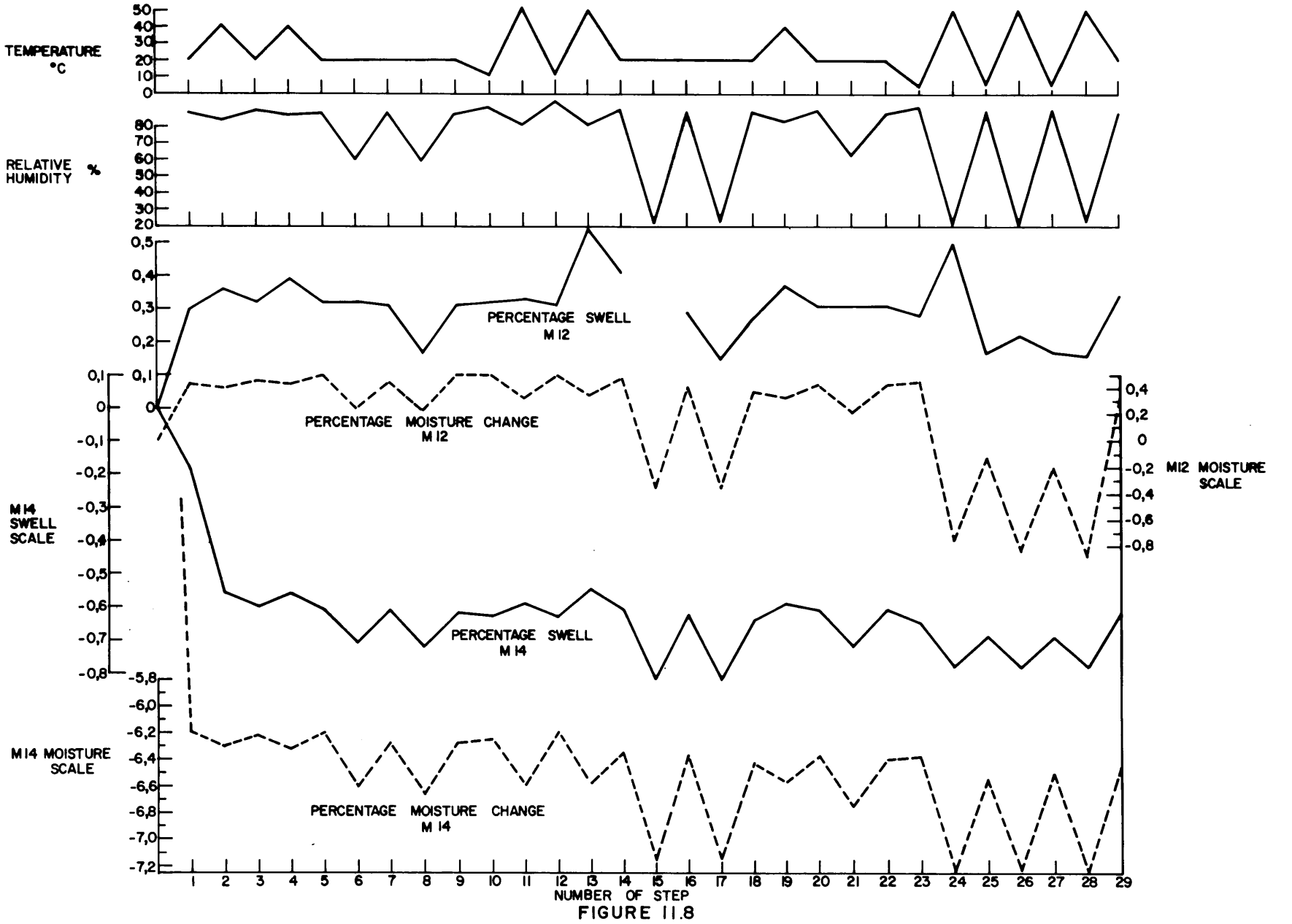


FIGURE 11.8

SWELL AND MOISTURE CHANGES WITH CHANGES IN TEMPERATURE AND HUMIDITY

TABLE 11.3: SUMMARY OF BEHAVIOUR OF MUDROCK PRISMS DURING TEMPERATURE-HUMIDITY CHANGES

Step nos.	Purpose of steps	Actual temperature and humidity conditions	Discussion of swell and moisture changes		
			Swell changes	Moisture changes	General
1	To equilibrate all prisms at 20 °C and 88 % R.H.	20 °C and 88 % R.H.	All prisms except M14 expanded with swells ranging from 0,03 % (M13) to 0,74 % (M10) - M14 shrank 0,18 %	All prisms except M14 adsorbed moisture with adsorptions ranging from 0,19 %(M2 and M13) to 0,75 % (M6) - M14 lost 6,19 % moisture	All samples, except M14, gained moisture and expanded
2-5	To determine effect of small temperature changes (from 20 to 40 °C)	Temperature changed from 20° to 40 °C (R.H. changed from 84 to 89 % during first cycle and 87 to 88 % during second cycle)	Slight expansion occurred during heating - during cooling the prisms returned to their original dimensions - general swell about 0,03 to 0,04 % with some prisms swelling more e.g. M11 (0,08 %)	Moisture losses took place during heating - possible that slight changes in humidity caused this	Temperature changes from 20 to 40 °C only affected prisms negligibly
6-9	To determine effect of small changes in humidity (from 88 to 60 % R.H.)	R.H. changed from 88 to 60 % during first cycle and 88 to 59 % during second (temperature 20 °C)	All prisms shrank when humidity was lowered and expanded when it increased - similar changes took place during the two cycles - M7 expanded most (0,34 %) and M13 least (0,02 %)	All prisms lost moisture with a decrease in humidity - percentages varied from 0,72 (M6) to 0,09 (M13)	Humidity changes of 28 or 29 % affected the prisms markedly - moisture losses and shrinkages occurred when humidity decreased - Table 11.4 lists average percentages volume- and moisture changes for the two cycles - Figure 11.9 shows that amount of shrinkage is not strongly related to amount of moisture change
10-13	To determine effect of large temperature changes (from 10 to 50 °C)	Temperature changed from 11 to 51 °C during first cycle and 12 to 50 °C during second cycle (R.H. decreased from 91 to 81 % and 95 to 81 % during above cycles)	Slight or very slight swelling was shown by eight of the prisms during the temperature increases, three prisms remained stable whereas the remainder behaved erratically	All the prisms lost moisture during the heating - the humidity decreases probably contributed to this	Very little expansion took place during a 40 °C change in temperature. Moisture losses occurred but this may have been caused or increased by the humidity decreases
15-18	To determine effect of large changes in humidity (from 90 to 22 % R.H.)	R.H. changed from 90 to 22 % during the first cycle and 89 to 23 % during the second (temperature 20 °C)	All prisms shrank during humidity decreases and expanded when it increased - M7 shrank most (0,49 %) and M13 least (0,04 %) - changes were similar during the two cycles	Moisture losses took place in all the prisms during the the decreases in humidity and returned to former levels when the conditions were reversed - M6 lost most moisture (1,91 %) while M13 lost only 0,26 %	Large humidity changes affected mudrocks markedly, both as far as moisture changes and volume changes were concerned. Table 11.5 lists the average changes for the two cycles and Figure 11.10 (like Figure 11.9) shows that there is no strong relationship between the two above-mentioned parameters

TABLE 11.3: (continued)

Step nos.	Purpose of steps	Actual temperature and humidity conditions	Discussion of swell and moisture changes		
			Swell changes	Moisture changes	General
19-20	To check original behaviour during small temperature changes (steps 2 to 5)	Temperature changed from 20 to 40 °C (humidity decreased slightly)	Changes similar to those experienced during same treatment at beginning i.e. around 0,03 % swell change	Moisture decreased in ten prisms during heating and increased slightly in three- changes similar to those during steps 2 to 5	Behaviour of samples during small temperature changes were similar to behaviour at the start of the experiment
20-21	To check original behaviour during small humidity changes (steps 6 to 9)	R.H. changed from 90 to 63 % (temperature 20 °C)	All prisms except M7 and M9 behaved almost exactly the same as before	Moisture losses almost exactly similar to those during steps 6 to 9	Behaviour of prisms did not change because of previous treatments
23-28	To simulate field conditions (changing from "night" to "day" conditions)	Three cycles from "night" (about 5 °C and 90 % R.H.) to "day" (about 50 °C and 21 % R.H.) conditions	Eight samples shrank while three did not show significant movement when "day" conditions were applied - swell changes similar to changes experienced during steps 6 to 9 i.e. small humidity changes on their own	Moisture losses when "day" conditions were applied were in the same range as the losses experienced during steps 15 to 18 i.e. large humidity changes on their own	Extreme temperature and humidity changes did not affect the prisms more than humidity changes on their own. Table 11.6 lists average swell- and moisture changes for the last two cycles
1, 14, 18, 22 and 29	To determine whether prisms will return to the same volume and moisture states at identical atmospheric conditions throughout the experiment	20 °C and 88 % R.H.	Percentage swells at these conditions were remarkably similar considering the large volume changes which took place during steps where the humidity was changed (Table 11.7, Figure 11.11). M14 shrank markedly between steps 1 and 14 due to the fact that it was still losing moisture	Moisture contents were fairly stable although there is a general trend to decrease slightly through the experiment (Table 11.8, Figure 11.12). M6, M7, M9 and M14 exhibited larger decreases but these were small compared to changes during humidity variations	The state of expansion and moisture content of the prisms remained relatively constant whenever there were returns to the original conditions during the experiment. The severe temperature and humidity changes therefore did not markedly affect the nature of the prisms as far as the above-mentioned properties are concerned

TABLE 11.4: AVERAGE PERCENTAGE SWELL AND MOISTURE CHANGES WITH A 28 AND 29 PER CENT DECREASE IN HUMIDITY

Sample number	Average percentage swell change	Average percentage moisture change
M1	-0,12	-0,16
M2	-0,08	-0,13
M4	-0,04	-0,26
M5	-0,06	-0,28
M6	-0,12	-0,72
M7	-0,34	-0,70
M8	-0,13	-0,21
M9	-0,29	-0,54
M10	-0,18	-0,39
M11	-0,29	-0,33
M12	-	-0,23
M13	-0,02	-0,09
M14	-0,11	-0,41

TABLE 11.5: AVERAGE PERCENTAGE SWELL AND MOISTURE CHANGES WITH A 68 AND 66 PER CENT DECREASE IN HUMIDITY

Sample number	Average percentage swell change	Average percentage moisture change
M1	-0,20	-0,52
M2	-0,11	-0,44
M4	-0,07	-0,52
M5	-0,08	-0,57
M6	-0,13	-1,91
M7	-0,49	-1,69
M8	-0,23	-0,54
M9	-0,35	-1,76
M10	-0,21	-1,01
M11	-0,42	-0,86
M12	-	-0,79
M13	-0,04	-0,26
M14	-0,20	-0,79

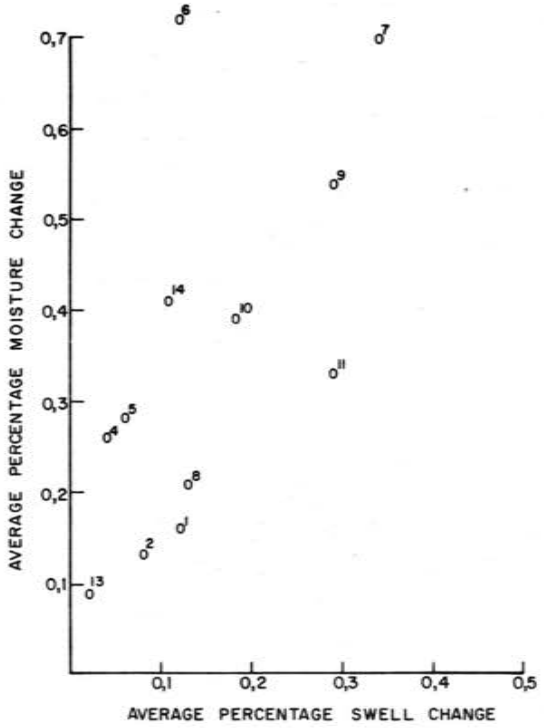


FIGURE II.9

RELATION BETWEEN PERCENTAGE SWELL AND PERCENTAGE MOISTURE CHANGE FOR A HUMIDITY CHANGE FROM 88 TO 60% RH.

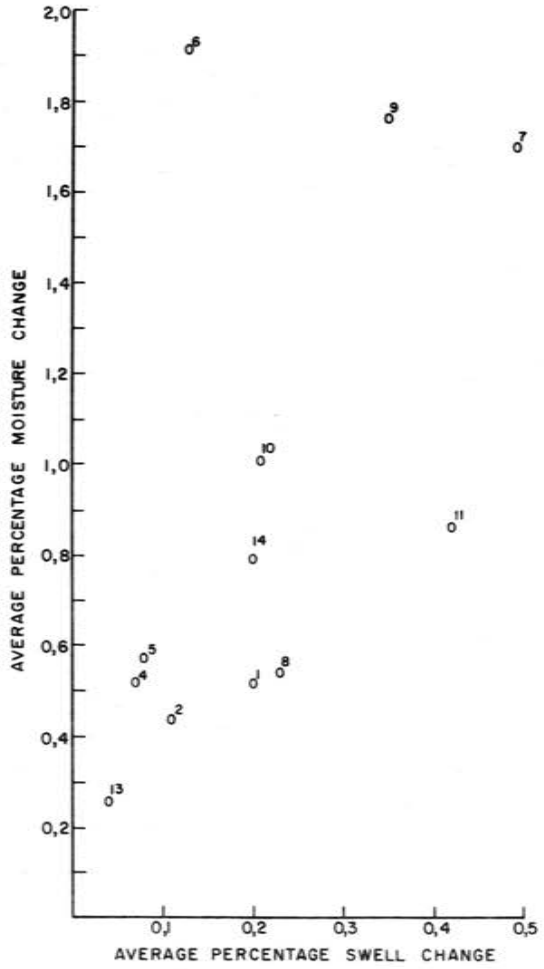


FIGURE II.10

RELATION BETWEEN PERCENTAGE SWELL AND PERCENTAGE MOISTURE CHANGE FOR A HUMIDITY CHANGE FROM 90 TO 22 % R.H.

TABLE 11.6: PERCENTAGE SWELL AND MOISTURE CHANGES FROM A CONDITION OF 5 °C AND 90 PER CENT R.H. TO A CONDITION OF 50 °C AND 21 PER CENT R.H.

Sample number	Average percentage swell from "night" to "day"	Average moisture change from "night" to "day"
M1	-0,09	-0,48
M2	0	-0,41
M4	0	-0,47
M5	0	-0,48
M6	-0,06	-1,73
M7	-0,40	-1,54
M8	-0,16	-0,51
M9	-0,24	-2,65
M10	-0,06	-0,96
M11	-0,22	-0,80
M12	-	-0,69
M13	+0,06	-0,23
M14	-0,09	-0,71

TABLE 11.7: PERCENTAGE SWELL AT IDENTICAL CONDITIONS (20 °C AND 88 %R.H.) DURING THE EXPERIMENT

Sample number	Percentage swell at step				
	1	14	18	22	29
M1	0,18	0,23	0,22	0,23	0,20
M2	0,12	0,16	0,14	0,16	0,16
M4	0,06	0,18	0,15	0,17	0,18
M5	0,09	0,15	0,15	0,16	0,17
M6	0,15	0,19	0,20	0,21	0,23
M7	0,36	0,45	0,42	0,44	0,69
M8	0,24	0,30	0,28	0,30	0,32
M9	0,21	0,22	0,16	0,18	0,17
M10	0,74	0,77	0,78	0,77	0,77
M11	0,41	0,48	0,46	0,49	0,65
M12	0,30	0,41	0,27	0,31	0,34
M13	0,03	0,04	0,02	0,04	0,05
M14	-0,18	-0,61	-0,64	-0,61	-0,62

TABLE 11.8: PERCENTAGE MOISTURE CHANGE AT IDENTICAL CONDITIONS (20 °C AND 88 %R.H.) DURING THE EXPERIMENT

Sample number	Percentage moisture change at step				
	1	14	18	22	29
M1	0,26	0,23	0,14	0,12	0,12
M2	0,19	0,16	0,03	0,02	0,01
M4	0,49	0,48	0,43	0,45	0,45
M5	0,42	0,39	0,31	0,37	0,35
M6	0,75	0,65	0,30	0,41	0,39
M7	0,59	0,44	0,02	0,12	0,08
M8	0,42	0,36	0,34	0,36	0,34
M9	0,34	0,24	0,04	0,10	0,02
M10	0,55	0,58	0,46	0,55	0,52
M11	0,47	0,46	0,39	0,45	0,43
M12	0,43	0,47	0,37	0,43	0,33
M13	0,19	0,20	0,12	0,19	0,17
M14	-6,19	-6,35	-6,43	-6,41	-6,45

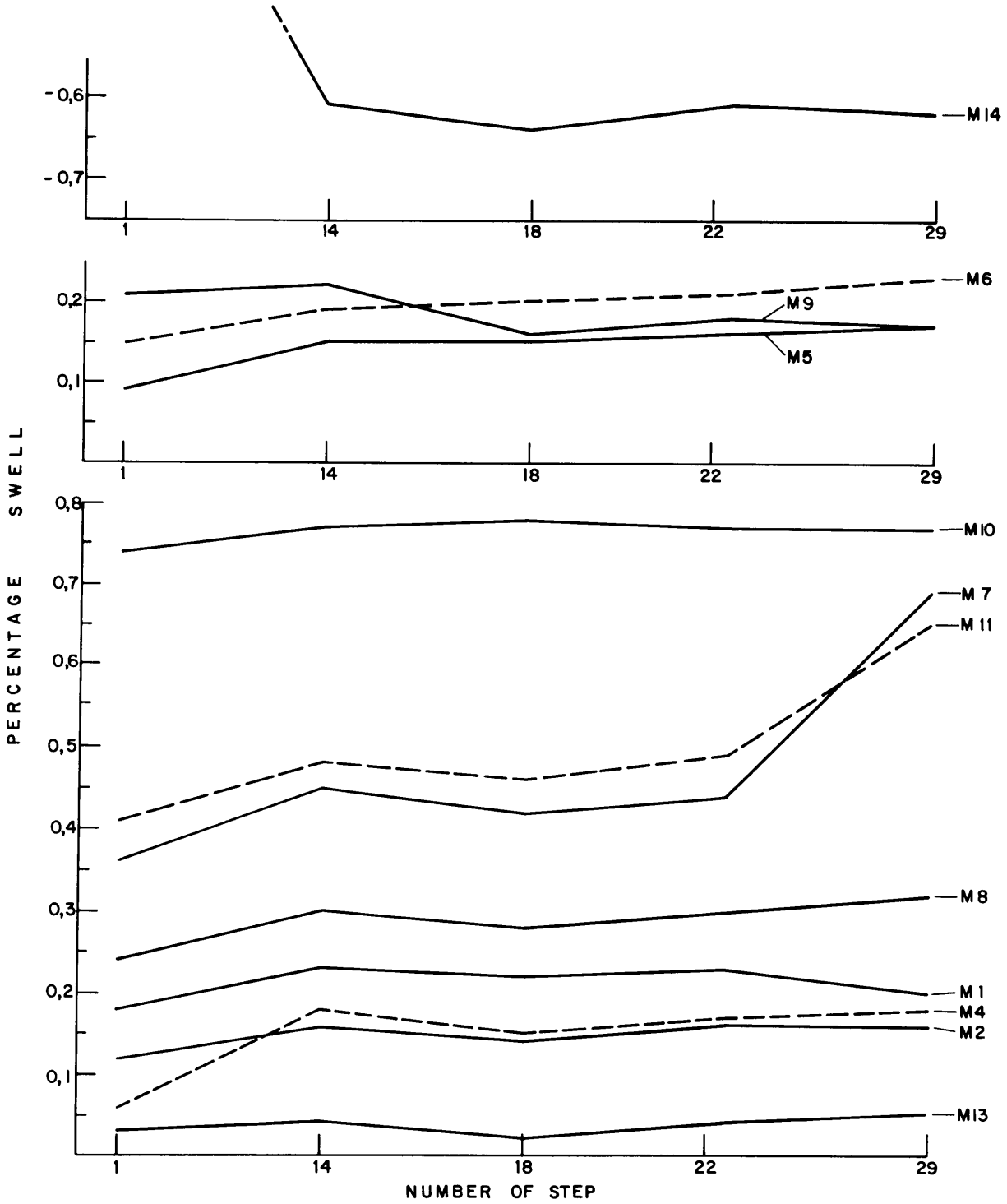


FIGURE II.11

PERCENTAGE SWELL AT IDENTICAL CONDITIONS (20°C AND 88 % R.H.) DURING EXPERIMENT.

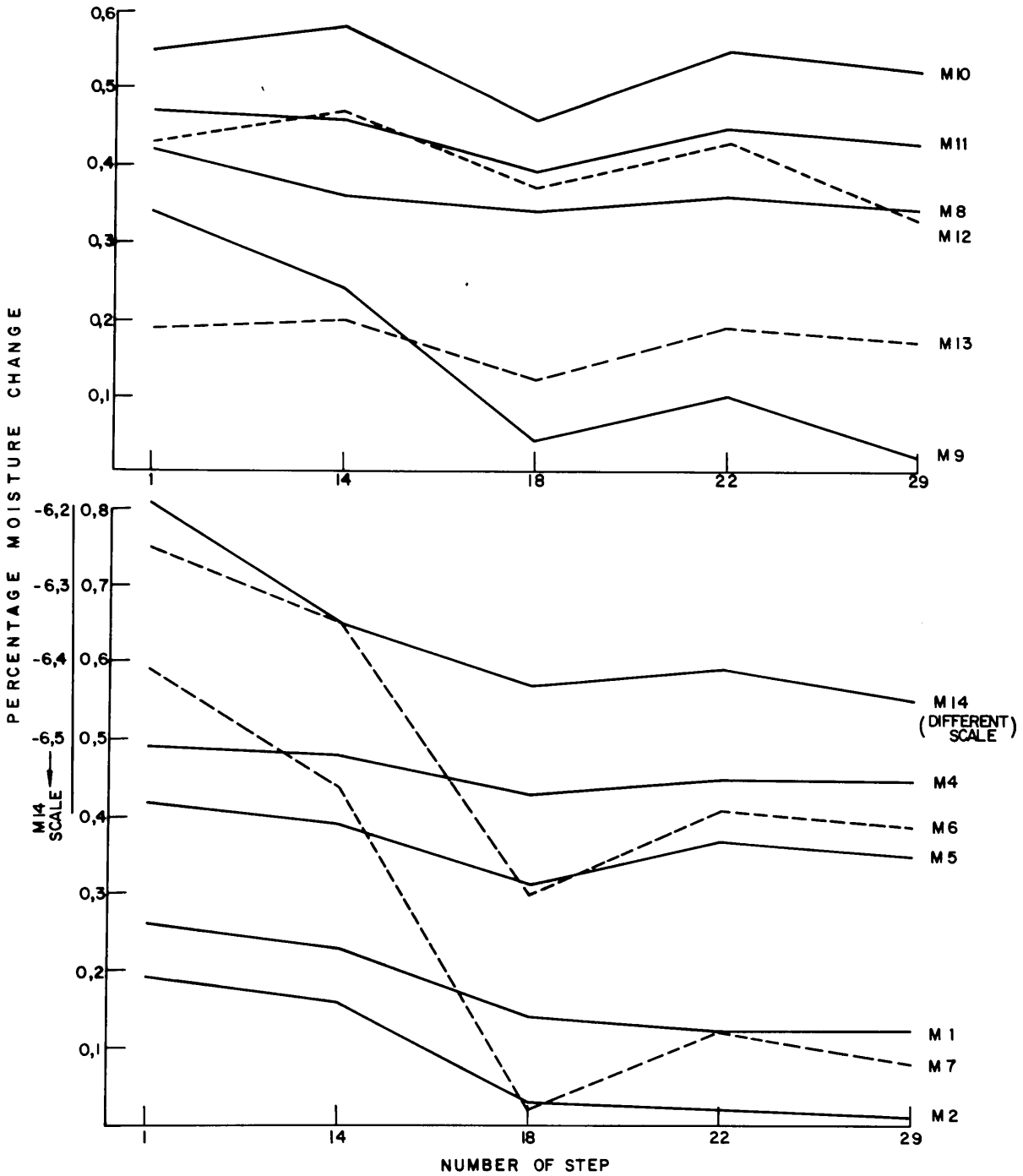


FIGURE 11.12

PERCENTAGE MOISTURE CHANGE AT IDENTICAL CONDITIONS (20°C AND 88 %R.H) DURING EXPERIMENT.

11.9 Summary

(a) Temperature changes on their own do not affect the mudrock samples much, both as far as volume and moisture are concerned. On the other hand mudrocks are very sensitive to humidity changes and even a small change causes fluctuations in volume and moisture content. A maximum shrinkage of 0,34 per cent (M7) and a maximum moisture loss of 0,72 per cent (M6) took place with a 28 per cent drop in relative humidity (from 88 to 60 per cent) while a maximum shrinkage of 0,49 per cent (M7) and moisture loss of 1,91 per cent (M6) took place with a 68 per cent drop in relative humidity (from 90 to 22 per cent).

(b) Severe "night" and "day" cycles where both temperature and humidity were changed (from 5 °C and 90 per cent R.H. to 50 °C and 21 per cent R.H. respectively), did not affect the samples to a greater extent than severe humidity changes of the same magnitude without temperature changes.

(c) All the samples, except M14, adsorbed moisture during the initial stage when the natural samples were put in an atmosphere of 20 °C and 88 per cent R.H. M14 is a weathered sample and it lost more than 6 per cent moisture during this equilibration stage.

(d) Temperature and humidity changes on their own did not succeed in disintegrating the present mudrock samples and the nature of the samples was not seriously affected. This is proved by the fact that the samples were able to return to their original volume and moisture conditions throughout the experiment when the conditions were returned to the original state. Free water, such as dew, seepage water or rain, is necessary to start the severe fracturing, disintegration or slaking. This is contrary to conclusions reached by Olivier (1979b) on the disintegration of the Beaufort mudrocks in the Orange-Fish Tunnel.

(e) Samples which disintegrate or slake are not characterized by any different behaviour during the cycles although these samples were generally among those which showed higher changes in volume and moisture.

CHAPTER 12

CLASSIFICATION TESTS

A wide range of classification tests which showed promise (see Chapter 5) and which test a variety of rock properties were conducted on the mudrock samples. In addition test methods were developed incorporating certain processes which may be useful for the classification of mudrocks. These include wet abrasion, ultrasonic cavitation and the use of wet-dry cycles and different "weathering" agents.

12.1 Rock strength tests

12.1.1 Uniaxial compressive and Brazilian tensile strengths

12.1.1.1 Introduction

The compressive and tensile strengths of rock are important engineering parameters. Both of these have been used in studies to classify rock. Drew and Woods (1970) tried a uniaxial compressive strength test for predicting the durability of granites. They found the results of the test to be erratic and the values unreliable criteria for durability. De Puy (1965) used both tests to predict the durability of various rock types and found them to be of some value as they can indicate weaknesses in rock. He found that tensile strengths rated better than compressive strengths. Saltzman (1975) used the compressive strength test and an indirect (Brazilian) tensile strength test in an investigation of tests to predict the performance of stone in protective blankets. Both tests were found to be "conditionally acceptable" for prediction purposes, but none was included in his classification system. Olivier (1979a) did extensive compressive strength testing in his work on the classification of mudrocks in the Orange-Fish Tunnel and proposed the test in combination with a free swell test in his "Geodurability" classification system. O'Flynn (1977) is of the opinion that if clay-bearing rocks have high enough tensile strength to withstand the expansive forces of

the clay minerals, these rocks will not disintegrate. Compressive strengths are also important and should be high enough for the materials to be adequate for road construction. He, therefore, felt that the measurement of these properties is the best direct means of rating rocks susceptible to weakening by water.

12.1.1.2 Method

All the known work on mudrock has been done on cores obtained by means of drilling with water. As the addition of water may influence the strength properties of mudrock to various degrees, it was decided to test the samples at natural moisture content, i.e. as sampled. The Geomechanics Division of NMERI, CSIR kindly agreed to carry out this specialized testing.

Large sample blocks were taken and cored perpendicular to the bedding using only compressed air for cooling. Test methods ISRM (1972a) and ISRM (1977) were followed for determining the compressive and Brazilian tensile strengths respectively. For ideal compressive strength testing an NX core (diameter 54,9 mm) with length 2,5 to 3,0 times the diameter (i.e. between 137 and 165 mm) is required while for the Brazilian test an NX disc with a length of half the diameter (i.e. 27 mm) is needed.

Numerous problems were experienced in the preparation of the cores mainly because the samples broke before the necessary lengths of core were reached. The long core samples, naturally, presented more problems than the shorter ones required for the Brazilian test. The heat generated by the drilling often caused breakage along weak planes such as the bedding and to a lesser extent along closed joints. This necessitated very slow drilling and in the case of some samples a day was spent without obtaining one suitable core specimen. Eventually it was decided to saw prismatic samples for the uniaxial compressive strength tests. This method proved to be more successful. Prisms measuring approximately 49 x 49 mm at the ends were sawn. This gave an area similar to that of an NX core. The objective was to obtain prisms of 130 mm length or longer. For the Brazilian test cylindrical discs were essential but because of their short lengths this could be done by coring. It was impossible to prepare three of the samples dry and in these cases water was used. Water would probably have influenced these hard samples to a lesser extent than the softer samples.

The tests were performed by applying an increasing load at a steady rate to cause failure within 5 to 15 minutes. In the uniaxial compressive strength test the prisms or cylinders were simply compressed between two platens until failure took place. In the Brazilian test the specimen was diametrically compressed until it failed in tension, i.e. when it split in two. The apparatus used is shown in Plates 24 and 25 while Plates 26 and 27 show some of the samples used in compressive strength and Brazilian tensile strength tests after failure.

The results, as tabulated by the Geomechanics Division, are given in Tables 12.1 and 12.2.

12.1.1.3 Discussion

More problems than expected were encountered during the preparation of the samples but the results are valuable as they indicate the range of strengths for a variety of southern African mudrocks at natural moisture content.

Some duplicate (and even up to quadruplicate) tests indicated significant variations. This was usually due to a hidden plane of weakness, such as a closed joint, in the specimen. For purposes of comparison with other test results the highest values obtained for any particular sample were used. This is acceptable as the specimens for any one sample were cored or sawn from the same layer, i.e. next to one another. The highest value would be more representative of the intact strength than the average value. It should be pointed out, however, that even though the samples were cored or sawn next to each other, they were not necessarily exact duplicates as far as engineering-geological properties are concerned.

Apart from the weathered Timeball Hill mudstone (M14), which gave very low strength values, the compressive strengths varied from 28 to 169 MPa and the tensile strengths from 3,5 to 22,6 MPa. Values reported by Olivier (1976a) for Beaufort mudrocks varied between 40 and 168 MPa for compressive strengths and 3,0 to 11,8 MPa for tensile strengths.

12.1.2 NCB cone indenter

The NCB cone indenter was developed by the National Coal Board in the United Kingdom to give a measure of rock strength without the extensive

Plate 24: Apparatus for uniaxial compressive and Brazilian tensile strength tests

Plate 25: Disk being split during Brazilian tensile strength test

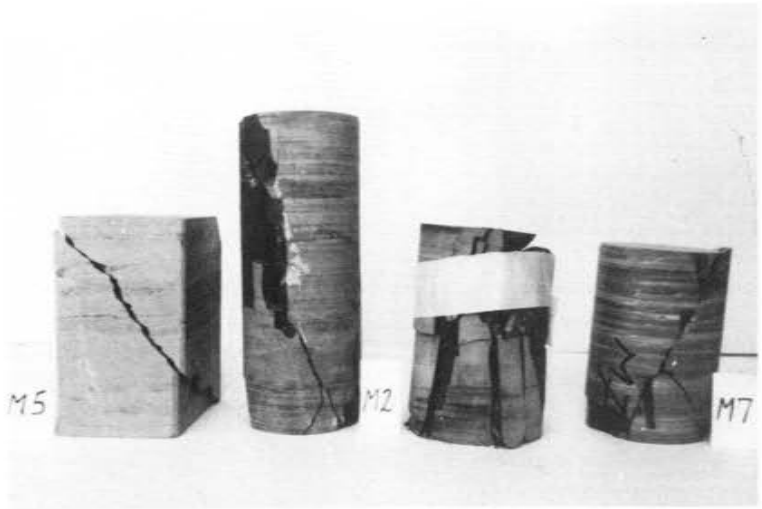


Plate 26: Examples of prismatic and cylindrical specimens after the uniaxial compressive strength test

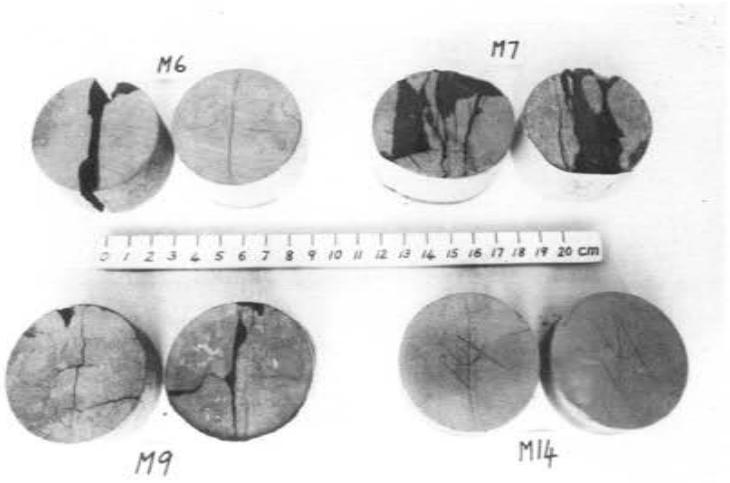


Plate 27: Examples of specimens after the Brazilian tensile strength test

TABLE 12.1: RESULTS OF UNIAXIAL COMPRESSIVE STRENGTH TESTS

Specimen							Failure load kN	Uniaxial compressive strength MPa	Remarks**
Number	Shape*	Height mm	Diameter mm	Length mm	Width mm	Area (corrected) mm^2			
M1 - C1	PR	128	-	56,7	53,9	3 045	341	112	
M1 - C2	PR	133	-	58,3	53,5	3 119	286	92	
M2 - C1	CY	145	54,8	-	-	2 359	123	52	
M2 - C2	CY	95	54,6	-	-	2 341	273	117	
M2 - C3	PR	118	-	59,0	49,6	2 904	235	81	
M3 - C1	CY	115	54,8	-	-	2 359	286	121	1
M3 - C2	CY	118	54,8	-	-	2 359	313	133	1
M4 - C1	CY	86	55,0	-	-	2 376	68,9	29	
M4 - C2	CY	87	55,0	-	-	2 376	59,0	25	3
M5 - C1	PR	123	-	55,2	53,0	2 893	51,5	18	
M5 - C2	PR	99	-	73,3	55,0	4 004	114	28	
M6 - C1	CY	93	54,9	-	-	2 367	86	36	
M7 - C1	CY	113	55,0	-	-	2 376	97	41	
M7 - C2	CY	88	55,0	-	-	2 376	116	49	
M8 - C1	PR	113	-	53,0	52,2	2 765	467	169	
M8 - C2	PR	119	-	56,2	51,8	2 911	215	74	
M9 - C1	PR	115	-	58,5	55,3	3 203	105	33	
M9 - C2	PR	123	-	57,7	55,4	3 182	94	30	
M10 - C1	PR	118	-	58,0	53,2	3 085	115	37	
M10 - C2	PR	113	-	58,6	50,7	2 960	168	57	
M11 - C1	PR	115	-	57,6	57,4	3 306	175	53	
M11 - C2	PR	112	-	57,1	55,7	3 175	205	65	
M12 - C1	PR	128	-	59,8	54,5	3 256	211	65	
M12 - C2	PR	105	-	58,0	53,9	3 126	260	83	
M13 - C1	CY	121	54,9	-	-	2 367	216	91	1
M13 - C2	CY	108	54,8	-	-	2 359	279	118	1
M14 - C1	CY	127	55,0	-	-	2 376	6,54	2,75	
M14 - C2	CY	115	55,0	-	-	2 376	6,70	2,82	
M14 - C3	PR	115	-	53,2	51,5	2 740	7,24	2,64	
M14 - C4	PR	111	-	51,7	51,2	2 647	7,64	2,89	

* PR = Specimen prismatic
CY = Specimen cylindrical

** REMARKS: 1. Specimen machined using water as a coolant
3. Specimen cracked before test

TABLE 12.2: RESULTS OF BRAZILIAN TENSILE STRENGTH TESTS

Specimen			Load at failure kN	Tensile strength MPa	Remarks*
Number	Thickness mm	Diameter mm			
M1 - B1	28,0	54,8	21,3	8,8	1
M1 - B2	28,5	54,8	25,9	10,6	1
M1 - B3	28,4	54,8	29,4	12,0	1
M2 - B1	24,4	54,9	14,9	7,1	2
M2 - B2	27,7	54,9	28,1	11,8	
M3 - B1	29,0	54,7	29,2	11,7	1
M3 - B2	26,3	54,7	27,5	12,2	1
M4 - B1	29,9	54,8	9,3	3,6	
M4 - B2	28,4	54,7	7,6	3,1	3
M4 - B3	28,1	54,9	7,1	2,9	3
M4 - B4	29,3	54,9	7,6	3,0	3
M5 - B1	28,6	55,0	13,6	5,5	
M5 - B2	27,5	54,9	11,0	4,6	
M6 - B1	29,8	54,9	17,8	6,9	
M6 - B2	29,8	54,9	12,2	4,7	
M6 - B3	30,0	54,9	15,4	6,0	
M6 - B4	26,3	55,0	11,0	4,8	3
M6 - B5	13,8	55,0	5,7	4,8	3
M6 - B6	27,2	55,0	8,0	3,4	3
M7 - B1	25,0	55,0	15,9	7,4	
M7 - B2	26,3	55,0	13,4	5,9	
M7 - B3	29,4	55,0	12,7	5,0	
M8 - B1	28,6	54,8	55,6	22,6	1
M8 - B2	28,4	54,8	48,4	19,8	1
M9 - B1	27,4	55,0	5,7	2,4	
M9 - B2	27,8	55,0	8,5	3,5	
M9 - B3	26,2	55,0	5,1	2,3	
M10 - B1	27,4	54,8	11,6	4,9	
M10 - B2	22,5	54,7	11,4	5,9	
M11 - B1	23,6	54,6	16,5	8,2	
M11 - B2	27,5	54,6	18,3	7,8	
M11 - B3	27,8	54,6	21,0	8,8	
M12 - B1	27,4	54,8	37,3	15,8	
M12 - B2	22,8	54,8	15,1	7,7	2
M12 - B3	25,5	54,7	19,7	9,0	2
M13 - B1	28,2	54,7	23,6	9,7	1
M13 - B2	27,6	54,7	28,6	12,1	1
M13 - B3	26,6	54,8	29,6	12,9	1 : 3
M14 - B1	26,4	55,0	0,96	0,42	
M14 - B2	26,6	55,0	1,10	0,48	
M14 - B3	24,7	55,0	1,20	0,56	
M14 - B4	24,3	55,0	1,24	0,59	

* Remarks

1 Specimen machined using water as coolant

2 Specimen did not fail in typical fashion

3 Specimen cracked before test

preparation of samples.

The cone indenter is shown on Plate 28. The method followed is given by the National Coal Board (1972). Four to six chips for testing, measuring about 12 x 12 x 6 mm, were sawn for each mudrock sample and tested. The instrument measures the hardness of the rock by measuring its resistance to indentation by a hardened cone. The cone indenter number is basically the force required to indent the sample divided by the depth of indentation (0,2 -0,6 mm in the case of the mudrocks). An estimate of the uniaxial compressive strength of a core, 51 mm long and 25 mm diameter, can be obtained by multiplying this number by 24,8 (National Coal Board, 1972).

The results are listed in Table 12.3. Ten to 20 readings were taken for each sample, usually about four readings per chip. The samples were tested at their natural moisture content, i.e. as sampled. It was not possible to obtain results for M14 as the sample split before the required stress could be applied. The same happened even after the sample had been dried in the oven.

TABLE 12.3: RESULTS OF NCB CONE INDENTER

Sample number	Number of readings	Average NCB cone indenter number	Standard deviation	Compressive strength (MPa) (x 24,8)	Remarks
M1	14	2,51	0,30	62	
M2	18	3,13	0,39	78	+
M3	17	2,60	0,32	64	
M4	12	1,54	0,24	38	+
M5	16	1,93	0,37	48	
M6	10	1,23	0,10	31	
M7	15	1,26	0,17	31	*
M8	18	2,49	0,68	62	
M9	17	1,63	0,22	40	
M10	19	1,44	0,16	36	
M11	16	1,52	0,19	38	
M12	14	1,69	0,29	42	
M13	15	2,89	0,45	72	
M14					✖

\+ = one chip splits

* = two chips split

✖ = all chips (natural or dried) split, not determined

The test was developed to give a quick indication of rock strength. Standard deviations of the cone indenter numbers were large and the narrow range of values obtained is also reflected in the relatively small variation in compressive strengths. Figure 12.1 shows the relation between actual compressive strengths and the cone indenter numbers for the mudrock samples. The method does not accurately reflect the compressive strengths. There is some relation but also an unacceptably large variation. The inability to test the weak samples confirmed that the cone indenter is not suitable for classifying mudrocks.

12.1.3 Schmidt hammer

Schmidt hammers of various types are popular instruments for estimating rock or concrete strength. A spring loaded plunger is automatically released against the rock when the instrument is pressed against it, and the rebound reading displayed is related to the compressive strength. A Type N hammer was used on the mudrock samples to determine its sensitivity for classification purposes.

A number of large blocks were selected for the test. They were put on a solid concrete structure and readings were taken with the blocks pressed firmly against the concrete. The readings were converted to compressive strengths using the graph supplied with the instrument (Proceq Company, 1977). The results are summarized in Table 12.4. Fifteen to 24 readings were taken for each sample and more than one block was tested for some samples.

It is evident from the high standard deviations that the results were not repeatable. However, when the Schmidt hammer results (expressed as compressive strengths) were plotted against the actual compressive strengths (Figure 12.2) a reasonable relationship was found. Sample M11 plotted away from the main trend but as this is not a homogeneous sample, it can be disregarded. In any further work, testing should be done on the intact rock. It appears to be a valuable instrument for the rapid determination of the approximate strength of the rock. It is probably not sufficiently accurate in its prediction of strength to be used for general mudrock classification e.g. samples M9 and M12 which differ in engineering properties gave similar Schmidt hammer values.

TABLE 12.4: SCHMIDT HAMMER RESULTS

Sample number	Number of blocks tested	Approximate size of block cm	Number of readings on block	Average compressive strength for block MPa	Standard deviation for block MPa	Average compressive strength for sample MPa	Standard deviation for sample MPa	Remarks
M1	1	15 x 15 x 40	17			56	5,9	
M2	1	20 x 15 x 20	17			53	6,4	
M3	1	30 x 20 x 15	16			60	9,0	*
M4	1	15 x 20 x 10	15			29	7,3	
M5	1	15 x 15 x 20	20			27	9,9	
M6	1	30 x 30 x 20	17			33	7,1	
M7	1	15 x 15 x 20	22			25	9,9	
M8	1	25 x 25 x 10	22			62	8,5	
M9	1	20 x 20 x 30	22			32	7,3	
M10	2	10 x 15 x 15 10 x 10 x 10	10 14	26 29	4,0 9,2	28	7,6	+
M11	2	10 x 10 x 7 10 x 10 x 7	9 12	18 12	5,2 3,8	15	5,3	+
M12	2	20 x 20 x 7 15 x 15 x 10	10 12	33 35	7,7 9,1	34	8,4	
M13	2	15 x 15 x30 20 x 20 x 10	9 7	63 53	5,2 3,5	59	6,8	x
M14	1	15 x 15 x 10				<10		✖

Remarks: * One surface flat (sawn)

\+ Small cracks present

x Some holes drilled in blocks tested

✖ Too soft to obtain results

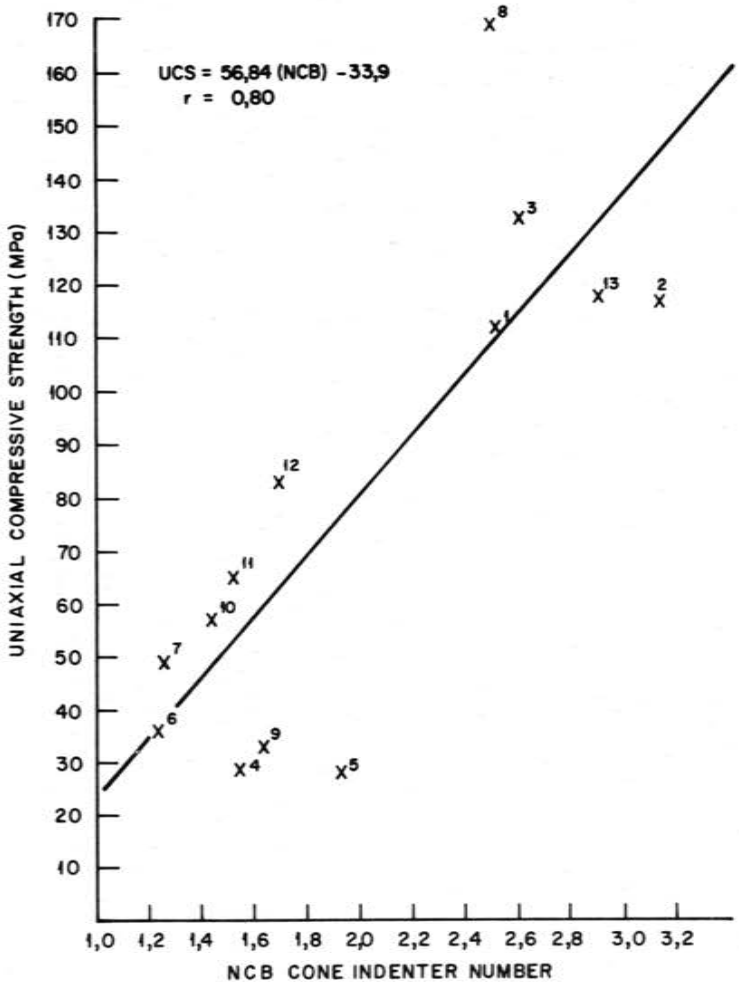


FIGURE 12.1

RELATIONSHIP BETWEEN NCB CONE INDENTER NUMBER AND UNIAXIAL COMPRESSIVE STRENGTH

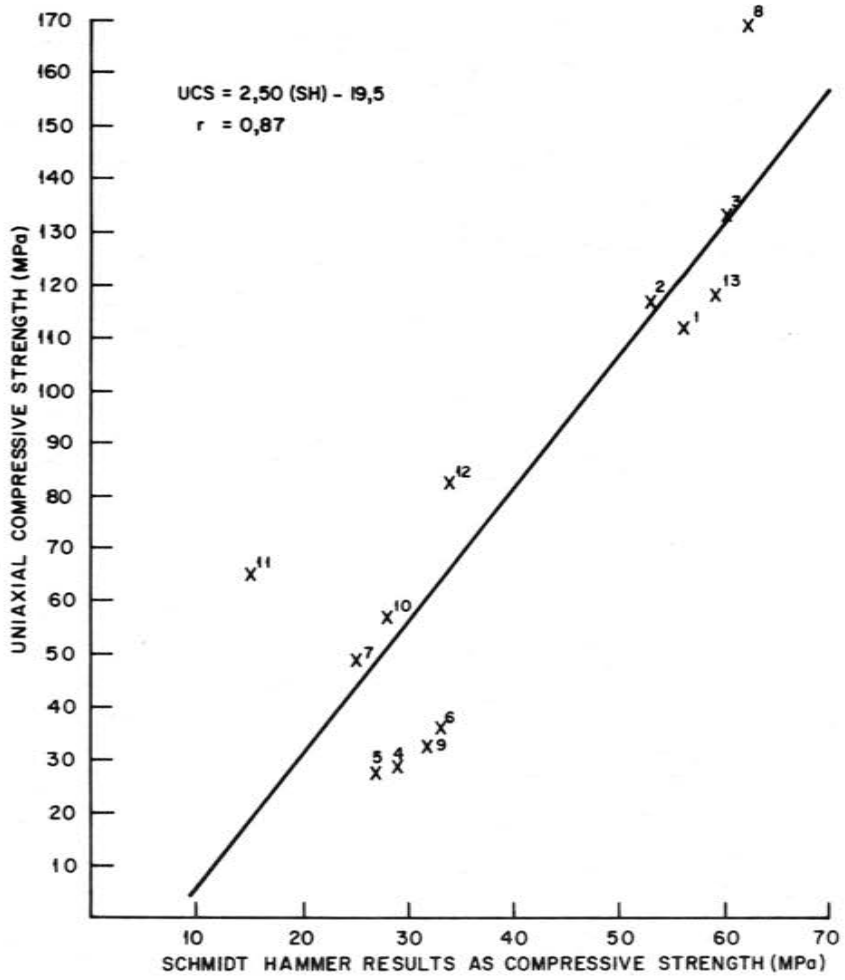


FIGURE 12.2

RELATIONSHIP BETWEEN SCHMIDT HAMMER RESULTS (EXPRESSED AS UNIAXIAL COMPRESSIVE STRENGTHS) AND ACTUAL UNIAXIAL COMPRESSIVE STRENGTHS.

12.1.4 Mohs hardness and point load test

Mohs hardnesses were determined on clean sawn surfaces of the mudrock samples. The results were all within a small range, between 2 and 3, and because of these narrow limits it is unlikely that this parameter is suitable for classifying mudrocks.

The point load test was used by Olivier (1976a) to predict the uniaxial compressive strengths of mudrocks. He found, however, that a large number of tests were necessary on any particular rock type to obtain a meaningful relation between uniaxial compressive strength and point load results. The main reason for the problem was found to be the strong anisotropic strength behaviour of the majority of the mudrocks. The point load strength index determined in the usual diametrial direction, i.e. parallel to the bedding, was in many instances considerably lower than the strength index determined in the axial direction, i.e. perpendicular to the bedding. The latter test method requires very careful trimming of the test specimens to a standard length and can therefore not be used as a field test which necessitates non-sophisticated test apparatus.

12.2 Aggregate crushing value (ACV)

The ACV test is very popular in South Africa for evaluating the strength of construction materials, both for the upper layers of road pavements and for use in structural concrete. The test originated in the United Kingdom (Markwick and Shergold, 1946) and was investigated by Shergold (1955). It is used as a specification test in countries such as the United Kingdom, Australia and South Africa. References to its use in the United States of America could not be found.

The apparatus used to determine the ACV is shown on Plate 29. Test method B1 (Department of Transport, 1971) was used. It involves the crushing of aggregate in a mould by applying a load of 400 kN. Aggregate graded between 13,2 and 9,5 mm is used and the percentage crushed to minus 2,36 mm is the aggregate crushing value. Duplicate tests were performed on dried and soaked samples. The averages of the results are given in Table 12.5.

Problems were experienced with the tests on soaked samples M9 and M14. These materials formed clayey cakes when compressed which made accurate

TABLE 12.5: AGGREGATE CRUSHING VALUE RESULTS

Sample number	ACV (%)		$\frac{\text{Dry}}{\text{Soaked}} \times 100$ %
	Dry	Soaked	
M1	26,2	31,9	82
M2	19,1	23,4	82
M3	21,6	27,0	80
M4	26,4	30,8	86
M5	34,0	34,5	99
M6	29,8	32,7	91
M7	35,1	38,1	92
M8	21,9	23,8	92
M9	38,9	30,6	127
M10	32,0	31,0	103
M11	30,7	30,5	101
M12	29,7	29,3	101
M13	16,4	19,4	85
M14	50,0	31,6	158
% accuracy (80 % C.I.)	5,7	5,4	

results impossible. The values on dry samples were calculated as a percentage of the values on soaked material but these results were not satisfactory. The weak samples gave higher strengths for the soaked than for the dry samples which shows that the tests on soaked material yield misleading results.

The NITRR (1970) does not specify the ACV test for subbase materials. For base materials the limit is set at 30 per cent (dry test). Eight of the 14 samples tested satisfy this criterion.

12.3 10 Per cent fines aggregate crushing test (10 per cent FACT)

The 10 per cent FACT was developed by Shergold and Hosking (1959) for testing the strength of the weaker road-building materials. They are of

the opinion that the ACV test is too insensitive for weak materials. Shergold and Hosking (1963) also introduced the testing of soaked (saturated with water) material and the use of a smaller mould. The results of the tests using the smaller mould can be multiplied by four to give the "correct" values for the normal mould. Loubser (1967) proposed the dry and soaked tests for testing mudrocks for road-building purposes, as did Weinert (1979).

Test method B2 (Department of Transport, 1971) was used to determine the 10 per cent FACT value. The apparatus is similar to that used for the ACV test and is shown on Plate 30. The 10 per cent FACT value is the force (kN) required to crush the aggregate in the mould so that 10 per cent of the sample passes the 2,36 mm sieve. The test specifies the use of 13,2 to 9,5 mm material but for the tests on the mudrocks the 9,5 to 6,7 mm fraction was used. This was done because large amounts of rock were needed to be crushed to supply enough material for the ACV and 10 per cent FACT tests. All the tests, except for sample M1, were done in the small mould and the results multiplied by four. Tests were done in duplicate on dry and soaked samples and the average results are summarized in Table 12.6. The soaked/dry percentages, which are used in some specifications, were also calculated.

Dry and soaked values varied over a wide range. The NITRR (1970) specifies a minimum dry 10 per cent FACT value of 110 kN for basecourse material. Only four of the samples do not satisfy this criterion. No criterion is set for subbase material. Weinert (1979) suggested 160 kN minimum for subbase and a soaked value of at least 75 per cent of the dry value. From Table 12.6 it is evident that only three samples pass this specification. These suggested values seem somewhat high as some of the rejected materials and similar mudrocks have been used with apparent success on roads in the Cape Province and Natal.

TABLE 12.6: 10 PER CENT FACT RESULTS

Sample number	10 % FACT values (kN)		$\frac{\text{Soaked}}{\text{Dry}} \times 100$ %
	Dry	Soaked	
M1	166	123	74
M2	238	184	77
M3	210	148	70
M4	138	82	59
M5	90	50	56
M6	118	66	56
M7	82	44	54
M8	204	168	82
M9	50	26,2	52
M10	135	69	51
M11	107	64	59
M12	138	87	63
M13	283	232	82
M14	18,0	11,8	66
% accuracy (80 % C.I.)	4,0	6,8	

12.4 Treton impact value

The origin of the Treton test is somewhat obscure. According to Biesenbach (1978) it originated in Sweden. It was used in South Africa by SATMAR (South African Torbanite Mining and Refining Company).

From literature studies it is evident that the test is not used widely. It was used in Brazil by Farjallat et al (1974) to measure the weakening of rock weathered by different means. In South Africa the Cape Roads Department specifies the test for the selection of surfacing chips. In a study by Shergold and Hosking (1963) a similar impact test (British Standards Institution, 1960) fared very well in rating argillaceous and gritty rocks according to their break-down under traffic. It predicted the behaviour of the materials better than tests such as specific gravity, water absorption, sodium sulphate soundness and 10 per cent FACT. The 10 per cent FACT prediction was almost as good as that of the impact test.

It was important, therefore, that this test or a similar test should be investigated for classifying southern African mudrocks.

Test method B7 (Department of Transport, 1971) was used. The apparatus is shown on Plate 31. Graded pieces of aggregate are put on an anvil and a cylindrical hammer is dropped onto them through a guiding tube. The percentage material crushed to minus 2,0 mm after 15 blows is the Treton impact value.

Some minor problems were experienced during the test. The first was a double bounce when the hammer was dropped onto the anvil and baseplate. This was avoided by putting the baseplate on a 13 mm thick wooden plank. Some crushed material also came between the anvil and baseplate and this may have had a dampening effect on the later blows. It was also very difficult to prepare some of the mudrocks to the specified cubical shapes. The mass of the aggregate on the anvil should be 50 times the estimated relative density (expressed in g). It was often a problem to fit these masses in a single layer on the anvil. The test method does not specify the moisture condition of the samples before testing. The Cape Roads Department (Streicher, 1978) usually tests the samples "as received". The mudrock samples, however, were dried at 105 °C and cooled for about an hour before testing.

The tests were done in duplicate and the average results are summarized in Table 12.7.

TABLE 12.7: TRETON IMPACT VALUE RESULTS

Sample number	M1	M2	M4	M5	M6	M7	M8	M9	M10	M12	M13	M14
Treton impact value	22,6	17,7	25,1	38,0	25,1	30,5	19,7	49,4	32,7	29,2	16,4	56,1

% accuracy at the 80 per cent confidence interval: 6,0

Apart from the problems mentioned above, the test worked satisfactorily and has the advantages that it is a rapid test and requires inexpensive equipment. One of the few specifications in South Africa for the Treton value is a minimum value of 20 specified by the Cape Provincial Administration Roads Department (undated) for surfacing chips. Three of the mudrock samples satisfy this criterion but would probably fail on the grounds of

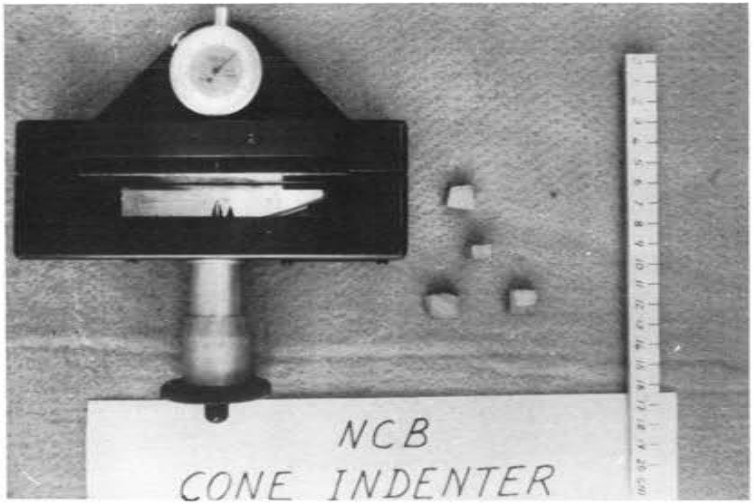


Plate 28: NCB cone indenter

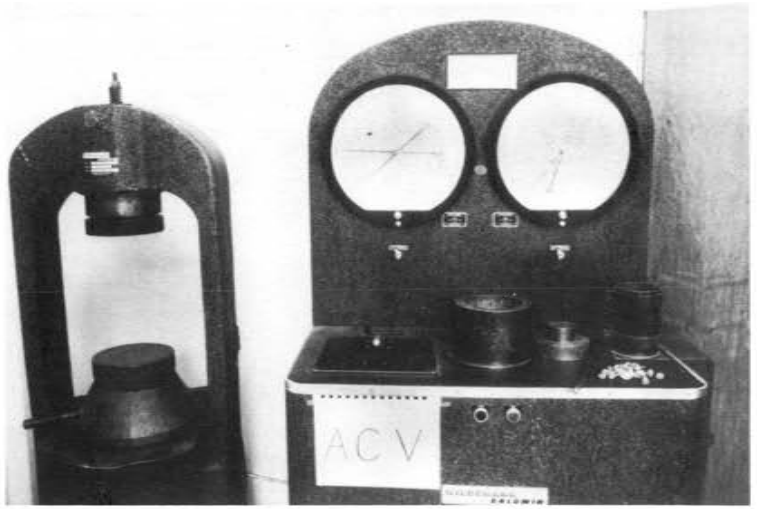


Plate 29: Apparatus for determining the aggregate crushing value

Plate 30: Apparatus for determining the 10% FACT value (large and small cylinders shown)

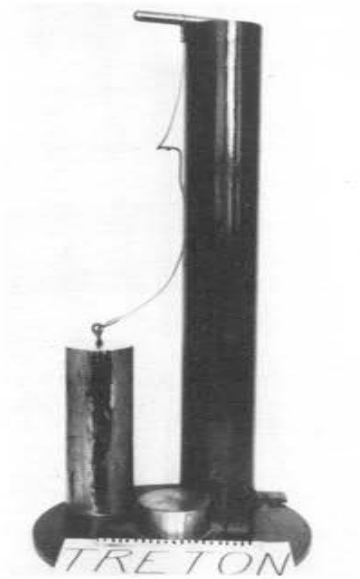


Plate 31: Apparatus for determining the Treton impact value

rock type. A minimum ACV of 30 per cent and Treton value of 40 is also specified for stone aggregate in bitumen-treated basecourse. According to Appelgryn (1975) the Treton test is done on basecourse material if the ACV values are close to the limit of 30 per cent (29 to 31 per cent), and a Treton value of 40 or less is then specified. Nine of the fourteen mudrock samples may be used as basecourse material according to these criteria.

12.5 Los Angeles abrasion

12.5.1 Introduction

The Los Angeles abrasion test is the most generally used abrasion test. The method involves the tumbling of a graded aggregate and steel spheres in a steel drum with one protruding shelf on the inside (Plate 32). Percentage losses through a 1,68 mm sieve are determined after 100 and 500 revolutions. The percentage loss after 500 revolutions is usually called the Los Angeles abrasion value but the ratio between the two above-mentioned losses is also used as an indication of the uniformity of the wear during the test.

The test has been tried in many forms by numerous investigators and with varied success. Drew and Woods (1970) considered the test suitable for determining abrasive resistance but unreliable for predicting chemical weathering. Erickson (1958) conducted a study because the Los Angeles and other abrasion tests did not predict the inability of aggregates to withstand the elements e.g. freezing and thawing during the winter, and suggested the addition of a freeze-thaw test. Yedlosky and Dean (1961) conducted studies on sandstones for road construction purposes and found very little relation between the test and properties such as porosity, permeability, grain size and compressive strength. De Puy (1965) also found the test to rate very poorly when compared to other durability tests and a petrographical (rock quality) index. Smith et al (1967) carried out research to find the most suitable tests for predicting the performance of rock slope protection material. The Los Angeles test gave poor correlations with observed performances and it was recommended that the test be discontinued. More discouraging results were obtained by Deo (1972) who used a modified test for evaluating the degradation of mudrocks in

embankments and found it unsatisfactory.

Other investigators obtained certain positive results from the test. Miles (1972) studied tests to predict the performance of all kinds of rock and recommended that metamorphic rocks should be evaluated with the abrasion test. Reidenouer et al (1974) studied classification tests for shale by comparing the results with a durability factor and found that the abrasion test gave a reasonable correlation. The test was, however, not included in their classification system. Chapman (1975) also used it on six mudrocks and found it to give a reasonable spread of values. In studying tests to predict the performance of rock in protective blankets, Saltzman (1975) found the Los Angeles test satisfactory for determining durability. Values for acceptibility were given. Another positive result came from Gaskin and Raymond (1976) who investigated tests for predicting the breakdown of railroad ballast and concluded that the test can indicate materials likely to give problems. Other tests in the study performed better, however.

In South Africa the test is specified for railroad ballast by the South African Railways. The main practical disadvantages of the test are the time spent on the preparation of the samples and the special equipment required.

12.5.2 Method

Test method ASTM C131-69 (1976) was used with some minor changes to prevent breaking down of the aggregate beforehand or afterwards. The aggregate was blown clean before the test and tested after drying in an oven. The coarse material was also not washed afterwards.

Duplicate samples were tested and the percentage wear determined after 100 and 500 revolutions. The ratio of the percentage losses after the above revolutions was also calculated. If this factor is equal to 0,2 it means that the wear was constant throughout the abrasion process and if it is higher it indicates that more fines were generated during the first 100 revolutions. This is usually the case as the sharp edges of the aggregate are abraded at a faster rate at the beginning. The results are given in Table 12.8.

TABLE 12.8: RESULTS OF THE LOS ANGELES ABRASION TEST

Sample number	Wear after 100 revolutions %	Wear after 500 revolutions %	Ratio 100 revs. wear / 500 revs. wear
M1	4,8	18,0	0,27
M2	4,2	16,6	0,26
M3	3,8	16,4	0,23
M4	5,1	23,6	0,22
M5	6,7	29,1	0,23
M6	5,8	24,8	0,23
M7	5,3	23,6	0,23
M8	3,8	15,6	0,24
M9	11,1	44,8	0,25
M10	6,5	26,1	0,25
M11	6,9	27,3	0,26
M12	6,6	25,7	0,26
M13	3,4	14,1	0,24
M14	21,4	74,7	0,29
% accuracy (80 % C.I.)	3,5	1,4	3,8

12.5.3 Discussion

The percentage wear after 500 revolutions varied between 14,1 and 74,7 per cent and only between 14,1 and 29,1 per cent if samples M9 and M14 were excluded. This is a small spread of values for samples with widely differing properties. The calculated ratios did not divide the samples into specific quality groups and do not seem to be of much use.

The South African Railways (1971) specifies a maximum loss of 22 per cent for ballast. Five of the samples satisfy this criterion but would probably not be used as ballast because of the rock type.

12.6 Washington degradation

12.6.1 Introduction

The Washington degradation test was developed by the Washington State Highway Department for testing basalts which degraded in the pavements because of the presence of secondary clay minerals. Minor (1960) gives details of the evolution of the test and the test method. The test involves the shaking of 1 kg of graded aggregate with water in a plastic container on a sieve shaker. The material is then washed through nested 2 mm and 0,075 mm sieves into a measuring cylinder. The mixture of silt and water is used to fill a sand equivalent cylinder into which some sand equivalent solution has been measured. After shaking, the material is allowed to settle for 20 minutes when the sediment height is read. The first formula used incorporated the results of the sieve analysis and the sediment height. Marshall (1967), also from the Washington State Highway Department, used results from nearly 600 tests and showed that the old formula could be replaced by a formula using only the sediment height. The correlation coefficient between results using the old and new formulas was 0,98.

The test has been used by various bodies in the USA and Australia. Platts and Lloyd (1966) carried out studies to find a quality test for predicting degradation properties of aggregates in pavements in Alaska and found the Washington test results to correlate excellently with field behaviour. Reidenouer (1970) and Reidenouer et al (1974) found relatively high correlation with a "durability factor" during their research on the classification of durable and non-durable Pennsylvanian shales and included the Washington test in their recommended specification.

Moors (1972) from Australia severely criticized the Washington degradation test. He is of the opinion that the test was developed for a particular aggregate in the State of Washington, that the test will only be of local use and that it should be calibrated for each new application. Chapman (1975) carried out some tests on mudrocks in Indiana and found that the Washington degradation test gave a poor spread of values.

12.6.2 Method

The "new" WSHD test method 113A (Washington State Highway Commission, 1969) was followed. The apparatus is shown in Plate 33. Problems were experienced obtaining the correct size Tupperware container and one was eventually supplied by the Washington State Highway Department. It is likely, however, that containers of a similar size, obtainable in South Africa, will give the same results. According to the method, the sieve shaker should have a 44,5 mm (1 3/4 inch) throw on the cam and oscillate at 300 ± 5 oscillations per minute. The shakers at the NITRR (W.S. Tyler Co.) used for the test have the correct throw but oscillated at 283 oscillations per minute. Doubts arose during the washing of the samples as to whether it was essential to wash all the minus 0,075 mm material through the sieve. In the case of the softer samples the amount of wash water allowed (approximately 500 mℓ), was inadequate to wash all the material into the measuring cylinder. A standard washing procedure was followed to compensate for this. Another problem was the accumulation of water on the 0,075 mm sieve and in some cases it was necessary to rub the mesh with a finger to allow the water, silt and clay to flow through. The results of the test are given in Table 12.9.

12.6.3 Discussion

There are some doubts about the applicability of the test to mudrocks because of the problems mentioned above. The influence of the amount of minus 0,075 mm material should be determined (Section 12.7.2). It would also be interesting to compare the "old" with the "new" formulae for mudrocks.

Very low values were obtained. Marshall (1967) specified a value of at least 15 for use in basecourse or ballast. Only three samples satisfy this criterion and most are far below with ten samples giving values of six and lower. Currie and York (1976) state that the Country Roads Board in Victoria, Australia requires a minimum value of 40 for the use of a material in a subbase. Only one mudrock sample satisfies this specification. The spread of values is also very small and it is doubtful whether this test is useful for classifying mudrocks in southern Africa.

TABLE 12.9: RESULTS OF THE WASHINGTON DEGRADATION TEST

Sample number	Sediment height mm	Washington degradation factor
M1	297	9
M2	249	16
M3	341	1
M4	358	2
M5	338	4
M6	361	2
M7	325	6
M8	168	32
M9	340	4
M10	338	4
M11	343	4
M12	328	6
M13	124	43
M14	351	3

12.7 Wet ball mill

12.7.1 Introduction

Wet ball mill tests involve the tumbling of graded aggregate with some abrasive charge (steel spheres, porcelain balls, etc.) in water. This is in contrast with the Los Angeles test where no water is used. The effect of the tumbling is usually measured by determining the percentage material lost through a certain mesh size.

Two standard wet ball mill tests, which require special apparatus, are the wet shot test (California Division of Highways, 1963) and the Texas ball mill test (Texas Highway Department, 1976). Both tests utilize steel drums and metallic spheres. In the Texas test the drum rotates around its axis while in the wet shot test, the drum is set at an angle to the rotating shaft. The Texas test specifies 600 revolutions and uses minus 44,5 mm

(1 3/4 inch) material while the wet shot test gives a choice of six gradings and specifies 10 000 revolutions. The aggregates are evaluated by determining the percentage loss through 0,425 and 1,68 mm sieves respectively. Unfortunately none of these apparatuses were locally available at the time of this investigation.

References to other non-standard ball mill tests are found in various publications. Mellville (1948) used 3 000 g flint pebbles, 500 g sample material and 1 000 mℓ water in a porcelain jar. Tumbling was at 69 rpm and continued for 72 to 120 hours. Various rock types were tested and the test was found to be more severe than the Los Angeles test. Breese (1966) described a jar mill test by Minor which is similar to the Washington degradation test except that the fines are generated by tumbling the material in a jar. Croft (1966) used a 254 mm (10 inch) diameter steel container, 500 g mudrock, 500 g steel balls and 500 mℓ water. The container was revolved at 80 rpm for 15 minutes. A relation between the results of the ball mill test and the total clay mineral content was found and the test was recommended for classifying mudrock in pavements. Smith et al (1967) used a 127 mm (5 inch) steel container and a silicon carbide abrasive. Tumbling was at 66 rpm and continued for eight hours. They found that 1 kg of stone and 35 g of 30 mesh abrasive plus just enough water to cover the sample provided optimum loss. The test, which was tried out in a study of rock slope protection material, showed promise and in a subsequent study by Smith et al (1969) it was found to be more accurate in predicting field behaviour than the tests in use at that time in California. A "durability-absorption ratio" was, however, preferred for prediction purposes.

12.7.2 Method

The above data were used in the design of another wet ball mill test. A set of rollers, porcelain tumbling jars and different sizes of porcelain balls were available at the NITRR. It was decided to use jars with inside diameters of 110 mm and inside lengths of 105 mm. A 200 g oven-dried sample, graded between 9,5 and 6,7 mm, 200 g porcelain balls with diameters in the range 11,0 to 12,5 mm and 200 mℓ distilled water, were put into the jar. The sample and porcelain balls filled about 30 per cent of the container when it was standing upright and the water covered the contents by

about 3 to 5 mm, depending on the absorptive characteristics of the sample. The samples were left to soak overnight (16 to 18 hours) before they were tumbled at 80 rpm for 7½ hours the next day. The porcelain jars and charge are shown on Plate 34.

It was felt that in addition to evaluation by sieving, a Washington degradation type evaluation, using a sand equivalent solution, should also be carried out.

Experiments were performed on samples M2 and M7, hard durable and soft disintegrating samples respectively. The minus 0,075 mm material was washed through 2,0 and 0,075 mm sieves into a 500 mℓ measuring cylinder as with the Washington degradation test. When this material was used to fill the sand equivalent cylinder, only 3 and less than 1 mm settlement resulted after 20 minutes for M2 and M7 respectively. It was obvious that the fines would have to be diluted and that because the amount of minus 0,075 mm seemed to influence the results, more wash water would have to be used to wash all the minus 0,075 mm material into a measuring cylinder. After trying out various dilutions, the following procedure was adopted to obtain a sediment height for the minus 0,075 mm material:

> The abraded material was washed into a 1 000 mℓ measuring cylinder. This quantity was sufficient to wash all the fines through the 0,075 mm sieve. The material in the measuring cylinder was thoroughly mixed by inverting it ten times. Two hunderd mℓ of this material was poured into a 500 mℓ measuring cylinder which was then topped up to 500 mℓ with distilled water. The material was again mixed by inverting this cylinder ten times and a sand equivalent cylinder, into which 7 mℓ sand equivalent solution is measured out beforehand, was filled up to the 381 mm (15 inch) mark with this silt and clay suspension. The contents of the cylinder were again inverted 20 times after which the suspension was allowed to settle for 20 minutes before a reading of the sediment height was taken.

The plus 0,075 mm material was dried in an oven at 105 °C after which the cumulative percentages passing 4,75, 2,0 and 0,075 mm were determined by carrying out a sieve analysis. The results for the above tests are given in Table 12.10.

TABLE 12.10: RESULTS OF WET BALL MILL TESTING

Sample number	Cumulative percentage passing			Sediment height mm
	4,75 mm	2,0 mm	0,075 mm	
M1	15,3	14,4	14,1	121
M2	9,3	9,1	9,0	70
M4	32,9	31,3	31,2	178
M5	34,3	32,3	32,2	124
M6	61,7	56,6	56,6	337
M7	86,6	67,3	64,6	378
M8	8,9	8,5	8,2	75
M9	100,0	100,0	99,5	128
M10	37,6	28,5	27,3	196
M12	20,3	15,4	14,7	78
M13	9,2	8,7	8,6	62
M14	76,3	69,1	69,0	239

12.7.3 Discussion

(a) On account of the dilution required to obtain a range of sediment height readings, it was already clear during the test that the amount of fines played a large part in the height of the sediment after 20 minutes. This is shown in Figure 12.3 where, with the exception of sample M9, a definite relationship exists between percentage passing 0,075 mm and sediment height and it is again illustrated in Figure 12.4 where the sediment heights from the ball mill test are compared to the sediment heights from the Washington degradation test. The only important difference between the two tests is the quantities of fines in the sand equivalent cylinder. If this were not an important factor one would expect a linear relationship. The figure shows that there is no such relationship. This indicates that the evaluation of mudrock fines in this manner is not suitable for general classification purposes

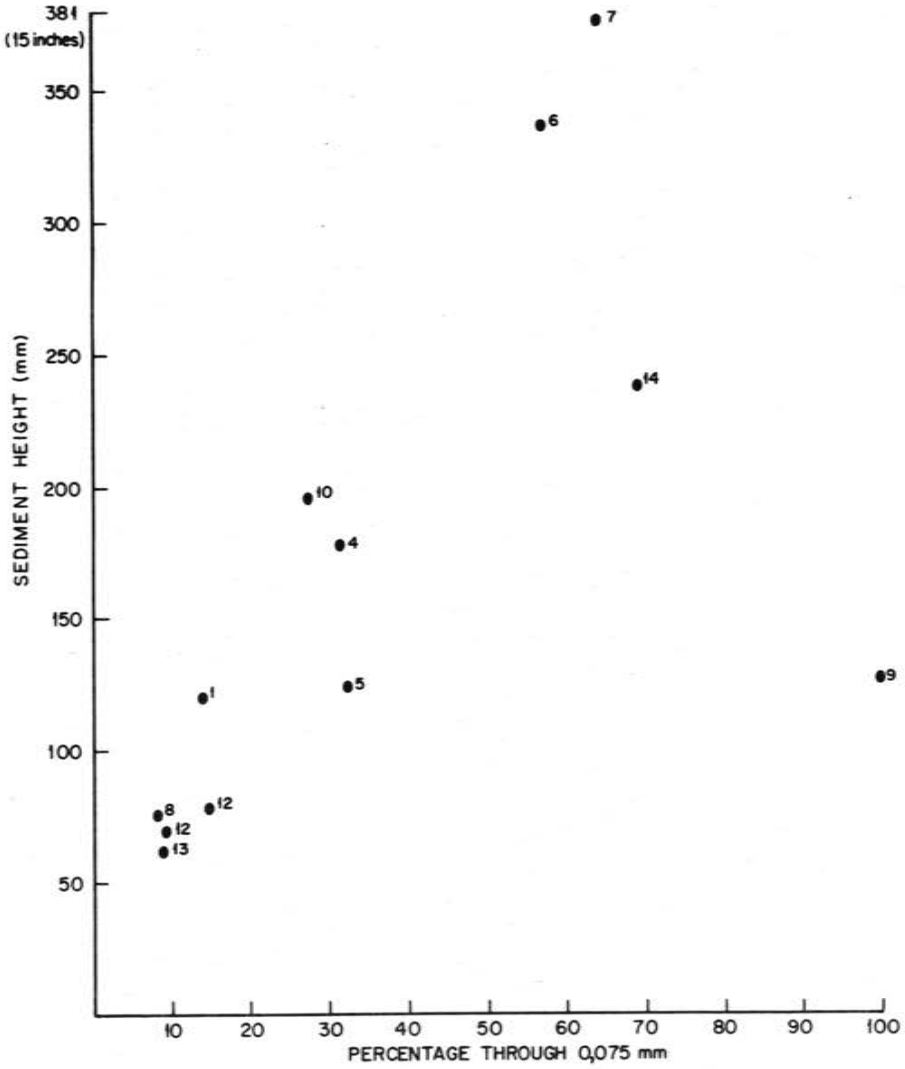


FIGURE 12.3

COMPARISON BETWEEN SEDIMENT HEIGHT AND PERCENTAGE PASSING 0,075 mm

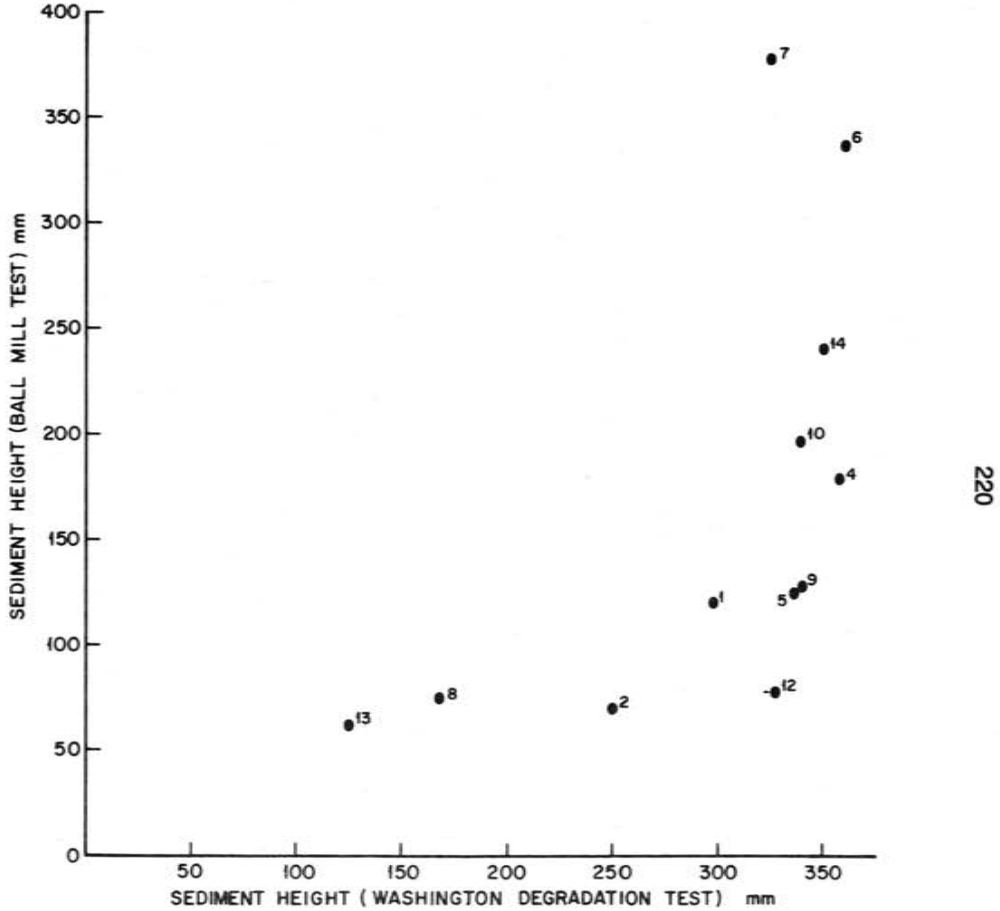


FIGURE 12.4

COMPARISON BETWEEN SEDIMENT HEIGHTS OBTAINED IN THE WASHINGTON DEGRADATION AND BALL MILL TESTS

but if a choice had to be made, the ball mill method would give a better spread of values. The sand equivalent test may, however, be of more use as this test is performed on the percentage fines naturally present in the crushed rock.

(b) As far as the sieve analyses are concerned, a very high percentage of the material abraded from the aggregate is ground to minus 0,075 mm. Table 12.10 shows clearly that losses through the three sieves are in most cases of a similar magnitude and that little of the material passing the 4,75 mm sieve is retained on the 2,0 or 0,075 mm sieves. The percentage loss through 0,075 mm is, therefore, considered to be the best value to use in the evaluation of rocks in the wet ball mill test. A wide spread of values, ranging from an 8,2 per cent loss to 99,5 percent loss, was obtained, and this test, or a similar method, shows promise as a possible classification test. The plus 4,75 mm material consisted mainly of almond-shaped small pebbles.

12.8 Slake durability test

12.8.1 Introduction

Various aspects of the slake durability test were investigated in pilot studies (Sections 5.2.2 and 5.2.3). Gamble (1971) did an extensive study of the test developed by Franklin and Chandra (1972) and suggested the method adopted by the ISRM (1972b) i.e. 200 revolutions per cycle and two cycles. He proposed the use of this test in combination with the plasticity index to classify mudrocks. Deo (1972) and Wood and Deo (1975) also investigated the test for classifying mudrocks. The test was modified by increasing the number of revolutions to 500 and by including the determination of slake durability on samples soaked in water beforehand. The test was found to be simple and inexpensive for measuring the durability of mudrocks which slake in water. The tests on dry and soaked mudrocks were included in a classification system for engineering uses in Indiana. Chapman (1975) used the above modified methods and agreed that the test should be applied to these materials. Aufmuth (1974) investigated

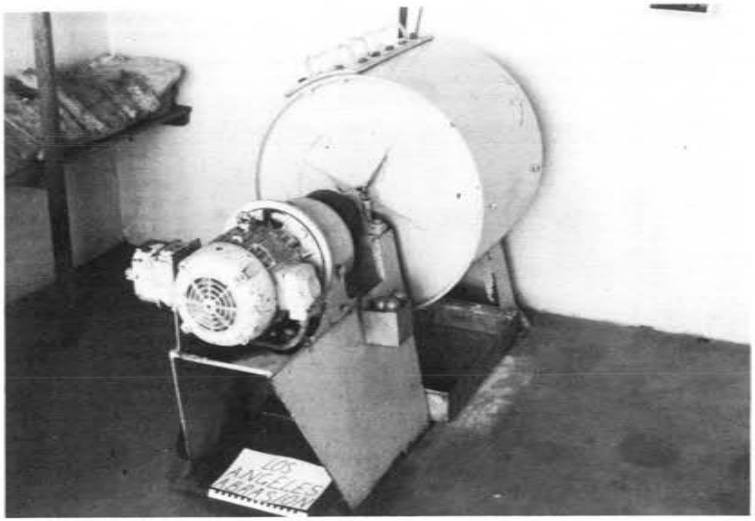


Plate 32: Apparatus for the Los Angeles abrasion test

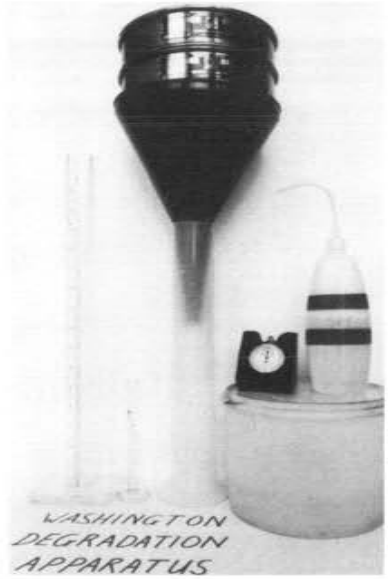


Plate 33: Apparatus for the Washington degradation test

Plate 34: Jars and charge for the wet ball mill test

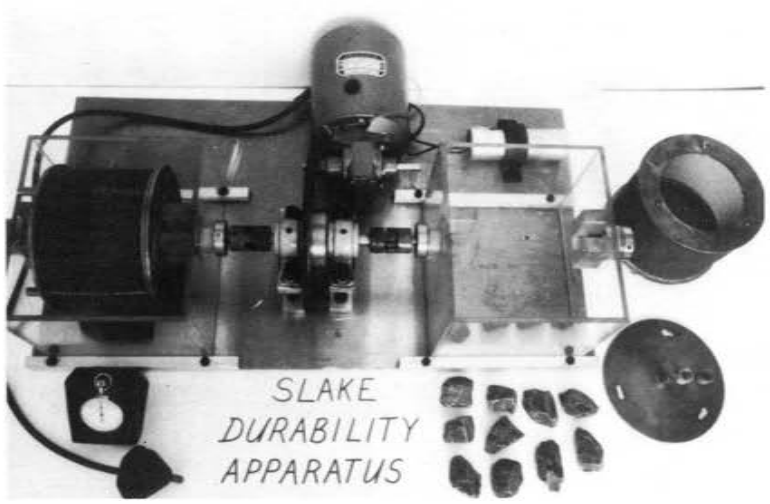


Plate 35: Apparatus for the slake durability test

the slake durability test for indexing the engineering properties of rock cores at the drill site. The test was changed to one cycle on one piece of core and limits for potential slake problems were set.

12.8.2 Method

For the testing of the mudrock samples the ISRM (1972b) method was followed but the number of cycles was increased to five. Slake durability indices were calculated for all the cycles and are expressed in terms of percentage of the material retained in the drum with 2 mm wire mesh walls. The apparatus used is shown on Plate 35.

Some other steps were added to the procedure:

(a) Samples were cooled for 30 minutes after drying at 105 °C (see Section 5.2.3.4). The object was to test the break-down behaviour of rocks in water and not the cracking due to sudden temperature changes.

(b) The behaviour of the samples e.g. slaking, flaking, abrasion, etc. was described during the test.

(c) A dry sieve analysis was done on the material retained in the drum using 26,5; 13,2 and 6,7 mm sieves.

(d) The material retained in the drums was photographed after the five cycles.

The tests were done in duplicate. The average slake durability indices after cycles one to five are shown in Table 12.11 and illustrated in Figure 12.5. Plate 36 shows the appearance of some of the samples before and after some slake durability cycles.

The notes made about the behaviour of samples during the test are summarized in Table 12.12.

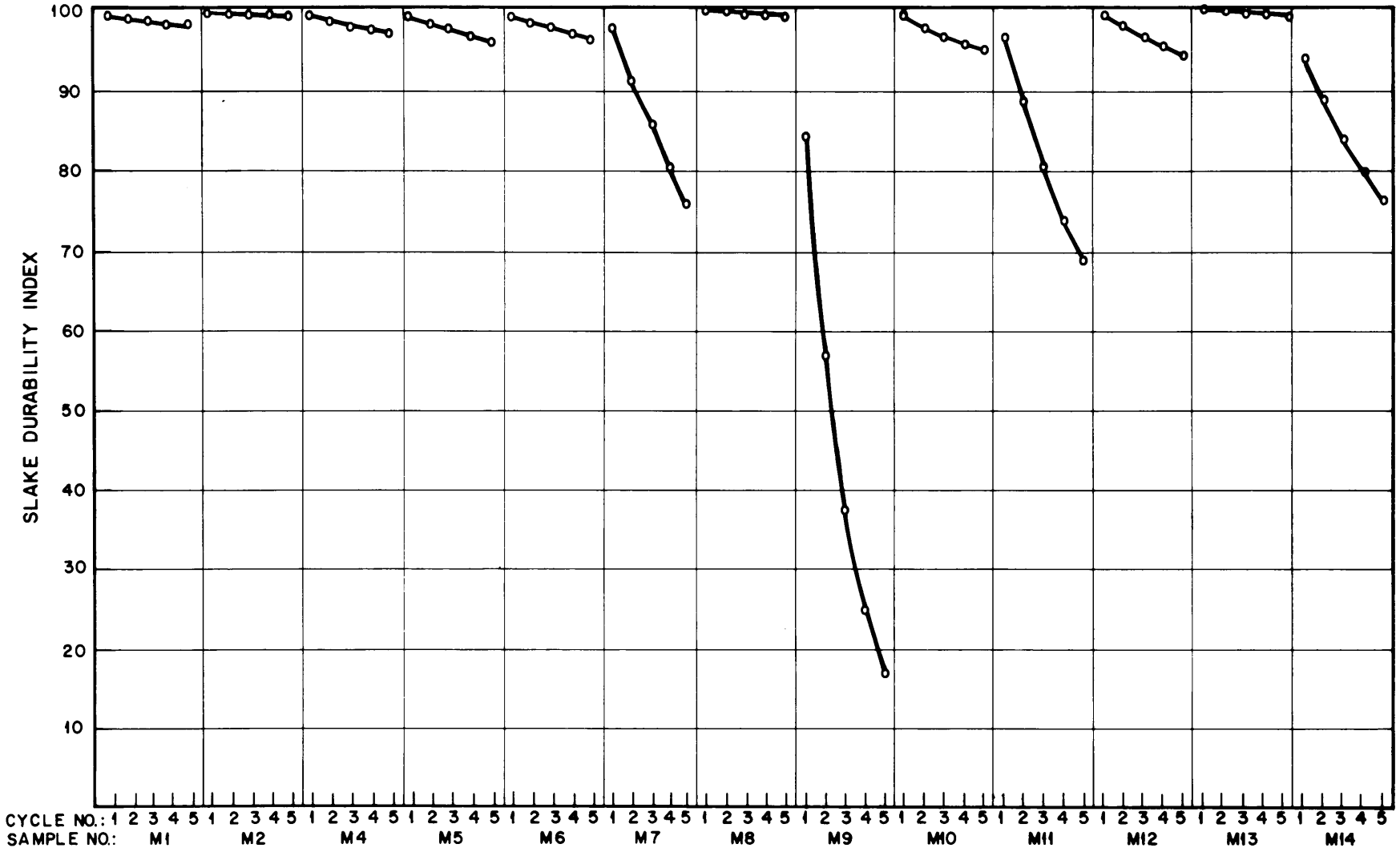
The results of the sieve analyses are given in Table 12.13. The total percentages retained in the drum listed in this table are higher than those mentioned in Table 12.11. This is caused by the fact that the samples were weighed in an oven-dried state during the determination of the slake durability indices. The sieving was done after the samples had been exposed to the atmosphere for a long time and, therefore, had adsorbed varying amounts of moisture.

TABLE 12.11: SLAKE DURABILITY INDICES FOR FIVE CYCLES

Sample number	Slake durability index after					% accuracy (80 % C.I.)
	1st cycle	2nd cycle	3rd cycle	4th cycle	5th cycle	
M1	99,5	99,1	98,7	98,4	98,0	0,1
M2	99,7	99,6	99,4	99,3	99,1	0
M4	99,1	98,4	97,9	97,3	96,8	0,1
M5	98,7	97,8	97,1	96,4	95,6	0,2
M6	99,0	98,2	97,5	96,7	96,0	0,1
M7	97,5	91,0	85,4	80,3	75,5	5,9
M8	99,8	99,6	99,4	99,3	99,2	0
M9	83,9	56,6	37,2	24,5	16,6	9,7
M10	99,0	97,7	96,6	95,6	94,7	0,5
M11	96,5	88,6	80,3	73,6	68,4	5,0
M12	99,3	97,9	96,5	95,4	94,2	0,3
M13	99,9	99,7	99,6	99,5	99,4	0
M14	93,9	88,7	83,7	79,6	76,1	0,6

12.8.3 Discussion

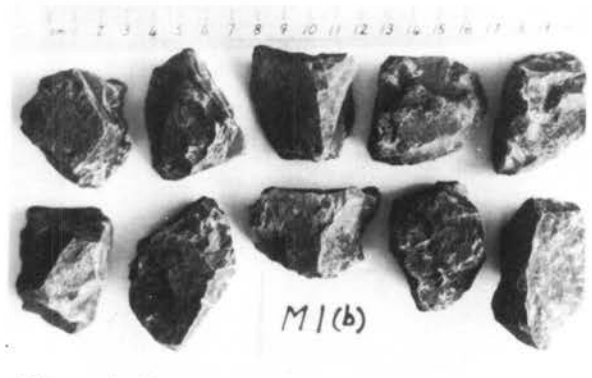
If it is assumed that the samples tested are representative of southern African mudrocks then this test cannot be used as a general classification test. This is obvious from Figure 12.5 where it can be seen that for nine samples the ISRM (1972b) slake durability indices are above 97 per cent, i.e. within a variation of only three per cent. From field observations it is clear that there are major differences in the engineering properties of some of these samples. The situation improves only slightly if the number of cycles is increased to five. The test succeeds well in showing up material which slakes, i.e. breaks down into its constituent particles at various rates when immersed in water. Sample M9 is an example of such behaviour. The test does not, however, show up the disintegration i.e. breaking into plus 2 mm flakes or plates. The sieve analysis can be used to obtain a measure of this. From Table 12.13 it can be seen that samples M1 and M10 disintegrated similarly whereas M12 broke down to a greater extent.



SAMPLE NUMBERS AND SLAKE DURABILITY CYCLES

FIGURE 12.5

SLAKE DURABILITY INDICES FOR 5 CYCLES



M1 — before test

M1 — after 5 cycles

M7 — before test

M7 — after 5 cycles

M14 — before test

M14 — after 5 cycles

M9 — after 2 cycles

Plate 36: Some samples before and after slake durability cycles

TABLE 12.12: BEHAVIOUR OF SAMPLES DURING SLAKE DURABILITY TEST

Sample number	Grain size of material lost	Break-down of lumps inside drum	Condition of lumps after test
M1	Small flakes - very little clay or silt	A small amount of plus 2 mm material	Lumps remain fairly intact - one broken in two
M2	Small amount of clay and silt	None	Lumps intact - edges rounded
M4	Some sand to clay size grains abraded off	None	Lumps intact - edges rounded
M5	Some silt to clay size grains abraded off	None	Lumps intact - edges rounded
M6	Sand to clay size grains abraded off	None	Lumps intact - edges rounded
M7	Fair amount of clayey and flaky material lost	Breaks down into flakes of different sizes	Lumps disintegrated
M8	Small amount of flakes and clay size particles	None	Edges of lumps rounded
M9	Large amounts of clayey and silty material	Material slakes off surfaces of lumps	Everything broken down some spherical pieces of different sizes retained
M10	Flakes and some clayey material	Breaks into flakes of various sizes	All lumps disintegrated but large percentage retained in drum
M11	Fair amounts of flaky and clayey material lost	Broken into flakes	All lumps broken down
M12	Small amounts of flakes and clayey material lost	Broken into plate-like fragments	All lumps disintegrated into mainly larger sized plates
M13	Very little clayey and silty material lost	None	Edges rounded
M14	Fair amounts of flakes and clayey material	Abrasion of surfaces and also some splitting up	Material retained consists of rounded discs of various sizes

TABLE 12.13: SIEVE ANALYSES OF MATERIALS RETAINED IN SLAKE DURABILITY DRUMS

Sample number	Percentage of total sample retained or lost through sieve					
	26,5 mm		13,2 mm		6,7 mm	
	Retained	Lost	Retained	Lost	Retained	Lost
M1	94,7	4,0				
	88,7	9,7	7,2	2,5	1,6	0,9
M2	99,8					
	99,8					
M4	97,4					
	97,6					
M5	96,0					
	96,2					
M6	97,4					
	97,6					
M7	10,3	72,3	39,3	33,0	13,4	19,6
	12,3	59,0	26,8	32,3	8,8	23,5
M8	99,5					
	99,5					
M10	80,9	15,3	12,5	2,8	1,4	1,6
	51,6	43,6	40,4	3,2	2,0	1,2
M11	41,5	31,0	24,0	7,0	4,4	2,5
	5,3	60,9	51,5	9,5	5,4	4,1
M12	54,8	39,9	32,9	7,0	2,8	4,3
	66,3	28,9	21,0	7,9	4,1	3,8
M13	99,6					
	99,8					
M14	50,8	26,2	24,4	1,8	1,3	0,5
	37,3	38,5	37,8	0,6	0,5	0,2

Note: Analyses only performed when quantity of material warranted it

M11 disintegrated to a smaller size and M7 broke down to even finer flakes. The results are unfortunately erratic and further work will have to be done to determine if the results from sieve analyses can be used quantitatively. The results from the sieve analyses strengthen the belief (Section 5.2.3.4) that the use of a larger mesh size on the drum would not be the answer, as it is impossible to select an ideal opening which will suit all mudrock samples.

12.9 Sodium sulphate soundness

12.9.1 Introduction

The sodium (or magnesium) sulphate soundness test is one of the best known tests for determining the durability of aggregates and has been used in many studies of a similar type. The test involves the soaking of various fractions of aggregate in baskets, in a saturated solution of sodium sulphate followed by oven drying. This process is repeated five times after which the fractions are washed, dried and sieved. The percentage of material lost is used as a measure of the soundness of the aggregate.

The test has often been criticized for various reasons, the most important of these being the problems in obtaining reproducible results and the tedious and time-consuming nature of the test. Garrity and Kriege (1935) investigated various aspects of the test. They found several factors which could cause differences in results and proposed that the test should be dropped from highway materials testing except for indicative purposes. Minty and Monk (1966) investigated the durability testing of rocks. Detailed studies were made of the sodium sulphate test, such as the effect of temperature variations of the solution, time of absorption, aggregate size and the use of seawater instead of the sodium sulphate solution. Temperature conditions were found to be the most important single factor influencing the results. The average statistical break-down of the aggregates using seawater was similar to the break-down in the normal test. The measurement of the loss of mass through sieving was considered to be the wrong way of quantifying the weathering and a variation of the test using cored

specimens was proposed. The Cape Provincial Administration Roads Laboratory (1967) is critical of the value of the test. After analysing the results obtained with both kinds of salt and a test using only one fraction of aggregate, they concluded that the reproducibility of the test is usually very poor and that the test is not a weathering test, but that it enhances physical disintegration. They therefore felt that the results have no practical significance.

The results of studies in which the test was tried for predicting durability were varied. Drew and Woods (1970) used it to evaluate granites for shore protection material and found that the test acted as an accelerated mechanical weathering test but did not measure resistance to chemical weathering. Shergold and Hosking (1963) investigated the test to rate argillaceous and gritty rocks for break-down under traffic. They found some "suggestion of a correlation" with break-down but considered the test to be too time-consuming. Dunn (1963) investigated methods to evaluate aggregates from quarries and found that the soundness tests did not have "simple correlations" with other tests or with the physical and chemical properties of the samples. The magnesium sulphate test was still considered to be one of the most reliable for determining soundness. In a comparison of durability tests, De Puy (1965) found that the sodium sulphate test did not rate well in comparison with other tests.

Miles (1972) used the test in an investigation to find a test to predict the performance of all types of rock. The sodium sulphate test gave the single best estimate of performance and showed even better correlations with sedimentary rocks. Smith et al (1967) carried out a study of specification tests for rock slope protection material in California. The rocks tested were also grouped into rock types and it was found that the results varied with the rock type. Sedimentary rocks yielded the highest losses in the test. The sodium sulphate test rated performance well but was not included in the recommended classification system (Smith et al, 1969).

Deo (1972) and Wood and Deo (1975) used a variation of the test by soaking a single fraction in a 50 per cent saturated solution. This test was included in their classification system for the engineering usage of mudrocks. Chapman (1975) used Deo's modified test and found it to be severe on soft mudrocks but to have little effect on hard rocks.

Reidenouer et al (1974) attempted to predict the behaviour of shales in Pennsylvania by this test but did not find a good correlation between the "durability factor" used and the sodium sulphate soundness results. Farjallat et al (1974) measured the strength deterioration of aggregates by determining Treton impact values during the test and found that the sodium sulphate treatment usually caused a marked decrease in the strength of the aggregates. In an investigation of tests to rate the field performance of ballast, Gaskin and Raymond (1976) came to the conclusion that the magnesium and sodium sulphate soundness tests gave the best relation with the break-down of the material.

The above discussion illustrates the diverse views and findings resulting from studies where these tests have been used. Although some of the comments were negative, the positive ones indicated that the test should be performed on the mudrock samples.

12.9.2 Method

The test method followed was ASTM-C88-73 (1976). Only the test for the coarse aggregate was done as interest centred on the break-down behaviour of mudrocks. Sodium sulphate was used as this is more common than magnesium sulphate in research work. The samples were not washed beforehand but blown clean using compressed air, and dried and cooled just before the first immersion. Specially constructed 2 mm mesh baskets were used as containers for the different fractions (Plate 37). The saturated solution was kept at 21 °C in a temperature-humidity cabinet. After five cycles, each involving the soaking of the material for 16 to 18 hours followed by drying to constant mass at 105 °C, the samples were washed free of sodium sulphate by moving the baskets slowly up and down in a washbasin filled with warm water. The wash water was replaced with clean water four or five times during the washing of each sample.

After drying, the samples were sieved carefully without any vigorous movements as this could easily have led to the further break-down of some of the samples.

The results are given in Table 12.14 and are illustrated graphically in Figure 12.6. No true weighted losses could be calculated as the samples were prepared by breaking up a rock artificially through crushing. To overcome this problem and to be able to assign a single value to each sample

TABLE 12.14: RESULTS OF THE SODIUM SULPHATE SOUNDNESS TESTS

Sample number	Percentage loss for fraction (mm)				Weighted loss %
	63-37,5	37,5-19,0	19,0-9,5	9,5-4,75	
	Sieved through (mm)				
	31,5	16,0	8,0	4,0	
M1	95,5	90,7	60,4	26,6	70,5
M2	19,6	34,6	18,9	7,8	22,2
M3	95,9	91,4	70,4	55,3	79,3
M4	18,0	9,8	9,6	8,6	11,0
M5	15,2	13,6	9,7	9,4	12,0
M6	97,6	94,8	93,8	91,0	94,3
M7	100,0	75,1	56,1	51,2	69,6
M8	8,2	6,7	6,6	4,3	6,5
M9	100,0	100,0	100,0	100,0	100,0
M10	89,3	85,2	86,7	56,3	80,7
M11	89,4	68,6	53,0	39,3	62,2
M12	80,2	76,6	33,8	16,9	53,6
M13	10,6	7,0	7,3	3,0	6,9
M14	98,2	93,7	83,7	85,7	90,2

an ideal grading envelope calculated by using the formula given in Section 7.2, and using 63 mm as the maximum size, was constructed. Percentages for the different fractions read from a grading curve drawn along the centre of this envelope were used to calculate the weighted losses for each sample.

Photographs of the samples were taken before, during and after the tests. Some of these are shown on Plates 37 and 38 to illustrate the different behaviour of samples during the test.

12.9.3 Discussion

The mudrock samples were affected in three ways by the sodium sulphate test:

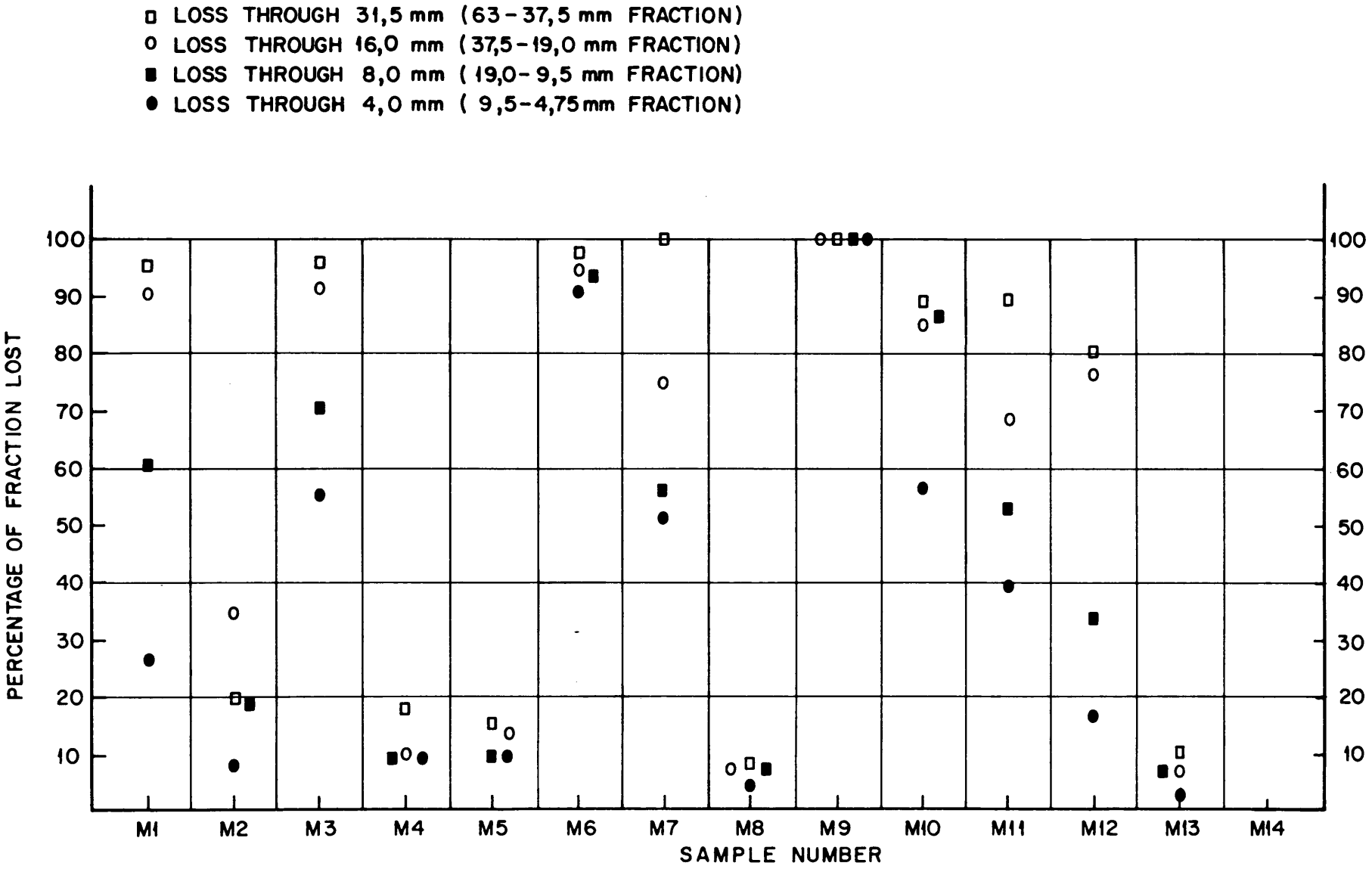
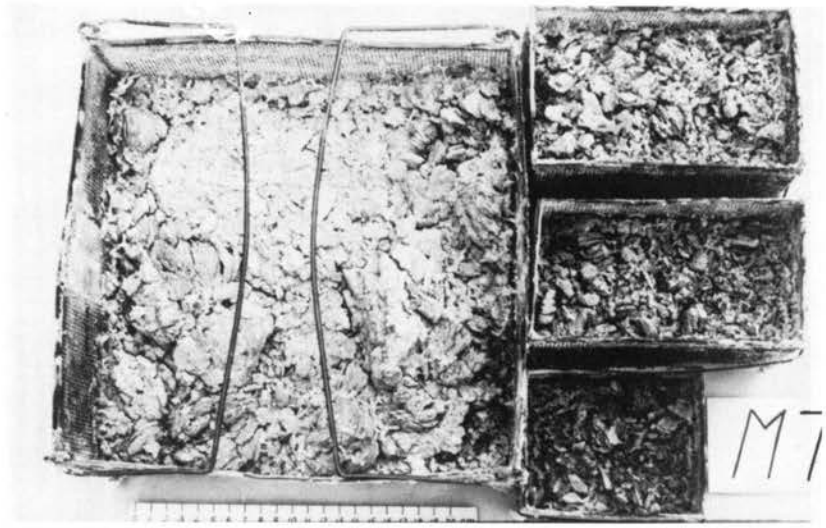


FIGURE 12.6

PERCENTAGE LOSSES FOR VARIOUS FRACTIONS IN THE SODIUM SULPHATE SOUNDNESS TEST

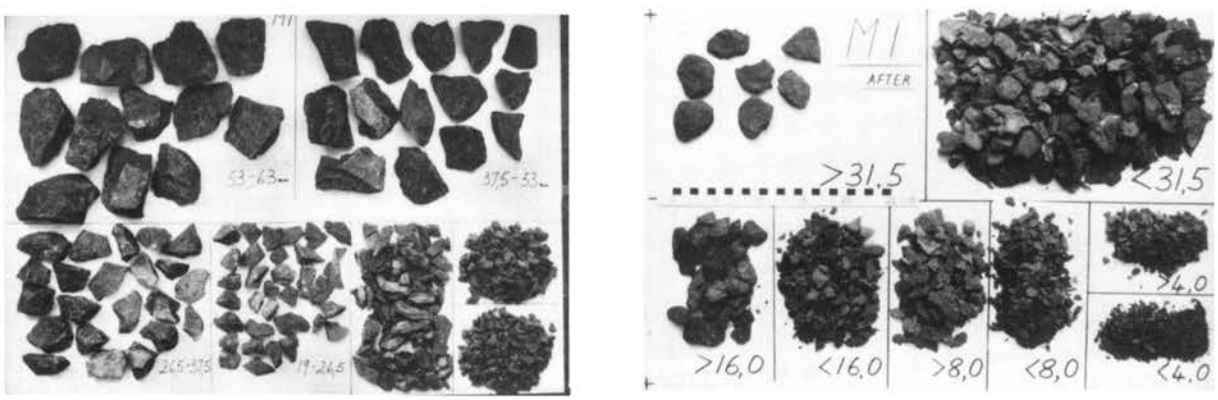
Before test



After test —
covered by salt

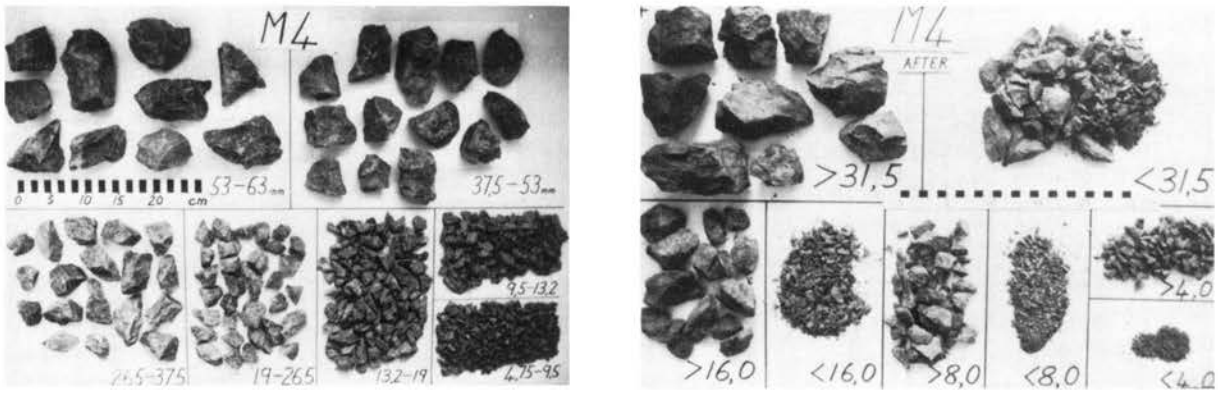
After test —
washed clean of salt
and dried

Plate 37: The behaviour of sample M7 during the sodium sulphate soundness test



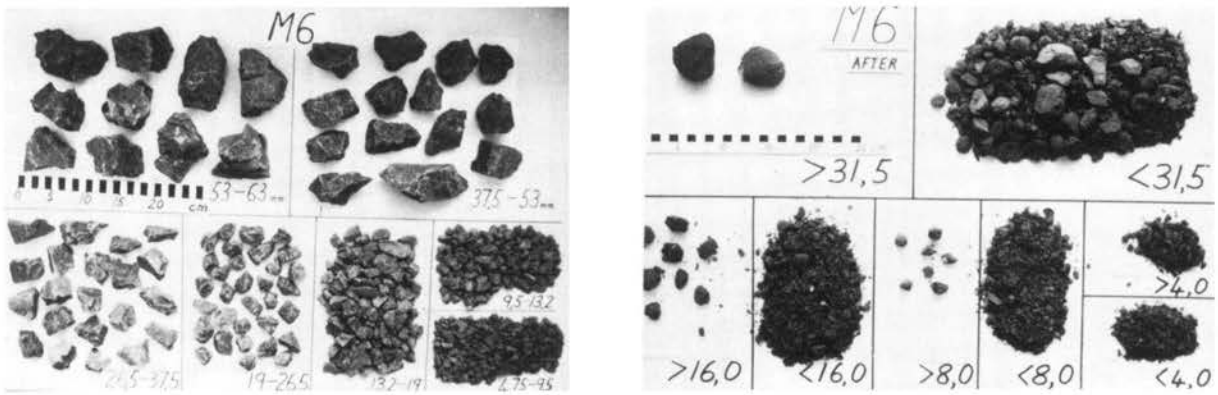
Before After

Sample M1 — disintegrating into flakes



Before After

Sample M4 — minor losses



Before After

Sample M6 — slaking into fine particles

Plate 38: Sodium sulphate soundness test — mudrock fractions before test and sieved after 5 cycles

(a) Some samples were not affected much, with low losses for all the fractions (samples M2, M4, M5, M8 and M13). Samples M2, M8 and M13 were fairly hard rocks but M4 and M5 were weathered Bokkeveld mudstones which were not broken down by this severe test.

(b) Some samples were broken into flakes or plates with resulting high losses in the coarse fractions and lower losses for the finer fractions (samples M1, M3, M7, M10, M11 and M12). These rocks tended to break down to a certain size and did not disintegrate further.

(c) Some samples broke down completely to form a mud (M6, M9 and M14). These samples suffered very high losses for all the fractions and M9 lost almost all the material halfway through the test.

12.10 Accelerated weathering using and comparing water, calgon and sodium sulphate

12.10.1 Introduction

Accelerated weathering by soaking the samples in water, drying in an oven afterwards and repeating this for a number of cycles has been done in many studies. No widely known standard test method exists, however, and this is unfortunate, as such a test resembles exposure of the rock material to the atmosphere and should not require any special apparatus.

Philbrick (1950) proposed wetting and drying a mudrock five times in water or ammonium oxalate to distinguish between "compacted" and "cemented" varieties. If the rock breaks into small grains, it is "compacted" and if it is unaffected or reduced to flakes, it is "cemented". Drew and Woods (1970) used ten wet-dry cycles on a 19 to 9,5 mm fraction followed by sieving through 4,75 mm to expose granites containing an expansive clay mineral. They recommended that the test be included in a specification. Croft (1966) attempted to correlate the results from a wet-dry test and the behaviour of mudrocks in a pavement in Australia but found a test using tumbling in water more effective for distinguishing mudrocks susceptible to weathering.

Smith et al (1967) studied classification tests for different kinds of rock slope protection material in California. A 15 cycle wet-dry test using water and sea water, a fraction graded between 63 and 50 mm and

sieving afterwards through 9,5 mm was carried out. This was followed by wet-dry tests using other fractions and evaluating the break-down with sieves having openings of half the minimum size of the fraction. The tests were found to lack severity and a quantitative test could not be developed. Reidenouer (1970) and Reidenouer et al (1974) used the results from a ten-cycle wet-dry test in a "durability factor" for their work on shales in Pennsylvania and compared all the other test results with this factor. Currie et al (1974) investigated the roadbuilding properties of a siltstone which behaved similarly to some of the disintegrating Karoo mudrocks. The samples were dried at 70 °C during the day and soaked in water at night without cooling down before immersion. The rapid disintegration of the rock was attributed to a thermal shock mechanism. Farjallat et al (1974) drew up curves of the weakening of some basalts and gneisses from dam sites in Brazil during certain "weathering" tests. Wetting and drying in water were found to have less effect than other tests, such as a sodium sulphate soundness test.

Guidelines for describing the behaviour of mudrocks after immersion in water were given by Deo (1972), Wood and Deo (1975) and Heley and MacIver (1971).

In the study of the wetting and drying of mudrocks it was decided to try to develop a fairly quick and simple classification test for mudrock for which no special equipment would be needed. It was, furthermore, decided to compare different wetting agents.

12.10.2 Wetting agents used

Water, calgon and sodium sulphate were chosen as wetting agents, the first being an obvious choice.

Calgon, which is made up by dissolving 35,70 g sodiumhexametaphosphate $\{(NaPO_3)_6\}$ and 7,94 g sodiumcarbonate (Na_2CO_3) in 1 ℓ of distilled water, seems to be the most widely used dispersing agent. Similar agents have been used by other authors to assist in the disaggregation of mudrocks. Philbrick (1950) suggested ammonium-oxalate for his five cycle classification test. Gipson (1963) used a solution of sodium-oxalate to assist in the breaking up of mudrocks before ultrasonic treatment while Savage (1969) used sodiumhexametaphosphate for the same purpose.

Sodium sulphate was chosen as it is important to compare its effect

with that of water and determine the feasibility of doing a short simple test to replace the laborious ASTM test.

12.10.3 Method

Eighteen lumps of mudrock graded between 37,5 and 26,5 mm were prepared for each sample and six were put into each basket. The baskets were made of stiff brass wire 2 mm mesh (Plate 39). Their dimensions were 140 x 100 mm with a height of 20 mm. This allowed enough space for the lumps to be arranged in two rows of three without touching one another. By doing this, it was possible to inspect all the lumps during the wetting and drying cycles without touching or moving them.

All the samples were dried at 105 °C and allowed to cool for an hour before weighing. Each of the three sets of samples was then immersed into one of the three agents, i.e. water, calgon and a saturated sodium sulphate solution, for a period of 16 to 18 hours (overnight). They were then removed and dried at 105 °C to constant mass. During the cycles the samples were always allowed 30 minutes' cooling time before re-immersion. The wetting and drying process was repeated five times after which the sodium sulphate and calgon-treated samples were washed clean of salts by moving the baskets up and down in a basin of water at a temperature of about 40 °C. The water was replaced four times with clean water and the water in which the sodium sulphate-treated samples had been washed, was tested with barium chloride to ensure the removal of all the sulphate. Most of the minus 2,0 mm material was washed away during the cleaning process. After drying at 105 °C, the samples were sieved through 13,2; 4,75 and 2,0 mm sieves. Vigorous sieving was avoided in order to prevent some of the fragile pieces from breaking down. The results are given in Table 12.17.

12.10.4 Description of break-down

The standardization of a description of break-down of mudrocks during immersion in water is important. Heley and MacIver (1971) suggested that three factors should be noted to describe the behaviour in water. They are:

(a) The volume of material which has become completely disaggregated.

(b) The rate at which the breaking down occurs.

(c) The size and shape of the pieces that were not disaggregated.

They then give standard descriptors for the above-mentioned effects. Unfortunately the descriptors are for "clay shales" and for only one cycle of immersion in water. The system was therefore modified and tried on the mudrocks. It was, however, not very successful as the rigid system could not really describe the wide variation in behaviour of the mudrocks tested. The system is more applicable to mudrocks which break down or start to break down within the first immersion. The third factor, i.e. the nature of the sample after the immersion, was, however, found to be very useful for descriptive purposes. This was slightly modified as follows:

No change - the material remains intact
Plates - the material is broken into plates of essentially uniform thickness
Flakes - the material is broken into flaky or wedge-shaped fragments
Chunks - the material is broken into large fragments (>3 mm)
Grains - the material is broken down to grains (approximately silt size to 3 mm)
Silt or clay - the material is broken down to almost particle size.

Detailed notes were kept during and after the first cycle and subsequently after the oven-drying stage of each cycle. The following aspects were found to be useful in describing the behaviour of the samples.

(i) Nature of crack - open or closed, wide or narrow. With the two salt solutions the salt lines after drying usually accentuated any cracks as the salt crystallized in the cracks during drying. This made minute cracks, which would probably not be visible on the samples immersed in water, quite conspicuous.

(ii) Orientation of cracks with respect to bedding.

(iii) Frequency of cracks

(iv) Nature of break-down into plates, flakes, chunks, grains, or silt and clay. (Using modified descriptors of Heley and MacIver (1971)).

(v) Description of the surfaces of samples - some resistant samples lose only some flakes from the surface or the surface becomes slightly flaky.

The behaviour of all the samples tested, except M7 and M9 and possibly M6 and M14, could quite adequately be described by investigating the samples after the drying stage of each cycle. The summarized descriptions after the first and fifth cycles are given in Tables 12.15 and 12.16. A visual comparison of the relative amount of break-down in the three agents is also given. The amount of break-down in the sodium sulphate solution was more difficult to assess because of the presence of a large amount of salt after drying.

With sample M7, cracks parallel to the bedding started forming within two minutes of immersion and after 40 minutes all the lumps were severely cracked parallel to and across the bedding. No lumps could be picked up without disintegrating into flakes. All the wetting agents affected the lumps to the same extent. Sample M9 started slaking within one minute of immersion and after 40 minutes all the lumps had wide cracks and had lost some completely slaked material. Water seemed to affect the lumps slightly more severely than calgon or sodium sulphate during these initial stages.

Sample M14, a weathered sample, was not affected much by any of the three agents during the first cycle but after the second immersion the lumps in sodium sulphate started slaking to silt and clay while the lumps in water and calgon still only showed a number of open cracks. Sample M6 behaved similarly in the sodium sulphate solution but only really fell apart into small flakes during the third immersion, although it broke down during the second.

12.10.5 Discussion

Visual observation

From visual observations it seemed that most of the samples, except M6 and M14, were affected in a similar way by all the wetting agents, but that the sodium sulphate treatment was more severe. The effect of the calgon seemed equal or often slightly more severe than that of water. The surfaces of samples M4 and M5 became flaky with the lumps remaining intact, whereas some cracks occurred in the hard samples (M2, M8 and M13). Samples M1, M7, M9, M10 and M12 disintegrated into plates, flakes, silt or clay.

As mentioned in Section 12.10.4 samples M6 and M14 reacted differently in that they were relatively unaffected by water and calgon but broke down

TABLE 12.15: COMPARISON OF THE BREAKING DOWN OF MUDROCKS IN DIFFERENT WETTING AGENTS AFTER THE 1st CYCLE

Sample number	After 1st cycle			
	Water	Calgon	Sodium sulphate	Comparison*
M1	No cracks	Narrow salt line cracks visible on some - one open crack	Salt line cracks on all - no open cracks - cracks parallel to bedding	N>C>H
M2	No cracks	No cracks	Random salt line cracks visible on lumps	N>C = H
M4	No cracks	No cracks	No cracks	Equal
M5	No cracks	No cracks	No cracks	Equal
M6	Random narrow open surficial cracks on two lumps	Random narrow cracks on two lumps	Narrow cracks on all the lumps	Probably equal
M7	Cracked into flakes - strong cracking parallel to bedding	Same as in water	Same as in water	Equal
M8	One narrow crack in one lump	One narrow crack	Narrow salt line cracks present	N>C = H
M9	Broken into rounded flaky pieces - lumps still visible	Broken into irregular fragments	Similar to calgon	H>C = N
M10	Cracked into flakes parallel to bedding - some cracks open	Same as in water	Same as in water but more cracks visible due to salt lines	Equal
M12	Cracks parallel to bedding visible	Cracks parallel to bedding visible on some lumps	Cracks parallel to bedding	H>C = N
M13	No cracking	One salt line crack on one lump	Some narrow salt line cracks visible	Equal
M14	Two open cracks parallel to bedding and some narrow open cracks	One or two narrow open cracks on each lump	Two narrow cracks on one lump	Equal or C>H = N

* H = Water C = Calgon N = Sodium sulphate

TABLE 12.16: COMPARISON OF THE BREAKING DOWN OF MUDROCKS IN DIFFERENT WETTING AGENTS AFTER THE 5th CYCLE

Sample number	After 5th cycle			
	Water	Calgon	Sodium sulphate	Comparison*
M1	Narrow cracks parallel to bedding on all lumps - all lumps fairly intact	Cracks parallel to bedding - some are open	Lots of cracks parallel to bedding - one lump falling apart - cracks are open	N>C>H
M2	No cracks	No cracks	Random cracking - two lumps falling apart - salt lines on four lumps - two lumps unaffected	N>C = H
M4	No cracks	No cracks	Surfaces flaky - flakes came off and some deeper cracks are present	N>C = H
M5	No cracks	No cracks	Surface affected - flakes coming off - some open cracks parallel to bedding	N>C = H
M6	All lumps exhibit narrow random cracks - one or two lumps are falling apart on the outside	Some lumps exhibit narrow cracks and some fragments fell off - three pieces are almost unaffected	Lumps completely disintegrated into fine flakes	N>>H>C
M7	Sample completely disintegrated into flakes	Same as water	Sample completely disintegrated into smaller flakes	N>C = H
M8	One crack on one lump	Open cracks on two lumps - other lumps almost unaffected	One or two salt lines on all lumps - two lumps exhibit open cracks	N>C>H
M9	Broken to silt and small flakes	Broken to flakes and slightly larger pieces	All material lost through basket after second cycle	N>>C>H
M10	All lumps broken down to flakes - some lumps falling apart	Same as water	Same as water but broken into smaller flakes and pushed apart by salt	N>C>H
M12	Five or so parallel cracks in each lump - lumps fall apart into flakes when picked up	Same as water	Same as water but more cracks and the plates are separated by open cracks	N>C = H
M13	One narrow crack on one lump	Narrow random cracks on two or three lumps - one crack slightly open	Random salt lines on all lumps - three lumps exhibit only one line each - angular fragments broke off three lumps	N>C>H
M14	About four cracks parallel to bedding on all lumps - three lumps broken along some of these cracks	Same as water but five lumps are broken along cracks	Sample completely disintegrated into thin flakes and silt or clay - a mass of slaked material	N>>C = H

* H = water C = Calgon N = Sodium sulphate

completely during the second and third cycles in the sodium sulphate solution. The reason for this may be that these more absorptive samples absorb dissolved salt into all the pores and thus allow the sodium sulphate to penetrate uniformly throughout the lump. When the salt hydrates during the second soaking, the whole lump falls apart. In the other samples penetration presumably takes place preferentially along planes of weakness and once these are broken apart, further rapid disintegration does not take place.

Plates 39 and 40 illustrate the effects of the different wetting agents on the mudrock samples.

Sieve analyses

Table 12.17 gives the results of the sieve analyses while Figures 12.7 to 12.9 graphically compare the percentage losses through the sieves after treatment in the three wetting agents.

Losses through 13,2 mm (Figure 12.7)

Wet-dry cycles, using the sodium sulphate solution, generally broke down the samples more than cycles in the other agents. For samples M6 and M14 the effects of sodium sulphate were drastically more severe than those of calgon and water, while for others, such as M1 and M12, break-down was significantly more severe. Losses after wetting and drying in calgon and water were similar, with the effects of calgon slightly more severe than those of water. Sample M6 reacted anomalously. It broke down more in water than in calgon while in a sodium sulphate solution it broke down completely.

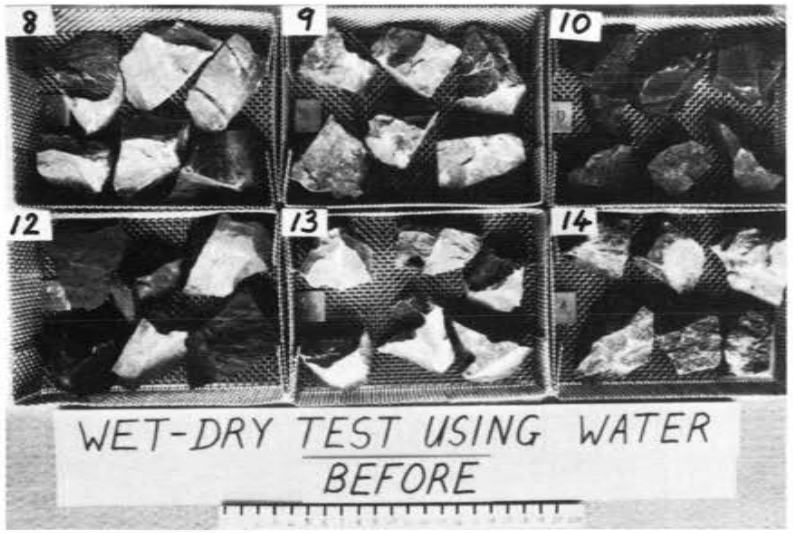
Losses through 4,75 mm (Figure 12.8)

Samples M6 and M14 were broken into fine particles in the sodium sulphate solution. Samples M1, M4, M5 and M10 showed much higher break-down when treated with this solution. Calgon affected M7 less and M10 more than water.

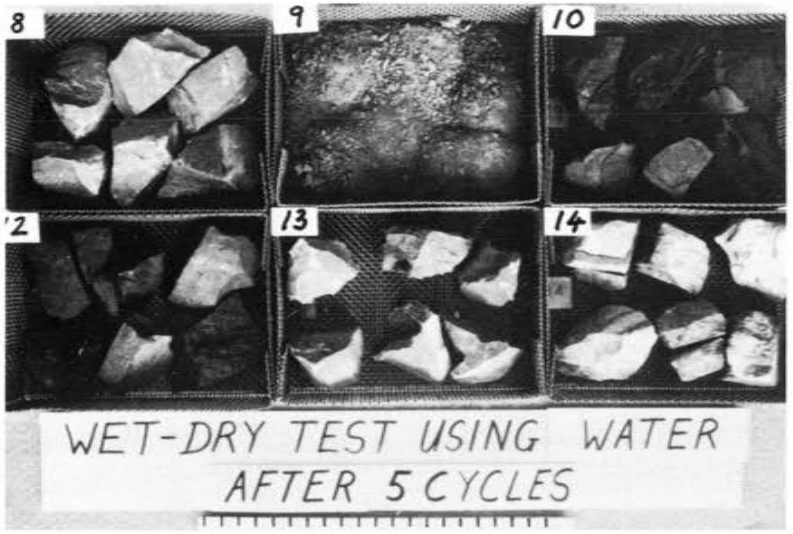
Losses through 2,0 mm (Figure 12.9)

Losses through 2,0 mm increased drastically with sodium sulphate solution treatment for samples M6, M7 and M14. Most of the other samples also exhibited larger losses due to this agent. Exceptions were sample M9, which suffered very high losses with all the treatments and M2, M8 and M13 which exhibited negligible losses with all the treatments.

Plate 39: Comparison of the effects of various wetting agents on some of the samples



Some samples before test



Same samples after 5 wet-dry cycles

Plate 40: Behaviour of samples during the accelerated weathering test when using water

TABLE 12.17: RESULTS OF SIEVE ANALYSES AFTER FIVE WET-DRY CYCLES IN WATER, CALGON AND SODIUM SULPHATE

Sample number	Water			Calgon			Sodium sulphate		
	Cumulative percentage passing			Cumulative percentage passing			Cumulative percentage passing		
	13,2 mm	4,75 mm	2,0 mm	13,2 mm	4,75 mm	2,0 mm	13,2 mm	4,75 mm	2,0 mm
M1	0,1	0,1	0,1	7,6	0,6	0,3	38,5	7,0	1,7
M2	0	0	0	1,3	0,3	0,2	10,7	1,0	0,4
M4	0,1	0,1	0,1	0,1	0,1	0	11,7	6,5	4,7
M5	0,1	0,1	0,1	0	0	0	11,5	6,7	5,0
M6	29,8	1,7	0,5	2,8	0,4	0,3	98,7	92,3	87,6
M7	97,6	72,4	14,3	92,8	59,2	13,8	100	86,9	72,7
M8	0	0	0	0,2	0	0	4,9	1,2	0,4
M9	100	100	98,0	100	100	100	100	100	100
M10	68,2	13,2	1,7	76,5	21,5	5,7	82,4	38,8	17,7
M12	8,5	1,7	0,2	10,9	1,4	0,2	49,1	9,2	4,2
M13	0	0	0	8,2	0,3	0,2	6,4	1,1	0,3
M14	0,3	0,3	0,3	2,1	1,8	1,7	97,3	90,3	85,3

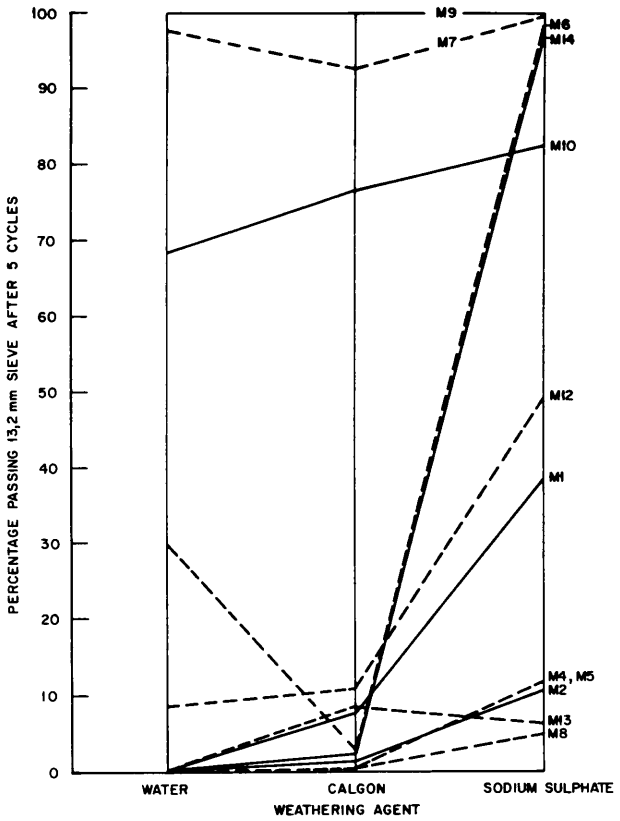


FIGURE 12.7
COMPARISON OF WEATHERING AGENTS (SIEVING THROUGH 13,2 mm)

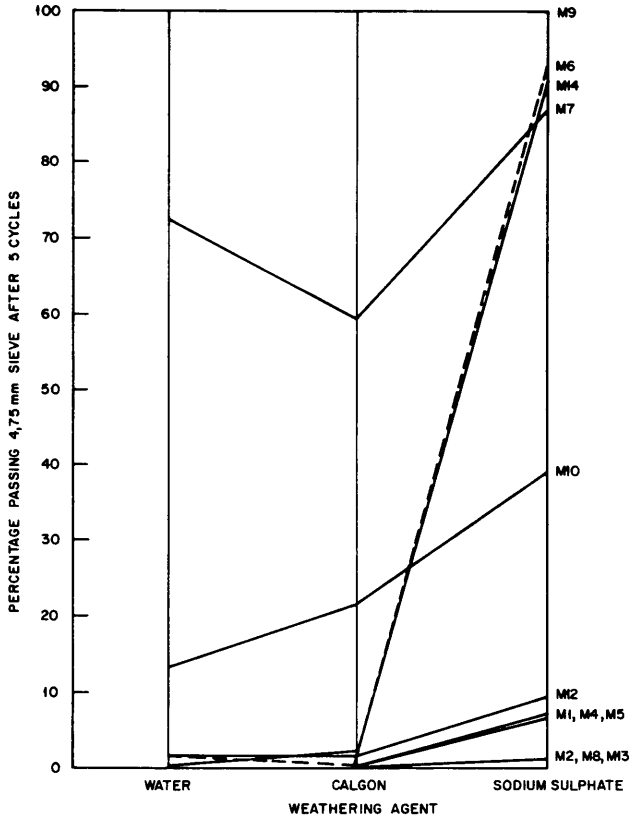


FIGURE 12.8
COMPARISON OF WEATHERING AGENTS (SIEVING THROUGH 4,75 mm)

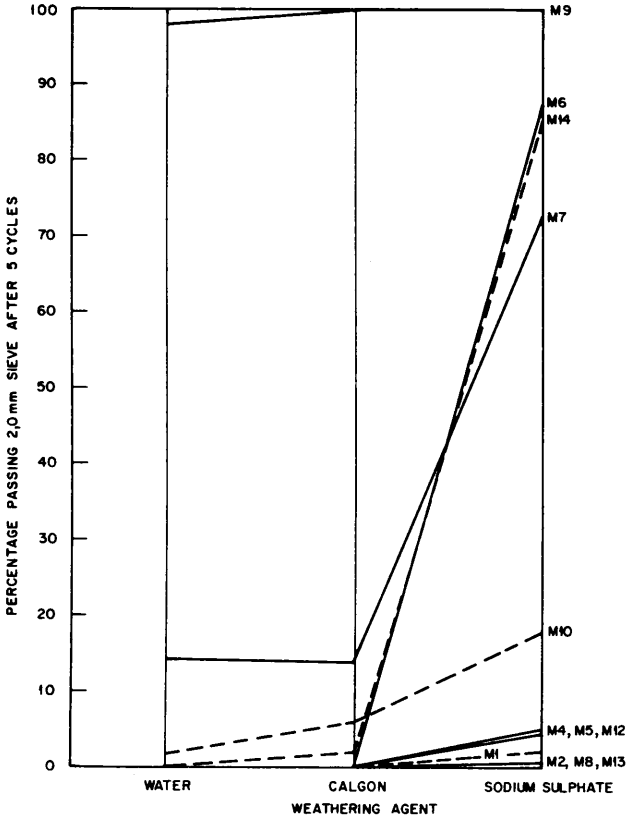


FIGURE 12.9
COMPARISON OF WEATHERING AGENTS (SIEVING THROUGH 2,0 mm)

12.10.6 Conclusions

(a) It is not necessary to use calgon as a "weathering" agent as its effect is very similar to that of water.

(b) Sodium sulphate is the most effective agent to accelerate break-down of mudrocks. It speeds up the process compared to the other two agents, and provides more visual proof of disintegration. While the other agents sometimes cause cracks which are difficult to detect, the sodium sulphate crystals force the lumps apart along these cracks. Samples M6 and M14 were, however, affected in an unusual way by the sodium sulphate and this casts doubt on the use of this solution in a general test. Three cycles using a sodium sulphate solution can, however, give a good indication of the long-term behaviour of disintegrating mudrocks.

(c) Losses through 13,2 and 2,0 mm should be used for evaluating the break-down of mudrocks. The larger diameter shows up the disintegration into larger flakes, plates and wedges, while the smaller diameter exposes slaking of mudrocks into the constituent or small particles.

(d) The wet-dry test using water, should be tried for classifying the break-down of mudrocks. The break-down should be described as in Tables 12.15 and 12.16 and quantitative work should be done by sieving through 13,2 and 2,0 mm. The repeatability of the test may present problems, but as a simple test for determining disintegration there is no other method at present to improve on it.

12.11 Ethylene glycol test

The standard ethylene glycol test described in the "Handbook for concrete and cement" (U S Army Engineers Waterways Experiment Station, 1969) involves the soaking of rock fragments in ethylene glycol for a period of 15 days, describing the break-down during the period of soaking, and evaluating break-down at the end by sieving. This test was done by Chapman (1975) in the study of classification systems for mudrock and found to be less severe than a similar water soaking test. Saltzman (1975) tried the test for predicting the performance of rock in protective blankets and found it unacceptable for determining the durability of rock. Reidenouer (1970)

and Reidenouer et al (1974) proposed the use of a similar test for classifying shales after an extensive study in Pennsylvania. They used 3,2 - 4,5 kg (7 - 10 lb) of rock graded between 76 and 19 mm (3 to 3/4 inch) and soaked it in ethylene glycol for 40 hours. The fragments were then inspected for cracking and splitting and also sieved through a 19 mm sieve. If more than three of the 50 to 70 fragments were cracked the material was rejected for use in road construction.

Farjallat et al (1974), working on basalts and gneisses, found that wet-dry cycles in ethylene glycol often weakened the samples drastically. Miles (1972) carried out accelerated soundness tests using different chemicals, including ethylene glycol, but found their relation to field performance poorer than that of standard tests such as sodium sulphate soundness, Los Angeles abrasion and water absorption.

Some small scale experiments of soaking mudrock samples in ethylene glycol indicated very little reaction and it was, therefore, decided to investigate the effect of ethylene glycol soaking on mudrocks using less material than in the standard test.

The mudrock samples were crushed to obtain six lumps of each, graded between 37,5 and 26,5 mm. These lumps were dried at 105 °C and cooled for half an hour after which they were inspected to ensure that no cracks were present. They were then put into 130 mm diameter crystallizing dishes and ethylene glycol was poured in to cover all the lumps. After 48 hours all the lumps were inspected for cracks. Examples of some of the samples before and after the soaking are shown on Plate 41.

Samples M1, M2, M4, M5, M6, M8, M12 and M14 exhibited no cracks on any of the lumps, although M14 lost some small flakes. Samples M7, M9 and M10 showed some change. M7 and M10 were cracked in random directions. The overall effect of the ethylene glycol on the samples was less than that of water (see Section 12.10).

It is therefore considered that the ethylene glycol test is not suitable for testing South African mudrocks. The effect of the soaking was so small that sieving was not carried out afterwards. More break-down would result from the use of water. The reason for the limited effect is probably due to the fact that limited amounts of highly expansive clays are present in the mudrock samples (Section 6.4). Ethylene glycol is very effective in expanding these clays.

12.12 Ultrasonic disaggregation

12.12.1 Introduction

The application of an ultrasonic field to a liquid causes the formation of bubbles which burst against solid particles in the liquid with tremendous force. The phenomenon is called cavitation and it has been used to disaggregate rock fragments. Tank-type sonifiers, where the field is generated by the walls of the tank, and probe-type sonifiers, where the field is generated by a probe immersed in the liquid, are used for disaggregation.

The process has been used to disaggregate mudrocks and sandstones for particle size analyses and for durability studies of various types of rock. Gipson (1963) and Savage (1969) described its use for the former purpose after soaking crushed material in dispersive agents for different periods. Laguros (1972) proposed an ultrasonic test to classify mudrocks for highway utilization. He found that the test disaggregated mudrocks effectively and that the optimum time of treatment was one hour. Laguros et al (1974) compared the field weathering of mudrocks with the effects of ultrasonic cavitation. They subjected material crushed to minus 2 mm to these processes and found that they simulated field weathering. One hour of ultrasonic treatment corresponded to two years of field weathering and the test was considered to be a good test for predicting the durability and weatherability of mudrocks. Laguros (1972) and Laguros et al (1974) preferred the use of the tank-type sonifier while Reidenouer et al (1974) and Saltzman (1975) preferred the probe-type. Reidenouer et al (1974) studied classification tests for shales for use in roads and found the ultrasonic test to be the best test for predicting durability. In their test method they subjected 30 g of 4,75 to 2,0 mm material to six hours of treatment with an ultrasonic probe and then evaluated the break-down by sieving through a 0,075 mm sieve. Saltzman (1975) developed a test whereby a small piece of core, mounted in a special holder on the tip of the probe, was subjected to ten minutes of cavitation. Various types of rock were investigated for their durability as rock slope protection material and this test was found to be the closest to an objective engineering test. Values of acceptability for the ultrasonic and other tests were given.

These studies clearly demonstrated that the ultrasonic method has strong possibilities for the classification of mudrocks.

12.12.2 Method

No standard method exists. Saltzman's method was considered somewhat cumbersome for general testing while Reidenouer's method required a very long testing period. A method similar to that of Reidenouer, but using only 20 minutes disaggregation time was therefore developed.

Samples were crushed to obtain 20 g of sample graded between 4,75 and 2,0 mm. This was dried at 105 °C to constant mass. After cooling, the sample was put in a graduated 400 mℓ beaker. The tip of the probe was lowered to the 100 mℓ mark and distilled water added to fill the beaker up to the 150 mℓ mark. This brought the tip 14 mm below the surface of the water. The probe was switched on for exactly five minutes after which the aggregate was washed over a 2 mm sieve. The plus 2 mm material was transferred back to the beaker and the whole process repeated four times. The sonifier used was from the Branson Sonic Power Company, a Model B30 and had a 19 mm diameter tip. The output control was set at 7. During the five minute treatment periods the temperature of the water rose from the ambient temperature (20 - 25 °C) to 70 °C. The apparatus used is shown on Plate 42.

Following the ultrasonic disaggregation, the minus 0,075 mm material was washed through a sieve into large dishes. These were dried at 80 to 90 °C in an oven to determine the mass and percentage minus 0,075 mm material. The plus 0,075 mm material was dried and sieved through 0,850 and 2,0 mm sieves. The results are given in Table 12.18.

12.12.3 Discussion

The test method worked well and gave a wide spread of values. The method should, however, be changed slightly for future tests. While it is necessary to change the water after five minutes cavitation because of the high temperatures it is not necessary to wash out all the minus 2,0 mm material. The washing presented problems as the grains tended to stick to the sieve. In future tests, only the water and the fines suspended in it should be poured off after each five minutes' cavitation time.

Cumulative percentage losses through the three sieves for all the samples are plotted in Figure 12.10. As the losses through the sieves are proportionate it is quite adequate to measure loss through only one sieve. Loss through 2,0 mm is the easiest to determine and should therefore be chosen.

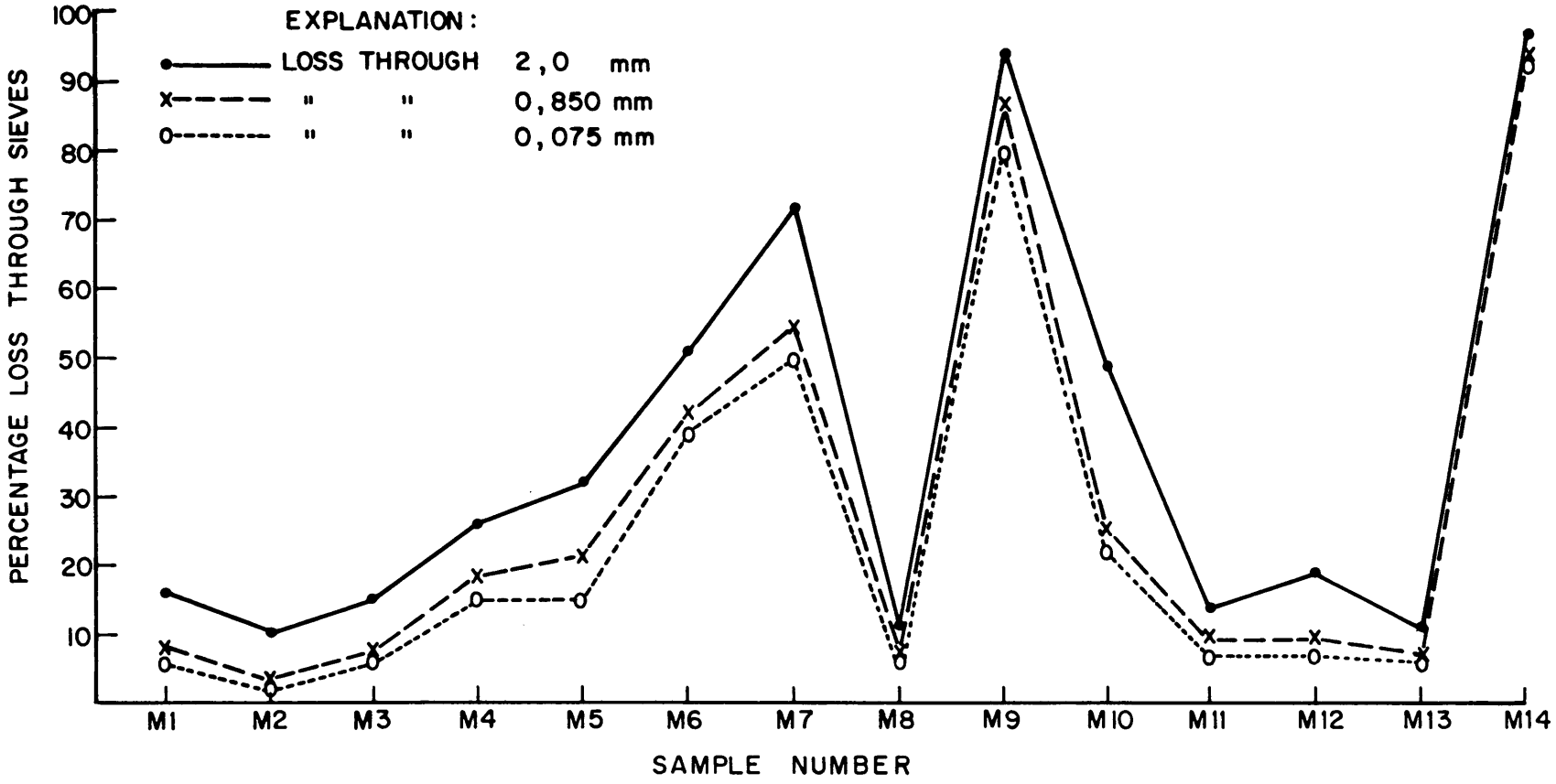


FIGURE 12.10

PERCENTAGE LOSS THROUGH VARIOUS SIEVES AFTER ULTRASONIC TREATMENT.

TABLE 12.18: RESULTS OF SIEVE ANALYSES AFTER ULTRASONIC DISAGGREGATION

Sample number	Cumulative percentage passing		
	2,0 mm	0,850 mm	0,075 mm
M1	15,9	7,4	5,8
M2	9,9	3,0	1,7
M3	14,7	7,0	5,6
M4	26,0	18,2	14,7
M5	31,9	21,1	15,1
M6	51,0	42,2	38,8
M7	72,2	53,6	50,3
M8	10,7	7,2	5,9
M9	93,8	78,2	80,1
M10	49,1	25,4	22,3
M11	14,1	9,4	7,3
M12	18,6	9,4	7,1
M13	11,0	6,9	5,9
M14	97,4	94,0	93,0

12.13 Sand equivalent test

The sand equivalent test was developed by Hveem (1953) to detect and indicate the presence of detrimental clay material in road building materials. It was used by Erikson (1958) to test the quality of the fines generated by compaction and Los Angeles abrasion. Platts and Lloyd (1966) used it for the same purpose on the fines of various gravels and rocks generated by different abrasion and degradation tests, such as the Washington degradation test. Laguros (1972) carried out a study on certain types of mudrock and concluded that the sand equivalent test is an important test for classifying these materials. A clay reading of 254 mm or higher was considered to indicate poor highway construction material.

Test method B19 (Department of Transport, 1971) was used and the test was performed on minus 4,75 mm material sieved from samples crushed in a jaw crusher. The method involves the shaking up of the material in a solution containing calcium chloride in a sand equivalent cylinder. The

material is allowed to settle and the levels of clay and sand are read after 20 minutes. The sand equivalent value is the sand/clay ratio expressed as a percentage. The effect of the calcium chloride solution is flocculation of the clay particles. According to Hveem (1953) the detrimental clay particles are flocculated more than less detrimental particles and higher clay readings are, therefore, obtained for the former.

The tests were done in duplicate and the results are summarized in Table 12.19. Sand and clay readings in inches were converted to millimeters. Problems were experienced in "irrigating" the samples, i.e. washing the coarse material during the addition of water. Half the specified volume of crushed material was therefore used.

A wide range of values was obtained. Unfortunately it is not known how the use of half the standard sample influenced the results and the results cannot, therefore, be compared with specifications.

TABLE 12.19: RESULTS OF SAND EQUIVALENT TESTS

Sample number	Clay reading mm	Sand reading mm	Sand equivalent value
M1	54,6	50,8	93
M2	61,6	53,3	87
M4	81,3	44,5	55
M5	63,5	39,7	63
M6	87,0	45,7	53
M7	85,1	39,7	47
M8	50,8	49,6	98
M9	90,2	32,1	36
M10	68,6	47,0	69
M12	57,2	43,2	76
M13	45,7	45,7	100
M14	99,8	30,5	31
% accuracy (80 % C.I.)	11,9	7,0	6,6

12.14 Methylene blue adsorption

12.14.1 Introduction

The methylene blue adsorption test has been used in Australia to measure the clay content of rocks (Croft, 1966; Webber, 1972). The method is based on the cation exchange capacity of the rock.

Croft (1966) found that mineralogy provided an insight into the nature of mudrocks but as these investigations were time-consuming, he tried methylene blue adsorption to determine whether this could serve as an index of composition. The test was found to reflect composition adequately but was not as useful an indicator as total clay content. In could, however, be used in predictions in combination with aggregate impact or ball mill tests. A methylene blue adsorption value (MBA value) of 5,0 was found to be suitable for distinguishing indurated and kaolinitic mudrocks from weathered indurated varieties and materials containing expansive clay minerals. Materials giving values above 11,0 should be rejected. Webber (1972) also investigated the methylene blue adsorption test. It was used to obtain a measure of the clay content by calculating the ratio of the MBA values of the rock sample and the clay size fraction. The estimation was not found to be very helpful and he preferred to use the MBA value (like Croft, 1966). An adsorption value of 2 milli-equivalents per 100 g indicated the boundary between fresh and weathered andesite and basalt.

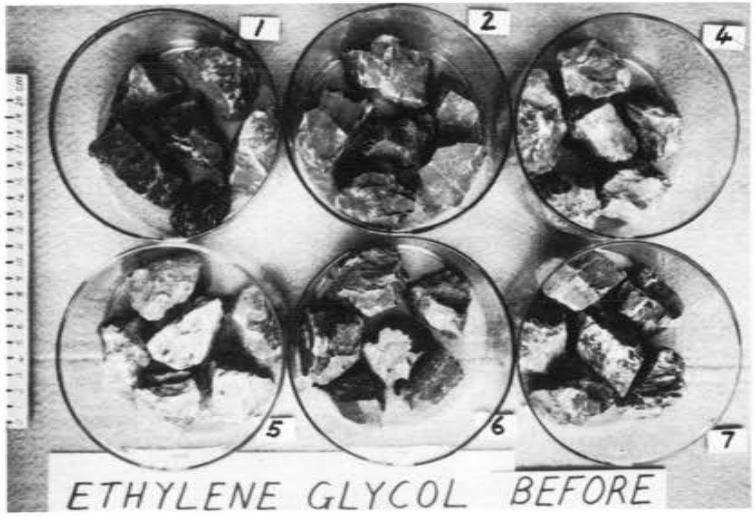
12.14.2 Method

Both Croft (1966) and Webber (1972), whose test method was applied here, used methods suggested by Professor Loughnan of the University of New South Wales. Minus 200 mesh (0,074 mm) instead of minus 350 mesh (0,044 mm) material was used and only the whole rock MBA value was determined. One gram of the ground material is shaken up with a 0,1 per cent solution of methylene blue powder (1 g Methylenblau B, Merck Art. 1283 in 1 ℓ distilled water was used) and allowed to stand for three days. The solutions were diluted and the optical density determined with a Pye Unicam SP8-100 ultraviolet spectrophotometer. An average optical density of 1,71 was obtained for the blanks. Webber (1972) gives a value of 1,68 optical density for a blank and

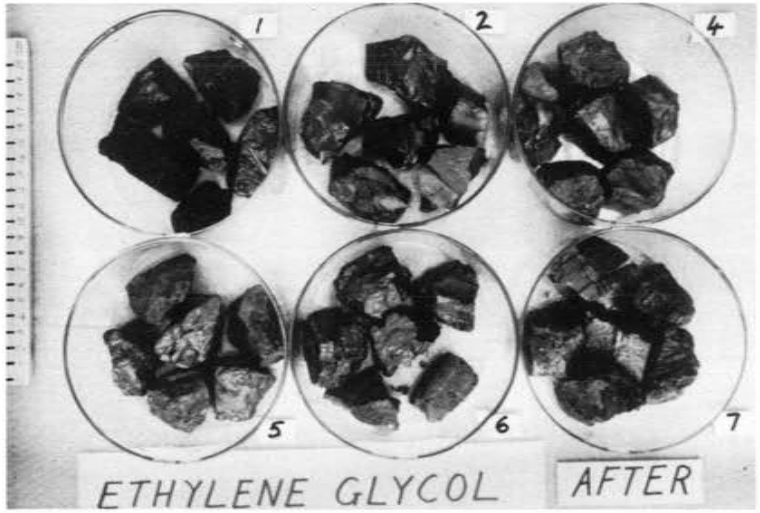
as this was sufficiently close, his table was used to read off the milligrams of methylene blue adsorbed by each sample. Samples of montmorillonite, kaolinite, and illite were tested in addition to the 14 mudrock samples to determine how the type of clay mineral influenced adsorption. Plate 43 shows some of the containers with the solutions and diluted solutions. The results are given in Table 12.20.

TABLE 12.20: RESULTS OF METHYLENE BLUE ADSORPTION TESTS

Sample number	Optical density	mg of methylene blue adsorbed
Blank 1A	1,80	-
Blank 1B	1,69	-
Blank 2A	1,69	-
Blank 2B	1,65	-
M1	1,35	11,5
M2	1,44	8,6
M3	1,08	19,3
M4	1,47	7,6
M5	1,56	4,4
M6	0,80	27,3
M7	0,57	33,9
M8	1,53	5,5
M9	0,43	37,9
M10	0,32	41,0
M11	1,26	14,2
M12	1,01	20,2
M13	1,51	6,2
M14	1,55	4,8
Illite	0,08	47,9
Montmorillonite	0,02	49,5
Kaolinite	1,33	12,1



Before



After 48 hours immersion

Plate 41: Behaviour of some mudrock samples during soaking in ethylene glycol

Plate 42: Ultrasonic disaggregation apparatus

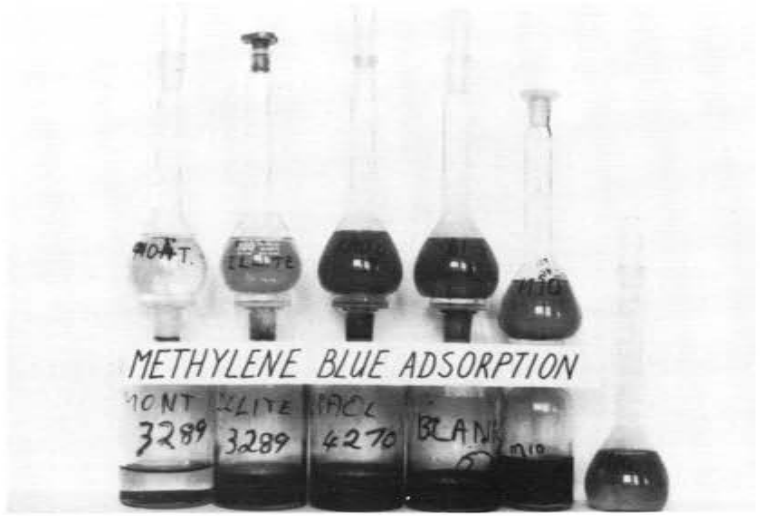


Plate 43: Examples of solutions during the methylene blue adsorption test

12.14.3 Discussion

The illite and especially montmorillonite samples were highly adsorptive while the kaolinite sample adsorbed less methylene blue than seven of the mudrock samples did. This clearly showed the influence of the clay mineral type. With respect to the mudrock samples, the hard rocks such as M2, M8 and M13 gave low adsorptions but M4, M5 and M14, which are softer rocks and weathered to various degrees, also gave low values. This can be attributed to the effect of the type of clay mineral present. It does not seem, therefore, as if the test can be used to rate mudrocks. Further experiments may, however, show it to be quite valuable in indicating the type of clay minerals present in mudrocks.

12.15 Bulk and apparent specific gravities and absorption

Bulk and apparent specific gravities and absorption are basic rock material properties and are normally determined when road building materials are investigated in detail. Bulk specific gravities of rocks are lower than apparent specific gravities because the permeable voids are included in the calculation of the bulk specific gravity.

Test methods for determining specific gravities and absorption are standardized to a large extent. There are no important differences between the methods prescribed by ASTM, AASHTO, SABS and the Department of Transport. Test method B14 (Department of Transport, 1971) was followed but two fractions were tested i.e. a 2,36 to 9,5 mm and a 19,0 to 26,5 mm fraction. This was done because Smith et al (1967) showed that the results are influenced by the grading of the sample tested.

The results are summarized in Table 12.21. The results for three of the samples tested are less accurate than for the others. Samples M7 and M10 disintegrated into flakes during soaking while M9 slaked into small particles during the same period.

It is evident that there is little difference between the specific gravities determined on the two fractions. For the bulk specific gravities the 9,5 to 2,36 mm fractions always yielded slightly lower values while for the apparent specific gravities the same fraction generally gave slightly higher values.

TABLE 12.21: RESULTS OF BULK AND APPARENT SPECIFIC GRAVITIES AND ABSORPTIONS

Sample no.	Bulk specific gravity		Apparent specific gravity		Water absorption (%)	
	Fractions (mm)		Fractions (mm)		Fractions (mm)	
	26,5 - 19,0	9,5 - 2,36	26,5 - 19,0	9,5 - 2,36	26,5 - 19,0	9,5 - 2,36
M1	2,67	2,62	2,77	2,76	1,36	1,92
M2	2,69	2,66	2,76	2,77	0,89	1,57
M4	2,55	2,49	2,72	2,76	2,45	3,87
M5	2,54	2,44	2,73	2,79	2,86	5,11
M6	2,43	2,39	2,70	2,74	4,17	5,40
M7*	2,34	2,27	2,73	2,76	6,15	7,80
M8	2,65	2,62	2,75	2,77	1,37	1,98
M9+	2,33	2,24	2,78	2,73	7,01	7,93
M10*	2,52	2,50	2,76	2,78	3,38	4,10
M12	2,48	2,45	2,64	2,66	2,49	3,20
M13	2,71	2,67	2,74	2,75	0,42	1,17
M14	2,06	2,00	2,78	2,87	12,50	15,28

* Breaks into flakes during soaking

+ Breaks down during soaking

Absorptions are always higher for the finer fraction than for the coarser one. This difference in absorption between fractions shows that if absorption limits are specified, the size fraction should also be specified.

12.16 Rate of slaking

The test was investigated in the pilot study and a test method was developed (Section 5.2.10). The apparatus used is shown in Plate 44. The results of the first absorption cycle of the rate of slaking test are given in Table 12.22 and are the average of four determinations. Some samples gave repeatable results while others behaved erratically.

TABLE 12.22: RESULTS OF RATE OF SLAKING TESTS

Sample number	Average "rate of slaking" (% moisture absorbed)	Standard deviation
M1	3,4	0,2
M2	3,2	0,4
M3	3,9	0,3
M4	4,6	1,0
M5	4,5	0,6
M6	5,8	0,1
M7	10,7	1,2
M8	2,8	1,1
M9	8,8	0,2
M10	6,0	1,9
M11	9,7	0,7
M12	4,3	0,6
M13	2,8	0,7
M14	15,1	1,3

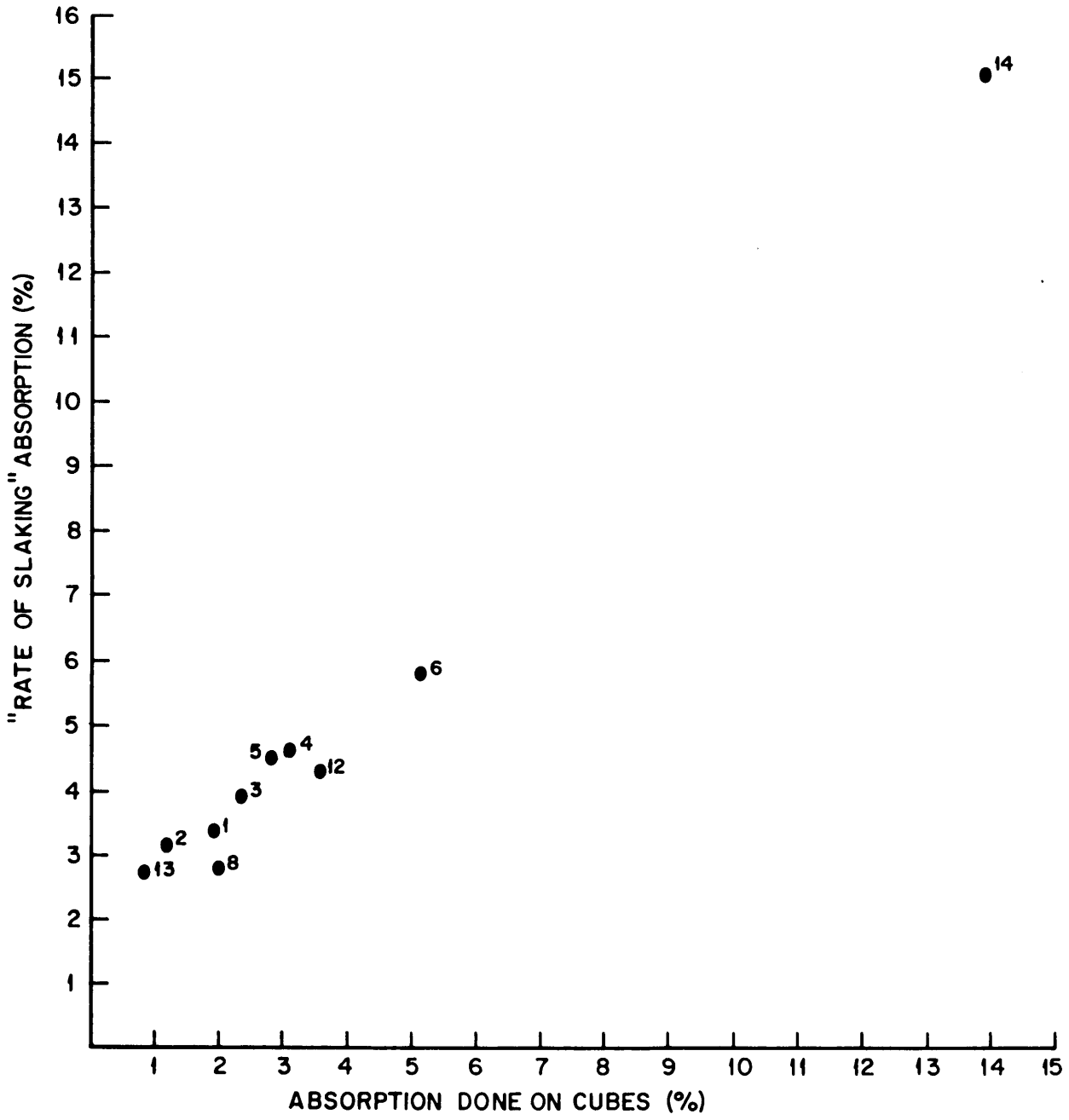


FIGURE 12.11

COMPARISON OF ORDINARY ABSORPTION OF WATER TO ABSORPTION IN "RATE OF SLAKING" TEST

Morgenstern and Eigenbrod (1974) proposed the rate of slaking test as an additional means for classifying clays and "mudstones". The results are used with Atterberg limits and their changes during soaking cycles in the proposed classification system. As is illustrated in Figure 12.11, where the percentage absorption of larger mudrock cubes determined in another way (Section 10.1) is plotted against the rate of slaking results, the test is a method of determining (repeated) water absorption. The advantage of the method is that it provides an easy way of determining the absorption of samples which slake or disintegrate badly during soaking. As some of the South African mudrocks tested have very low plasticities - some are even non-plastic - the application of this test to the whole range of South African mudrocks seems to be limited and repeated absorptions were therefore not carried out.

12.17 Porosity

No published data about the pore size distribution of southern African mudrocks could be found but it was established that the South African Coal Oil and Gas Corporation (SASOL) is in possession of a Micromeretics Model 900/910 Series mercury penetration porosimeter which was able to measure these expected low porosities.

To determine the pore volume (cm^3/g) for various pore diameters, mercury is forced into the samples. From the different pressures applied and the amounts of mercury forced into the samples at these pressures, pore volumes per gram for various pore diameters can be calculated.

Fifty grams of each sample, graded between 4,75 and 2,0 mm were supplied to the Sasol Research Department. After completing seven selected samples it was noted that the porosities were very low and mostly similar. It was then decided that these were sufficient to give a good general idea of the expected mudrock porosity range.

The results from the seven samples tested are listed in Table 12.23 and plotted graphically in Figure 12.12.

Samples M1, M2, M4, M7 and M9 were found to have roughly similar pore volume distributions. As these samples differ widely in other properties there does not seem to be a relation between these and other properties. Samples M4 and M9 with very similar distributions have very different engineering properties. Sample M14 and to a lesser extent M6, have higher porosities. This may be responsible for these samples being severely affected

TABLE 12.23: CUMULATIVE PORE VOLUMES FOR DIFFERENT PORE DIAMETERS

Pore diameter µm	Cumulative pore volume (cm^3/g) for samples						
	M1	M2	M4	M6	M7	M9	M14
88,4	0,005	0,003	0,009	0,005	0,001	0,005	0,003
44,2	0,006	0,004	0,010	0,006	0,001	0,006	0,004
22,1	0,006	0,005	0,010	0,007	0,002	0,007	0,005
17,733	0,007	0,005	0,011	0,008	0,002	0,007	0,006
0,884	0,009	0,007	0,015	0,012	0,006	0,011	0,019
0,354	0,010	0,008	0,017	0,013	0,006	0,014	0,072
0,177	0,011	0,009	0,021	0,015	0,007	0,020	0,102
0,088	0,011	0,009	0,023	0,016	0,008	0,022	0,113
0,044	0,012	0,009	0,028	0,020	0,010	0,024	0,119
0,022	0,012	0,010	0,032	0,030	0,018	0,027	0,124
0,010	0,014	0,011	0,034	0,042	0,033	0,032	0,128
0,005	0,015	0,013	0,036	0,049	0,039	0,039	0,131
0,004	0,016	0,015	0,039	0,055	0,042	0,041	0,133
0,0035	0,020	0,020	0,041	0,057	0,046	0,045	0,127

by the sodium sulphate test.

In Table 12.24 bulk specific gravities (Section 12.15) were used to calculate the porosities of the samples (pore volume per sample volume). From the table it can be seen that M1 and M2 have 5 per cent pore space, M4, M7 and M9 approximately 10 per cent and M6 and M14 higher at 14 and 28 per cent respectively.

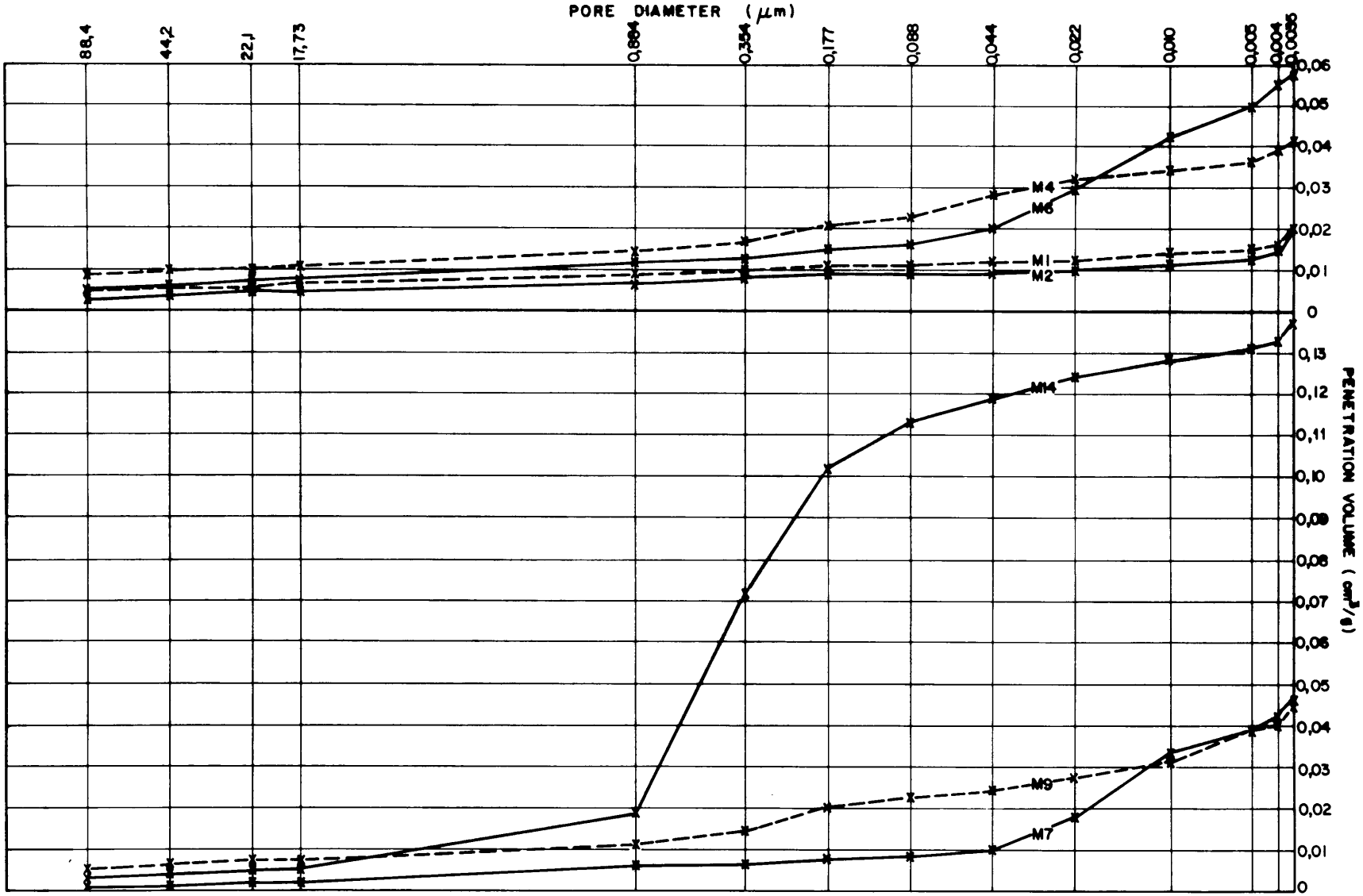


FIGURE 12.12

CUMULATIVE PORE VOLUME AGAINST PORE DIAMETER

TABLE 12.24: POROSITIES OF MUDROCKS

Sample number	Bulk SG	Cumulative pore volume cm^3/g	Porosity (pore volume per sample volume) cm^3/cm^3
M1	2,67	0,020	0,053
M2	2,69	0,020	0,054
M4	2,55	0,041	0,105
M6	2,43	0,057	0,139
M7	2,34	0,046	0,108
M9	2,33	0,045	0,105
M14	2,06	0,137	0,282

12.18 Conductivity and pH

The pH and conductivity of road building aggregates are often determined to estimate the soluble salt content. These tests were carried out on the mudrock samples as it is possible that soluble salts may be partially responsible for the slaking or disintegration of mudrocks.

Test method CA21 (NITRR, 1974) and mudrock samples crushed to minus 0,425 mm were used. The test involves the mixing of the crushed material with water up to "saturation" point i.e. up to the point when the surface of the mix glistens but no free water collects in hollows. This material is transferred to a special conductivity cell and the conductivity of the wet material is measured with a conductivity meter. Readings are taken in milli-Siemens per cm (mS/cm) and these are converted to percentage soluble salts using a graph supplied for the method or by multiplying with 0,1 if the conductivities are below 5 mS/cm. The pH of the same mix is determined using probes and a pH meter. A Radiometer Type CDM 2d conductivity meter and Pye Model 290 pH meter were utilized. The apparatus used is shown in Plate 45 and the results from duplicate tests are given in Table 12.25.

TABLE 12.25: CONDUCTIVITY AND pH RESULTS

Sample number	Average conductivity mS/cm	Estimated soluble salts %	Average pH
M1	0,21	0,02	8,1
M2	0,21	0,02	8,7
M4	0,25	0,02	6,9
M5	0,76	0,08	8,3
M6	0,36	0,04	7,6
M7	0,34	0,03	7,1
M8	0,24	0,02	7,9
M9	0,41	0,04	7,7
M10	0,76	0,08	8,1
M12	1,13	0,11	8,1
M13	0,19	0,02	8,9
M14	0,04	0	6,4
% accuracy (80 % C.I.)	1,5		1,2

Conductivities were found to be generally low. A limit of 2 mS/cm (equivalent to 0,2 per cent soluble salt) was set by Netterberg (1978) for road building materials and all the values were far below this limit. Two samples were slightly acidic with the others neutral to alkaline. pH values ranged between 6,4 and 8,9.

No relationship between the break-down behaviour and either of the two properties tested is indicated by these results. Similar samples, such as M1 and M12, showed a large difference in conductivity; neither could any trends indicative of engineering properties be obtained from the pH values. However, a highly leached sample, such as M14, showed a very low conductivity and the samples where salts were leached out during the wet-dry treatment (Section 8.5) generally exhibited higher conductivities.

Plate 44: Apparatus for the rate of slaking test

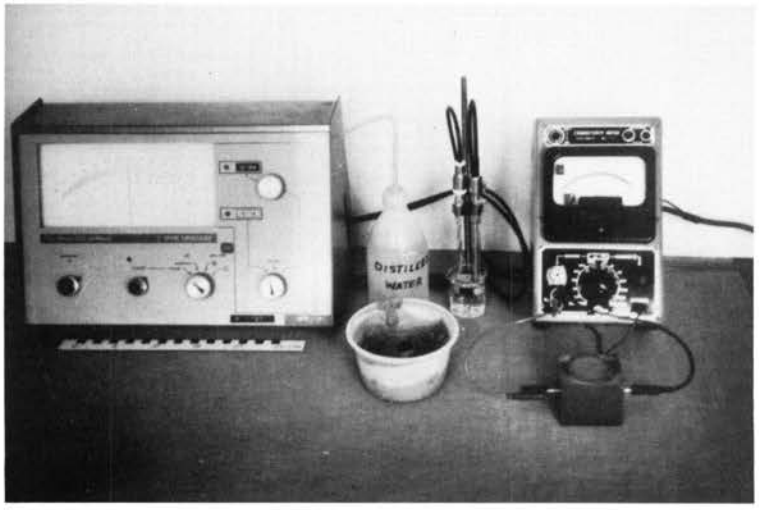


Plate 45: Conductivity and pH apparatus

12.19 Summary

(a) Uniaxial compressive and Brazilian tensile strengths were determined for mudrocks at their natural moisture contents. Apart from M14, a sample of a very poor quality, compressive strengths ranged from 28 to 169 MPa and tensile strengths from 3,5 to 22,6 MPa. NCB cone indenter and Schmidt hammer test results were compared with uniaxial compressive strength results. The cone indenter results did not provide a good estimate but the Schmidt hammer results provided a reasonable relationship with the actual uniaxial compressive strengths.

(b) The soaked values obtained in the aggregate crushing value test were unsatisfactory as they were often higher or close to the dry values. This happened especially in the cases of the weaker samples where it could not be true. The 10 per cent FACT proved to be more suitable for testing the dry and soaked crushing strength.

(c) The Washington degradation test procedure raised some doubts as all the fines generated by the weaker rocks during the shaking could not be washed through with the amount of water allowed for the test. During the wet ball mill test, Washington degradation type sedimentations were carried out with different quantities of sediment and it was found that this strongly influenced the sediment height. It is, therefore, important that all the sediment should be washed through in the Washington test as this is the only way to obtain repeatable results.

(d) Resistance against abrasion in a wet environment was considered to be an important property and a wet ball mill test, using a ceramic container and porcelain balls as the abrasive charge was, therefore, developed. Two types of evaluation, i.e. sieving and a Washington degradation type sedimentation of the fines, were investigated. The loss through the 0,075 mm sieve was found to be the most satisfactory for measuring the abrasion.

(e) A five-cycle slake durability test was carried out on the mudrock samples, followed by a sieve analysis of the material retained in the drum. Nine of the samples gave five-cycle indices in excess of 94 per cent even though some of these samples disintegrated inside the

drum. The test is therefore only suitable for classifying slaking samples, such as M9. An indication of disintegration can be obtained by doing a sieve analysis on the retained material but the repeatability of this is too poor for classification purposes.

(f) The break-down of mudrocks was studied by carrying out the ASTM sodium sulphate soundness test. From the sieve analyses performed at the end, the samples could be divided into three groups: samples with low losses for all the fractions, samples exhibiting higher losses for the coarse fractions and lower losses for the finer fractions and samples which were reduced to mud or fine flakes within the first three cycles. These three groups can be designated as durable, disintegrating and slaking mudrocks respectively.

(g) An accelerated weathering test, where the break-down of mudrocks during five wetting and drying cycles in three different agents i.e. water, calgon and a saturated sodium sulphate solution was compared, was performed. The effects of water and calgon were generally similar. Sodium sulphate was the most severe agent and it made visual interpretation easier as it actually broke samples apart, whereas the other agents only caused cracks in some of the more resistant samples. Two of the mudrocks were affected in a completely different way by the sodium sulphate than by the other agents and this poses a major uncertainty regarding its use for predicting the natural break-down behaviour of mudrocks.

(h) Soaking in ethylene glycol was found to have a lesser effect on the cracking of mudrocks than water. This is probably due to the complete absence of or to only negligible quantities of highly expansive clay minerals being present in the mudrocks.

(i) Ultrasonic disaggregation testing is a proven measure of durability. Such a test was developed using a probe-type ultrasonic generator and disaggregating a finely crushed gravel in water for a total of 20 minutes. A good spread of values was obtained for the mudrock samples and the most suitable method of evaluation was found to be sieving through a 2,0 mm sieve.

(j) The methylene blue adsorption test which uses the preferential adsorption of methylene blue by different clay minerals to classify rocks was performed on the mudrocks and on some pure clay minerals. It was

found that illite and montmorillonite were highly adsorptive while kaolinite adsorbed less than most of the mudrock samples. This sensitivity toward a particular clay mineral type was also reflected by the adsorption of the mudrocks.

(k) Bulk and apparent specific gravities and absorption tests were performed on two fraction sizes of the mudrock samples. Slightly different results were obtained for the different fractions and the size fraction should, therefore, be specified when these tests are done.

(l) The porosities of mudrocks are generally low and pore volumes for various pore diameters roughly similar. Only two samples have total porosities of 0,139 or higher. There does not seem to be a relationship between porosity and other properties although the higher porosities of samples M6 and M14 are quite possibly responsible for their being severely affected by sodium sulphate soundness tests.

(m) Other observations were that the Los Angeles abrasion test could not distinguish between mudrock samples of various qualities. The Treton test fared much better in this regard. The rate of slaking test is not suitable for classifying the whole range of southern African mudrocks but provides an easy way of determining the moisture absorption of disintegrating and slaking samples. pH and conductivity tests showed mudrocks to be largely alkaline and containing low amounts of soluble salts. They cannot, however, be used for classification purposes.

CHAPTER 13

COMPARISON OF CLASSIFICATION TESTS

13.1 General

To assist in the selection of the most suitable tests for the classification of mudrocks, Table 13.1, in which the samples are rated according to their performances in the different tests, was compiled. Standard road-building tests, such as compaction and indicator tests were not included in the table. The tests are grouped together into categories such as strength tests, abrasion tests and "durability" tests. If the rating of the samples by the individual tests is compared with the overall rating of the samples by all the listed tests it is evident that there is a general quality sequence but also that there is considerable variation in the ratings, especially in the middle order. Samples M2, M8 and M13 are almost invariably rated at the high quality end of the scale, while M9 and M14 are at the poor quality end, with the other samples rated inbetween.

The results from related tests listed in the table were studied and compared statistically and graphically to determine which tests are best suited for classification. Table 13.1 was also used to find possible relationships between "unrelated" tests. Those relationships which seemed strong or had some other significance were investigated in the same way. Linear regression analyses, including the determination of the equations and the correlation coefficients, were carried out when graphs showed them to be appropriate, either for illustrating a good relationship or for exposing a poor one. Table 13.2 compares some related tests, while "unrelated" tests are compared in Table 13.3. Linear regression equations are given in the above-mentioned tables where appropriate. They are not given if the relationship is weak or if it seems to be curvilinear.

TABLE 13.1: COMPARISON OF RATING OF MUDROCKS BY DIFFERENT CLASSIFICATION TESTS

Tests / Sample no:	Rating of samples according to different tests*													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Strength tests														
Uniaxial compressive strength	5	4	2	12	13	10	9	1	11	8	7	6	3	14
Brazilian tensile strength	5	6	4	12	11	9	8	1	13	10	7	2	3	14
Crushing strength														
Aggregate crushing value	5	2	3	6	11	8	12	4	13	10	9	7	1	14
10 Per cent FACT	5	2	3	6	11	9	12	4	13	8	10	6	1	14
Resistance against impact														
Treton impact value	4	2		5	10	5	8	3	11	9		7	1	12
Abrasion														
Los Angeles abrasion	5	4	3	6	12	8	6	2	13	10	11	9	1	14
Wet ball mill	4	3		7	8	9	10	1	12	6		5	2	11
Durability (including disintegration and slaking)														
Slake durability index (5 cycles)	4	3		5	7	6	11	2	13	8	12	9	1	10
Sodium sulphate soundness (weighted average)	9	5	10	3	4	13	8	1	14	11	7	6	2	12
Wet-dry weathering using sodium sulphate (13,2 mm loss)	6	3		5	4	10	11	1	11	8		7	2	9
Wet-dry weathering using water (13,2 mm loss)	4	1		4	4	9	11	1	12	10		8	1	7
Wet-dry weathering using water (2,0 mm loss)	4	1		4	4	9	11	1	12	10		7	1	8
Ultrasonic disaggregation	6	1	5	8	9	11	12	2	13	10	4	7	3	14
Clay mineralogy														
Sand equivalent	3	4		8	7	9	10	2	11	6		5	1	12
Washington degradation	4	3	14	12	7	12	5	2	7	7	7	5	1	11
Methylene blue adsorption	7	6	9	5	1	11	12	3	13	14	8	10	4	2
Absorption														
Cubes	3	2	5	7	6	10		4			9	8	1	11
9,5 - 2,36 mm fraction	3	2		6	8	9	10	4	11	7		5	1	12
Swell properties														
Maximum free swell (oven dried)	9	5	7	2	4	8	13	3	12	14	6	11	1	10
Density														
Bulk specific gravity	3	2		5	6	9	10	4	11	7		8	1	12
Average rating (Σ ratings/no. of tests)	4,9	3,1	5,9	6,4	7,5	8,8	9,5	2,3	11,8	9,1	7,8	6,9	1,6	11,2
Overall rating of samples	4	3	5	6	8	10	12	2	14	11	9	7	1	13

*Note: 1 - 14, good - poor

TABLE 13.2: COMPARISON OF THE RESULTS FROM SOME RELATED TESTS

Tests compared		Correlation coefficient r	Linear regression equations	Remarks
Uniaxial compressive strength (UCS)	Brazilian tensile strength (BTS)	0,91	(BTS) = 0,11(UCS) + 1,3 (UCS) = 7,76(BTS) + 1,9	Good relationship over wide range but with some scatter (Figure 13.1)
Aggregate crushing value - dry (ACV)	10 % FACT - dry (10%F)	-0,96	(ACV) = -0,11(10%F) + 45,5 (10%F) = -8,06(ACV) + 378,3	Excellent relationship - curvilinear at high and low values (Figures 13.2 and 13.3)
Los Angeles abrasion (LAA)	Wet ball mill (WBM)	0,69	(LAA) = 0,39(WBM) + 14,0 (WBM) = 1,21(LAA) + 2,3	Weak relationship - LAA yielded a small spread of values (Figure 13.4)
Slake durability index (SDI)	Wet-dry-water (6 lumps - loss through 2,0 mm) (Wa2,0)	-0,96	(SDI) = -0,81(Wa2,0) + 94,5 (Wa2,0) = -1,14(SDI) + 108,8	Most values concentrated in a very limited area (Figure 13.5)
Slake durability test (loss through 13,2 mm) (SD13,2)	Sodium sulphate soundness - weighted average (SoWA)	0,47	(SD13,2) = 0,36(SoWA) - 7,1 (SoWA) = 0,60(SD13,2) + 45,1	Very weak relationship
Slake durability test (loss through 13,2 mm) (SD13,2)	Wet-dry-water (6 lumps - loss through 13,2 mm) (Wa13,2)	0,76	(SD13,2) = 0,56(Wa13,2) - 2,0 (Wa13,2) = 1,04(SD13,2) + 12,6	Bad spread of values
Sodium sulphate soundness - loss through 31,5 mm (So31,5)	Sodium sulphate soundness - loss through 4,0 mm (So4,0)	0,80	(So31,5) = 0,94 (So4,0) + 28,4 (So4,0) = 0,68(So31,5) - 5,2	Weak relationship - very wide scatter in one area (Figure 13.6)
Sodium sulphate soundness - weighted average (SoWA)	Wet-dry-sodium sulphate (6 lumps - loss through 13,2) (So13,2)	0,94	(SoWA) = 0,84(So13,2) + 8,6 (So13,2) = 1,06(SoWA) - 3,4	Reasonable relationship apart from two scattered points (Figure 13.7)
Sand equivalent value (SE)	Washington degradation factor (WDF)	0,74		Relationship not usable - WDF has too small spread of values (Figure 13.8)
Methylene blue adsorption (MBA)	Sand equivalent value (SE)	-0,40		Very bad relationship
Absorption (9,5 - 2,36 mm fraction) (Abs-fr)	Absorption of cubes (Abs-cu)	0,99	(Abs-fr) = 1,07(Abs-cu) + 0,31 (Abs-cu) = 0,91(Abs-fr) - 0,17	Good relationship as to be expected - 9,5-2,36 mm fraction absorbed slightly more (Figure 13.9)

TABLE 13.3: COMPARISON OF THE RESULTS FROM SOME "UNRELATED" TESTS

Tests compared		Correlation coefficient r	Linear regression equations	Remarks
Uniaxial compressive strength (UCS)	Aggregate crushing value (ACV)	0,80	(UCS) = -4,50(ACV) + 206,1 (ACV) = -0,14(UCS) + 40,0	A reasonable relationship although the points are scattered (Figure 13.10)
Uniaxial compressive strength (UCS)	10 % FACT (10%F)	0,84	(UCS) = 0,56(10%F) - 5,0 (10%F) = 1,26(UCS) + 48,6	As above
Brazilian tensile strength (BTS)	Aggregate crushing value (ACV)	-0,70	(BTS) = -0,46(ACV) + 22,9 (ACV) = -1,06(BTS) + 39,2	Reasonable relationship which can give indication of values to be expected (Figure 13.11)
Brazilian tensile strength (BTS)	10 % FACT (10%F)	0,70	(BTS) = 0,055(10%F) + 1,5 (10%F) = 8,93(BTS) + 58,6	As above - quite a number of scattered points (Figure 13.11)
Treton impact value (TIV)	Aggregate crushing value (ACV)	0,95	(TIV) = 1,28(ACV) - 8,3 (ACV) = 0,71(TIV) + 8,6	Good relationships - not much scatter - available values suggest curvilinear relationships (Figure 13.12)
Treton impact value (TIV)	10 % FACT (10%F)	-0,89	(TIV) = -0,14(10%F) + 50,2 (10%F) = -5,53(TIV) + 305,2	
Ultrasonic disaggregation (UD)	Wet ball mill (WBM)	0,94	(UD) = 1,02(WBM) + 3,6 (WBM) = 0,87(UD) + 0,8	A good relationship with some scatter over the whole range (Figure 13.13)
Sand equivalent value (SE)	Wet ball mill (WBM)	-0,91	(SE) = -0,73(WBM) + 93,7 (WBM) = -1,13(SE) + 112,3	A good relationship - probably curvilinear (Figure 13.13)
Ultrasonic disaggregation (UD)	Aggregate crushing value (ACV)	0,87	(UD) = 3,09(ACV) - 53,9 (ACV) = 0,24(UD) + 20,4	Reasonable relationship - not very useful because of wide scatter in one area (Figure 13.14)
Ultrasonic disaggregation (UD)	10 % FACT (10%F)	-0,81	(UD) = -0,34(10%F) + 85,2 (10%F) = -1,92(UD) + 211,9	As above
Bulk specific gravity (BSG)	10 % FACT (10%F)	0,89	(BSG) = 0,0022(10%F) + 2,2 (10%F) = 360,17(BSG) - 761,2	Reasonable relationship - probably curvilinear (Figure 13.15)
Absorption (9,5 - 2,36 mm fraction (Abs-fr)	10 % FACT (10%F)	-0,85	(Abs-fr) = -0,04(10%F) + 11,1 (10%F) = -16,47(Abs-fr) + 219,8	A good relationship - probably curvilinear (Figure 13.16)
Absorption (cubes) (Abs-cu)	10 % FACT (10%F)			
Maximum free swell	Absorption (cubes)	0,39		A very weak relationship as illustrated in Figure 13.17)

13.2 Comparison of related tests

13.2.1 Strength tests

Figure 13.1 shows the good relationship between the compressive and tensile strengths of mudrocks at their natural moisture contents. The maximum value obtained for any particular sample was used. These tests cannot, however, be used for general classification purposes as the preparation of test specimens is very time consuming and sophisticated equipment is needed for preparation and testing.

13.2.2 Crushing strength tests

The two crushing strength tests, aggregate crushing value and 10 per cent FACT correlate excellently (Figure 13.2). The soaked values, as well as other values from Shergold and Hosking (1959) were incorporated in Figure 13.3. It is clear that the values for the mudrocks are in agreement with the relationship obtained with other types of material.

It is evident from the good correlation that only one of the tests has to be used and for mudrocks the 10 per cent FACT is more suitable. The main reason for selecting the 10 per cent FACT is that it is important to obtain a measure of the decrease in strength under soaked conditions. In this regard the 10 per cent FACT was shown to be more suitable for weak rocks, such as mudrocks, than the aggregate crushing value test.

13.2.3 Abrasion

Figure 13.4 shows the poor relationship between the results of the Los Angeles abrasion and wet ball mill tests. The wet ball mill test gave a good spread of values whereas the Los Angeles abrasion test did not succeed in separating samples of different quality. The Los Angeles test can, therefore, be abandoned for classification purposes of mudrock.

13.2.4 Durability

13.2.4.1 Slake durability index and wet-dry test using water

The slake durability test suffers from the limitation that it cannot classify disintegrating samples and the majority of southern African mudrocks which break down are of this type. This is illustrated in Figure 13.5 where the slake durability index (five cycles) is compared to the loss through the 2,0 mm sieve in the five-cycle wet-dry test. There is good agreement here, but the ranges of values are too limited. The slake durability test is suitable for exposing a highly weathered sample such as M14, and very applicable for the rating of slaking samples, such as M9.
A highly weathered sample would, however, be detected by some other standard specification test, such as a CBR test. Visual observation of and a grading analysis on the retained material overcome the problem of detecting disintegration to a certain extent but even evaluation through a 13,2 mm sieve does not give a much increased range of values.

The wet-dry test, using water, with visual observations and sieving after five cycles to obtain some measure of slaking and disintegration is preferred for general break-down classification. Even though this test suffers from some of the same limitations as the slake durability test (Figure 13.5) it has certain advantages. Some of these are: the lumps are not disturbed and their reaction with water can be visually observed; a soaking time of 16 to 18 hours is better because the rate of absorption tests (Section 10.2) showed that limited absorption occurs within ten minutes of immersion for most samples; and lastly, the test does not require any special equipment. The most important aspect of the test is the visual observation of the effect of wetting and drying during the five cycles which gives a good indication of the long-term behaviour under atmospheric conditions. Slaking samples can also be classified quantitatively very well in this test by sieving through 2,0 mm while the loss through a 13,2 mm sieve gives some measure of the disintegration which took place.

13.2.4.2 Sodium sulphate soundness test and wet-dry test using a sodium sulphate solution

The sodium sulphate solution used in the above-mentioned test succeeded in accelerating the disintegration and slaking of mudrocks as compared with the use of water, but unfortunately affected some samples in a completely different or "unnatural" way, probably due to the higher porosities of these samples. The results from the sodium sulphate soundness test also show that disintegrating mudrocks, such as M1, M7, M10, M11 and M14, break down to particular sizes of flakes or plates i.e. the larger sized fractions would lose higher percentages than the smaller fractions. This is illustrated in Figure 13.6 where losses for the 63 to 37,5 mm fractions (sieved through 31,5 mm) are compared with losses for the 9,5 to 4,75 mm fraction (sieved through 4,0 mm). It is evident that disintegrating samples break down largely to sizes smaller than 31,5 mm but that lesser percentages break down to sizes smaller than 4,0 mm. There is, therefore, a very poor relationship between losses through 31,5 mm and 4,0 mm sieve sizes.

The five cycle wet-dry test using sodium sulphate gives an indication of the results of the standard ASTM test, as is indicated in Figure 13.7 where the results are compared to a weighted average result of the standard test. Experienced engineers or geologists may find it quite useful to carry out a three cycle wet-dry test to obtain a quick indication of the long-term behaviour of the material. The study did not reveal sufficient reason to recommend the use of standard sodium sulphate soundness tests on mudrocks.

13.2.4.3 Ultrasonic disaggregation

The test developed during this study differs from the other durability tests discussed under this heading in that it cannot be used to predict disintegration or slaking behaviour. It shows promise, however, for mudrock classification purposes as has also been found by several other authors (Laguros, 1972; Reidenouer et al, 1974). Its relationship with the wet ball mill test (Section 13.3.3) is particularly interesting.

13.2.5 Clay mineralogy

The sand equivalent, Washington degradation and methylene blue adsorption tests classify materials to a large degree according to the type of clay mineral present. The first two tests flocculate different types of clay to different degrees and the last differentiates between clays by the different quantities of methylene blue adsorbed.

The methylene blue adsorption test was found to be very sensitive to the type of clay mineral. Samples M4, M5 and M14 were shown to contain kaolinite in the X-ray mineralogical analysis and these samples rated at the top end (little adsorption) with the very durable samples (M2, M8 and M13). Samples M6, M7 and M9, which contain some montmorillonite are rated at the lower end with sample M10. The reason for the low rating of sample M10 may be due to the fact that it is the only sample which contains a "medium" amount of chlorite. The methylene blue adsorption test did not succeed in rating mudrocks according to their durability. The test may, however, be very useful when the clay mineral type is an important factor.

Figure 13.8 compares the sand equivalent and Washington degradation tests. The sand equivalent test gave a good spread of values in contrast with the Washington degradation test. The latter test is unsuitable for classifying mudrocks as it is unable to differentiate between the weaker types of rock.

13.2.6 Absorption

A good relation - as expected - was obtained between the absorption on cubes and the absorption on a crushed fraction (Figure 13.9). Only nine results could be plotted as it was impossible to perform the cube absorption test on samples which slake or disintegrate to a large degree. The absorptions of the crushed fractions are usually slightly higher than those of the cubes, probably because of the presence of more free water on the larger surface areas of the crushed fraction.

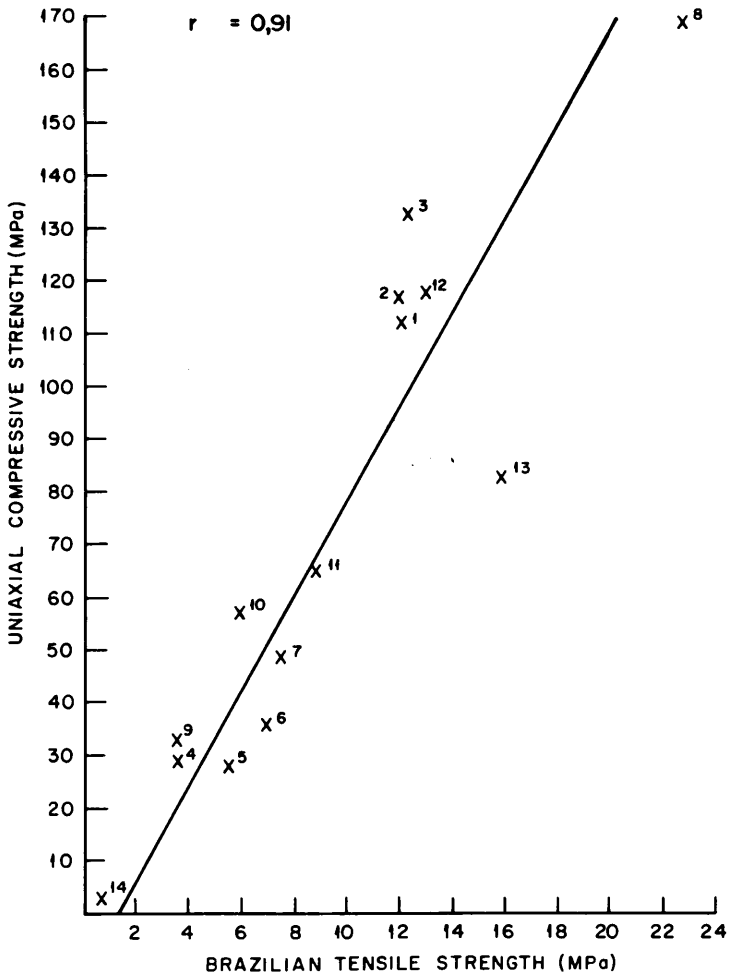


FIGURE 13.1

RELATIONSHIP BETWEEN UNIAXIAL COMPRESSIVE AND BRAZILIAN TENSILE STRENGTH

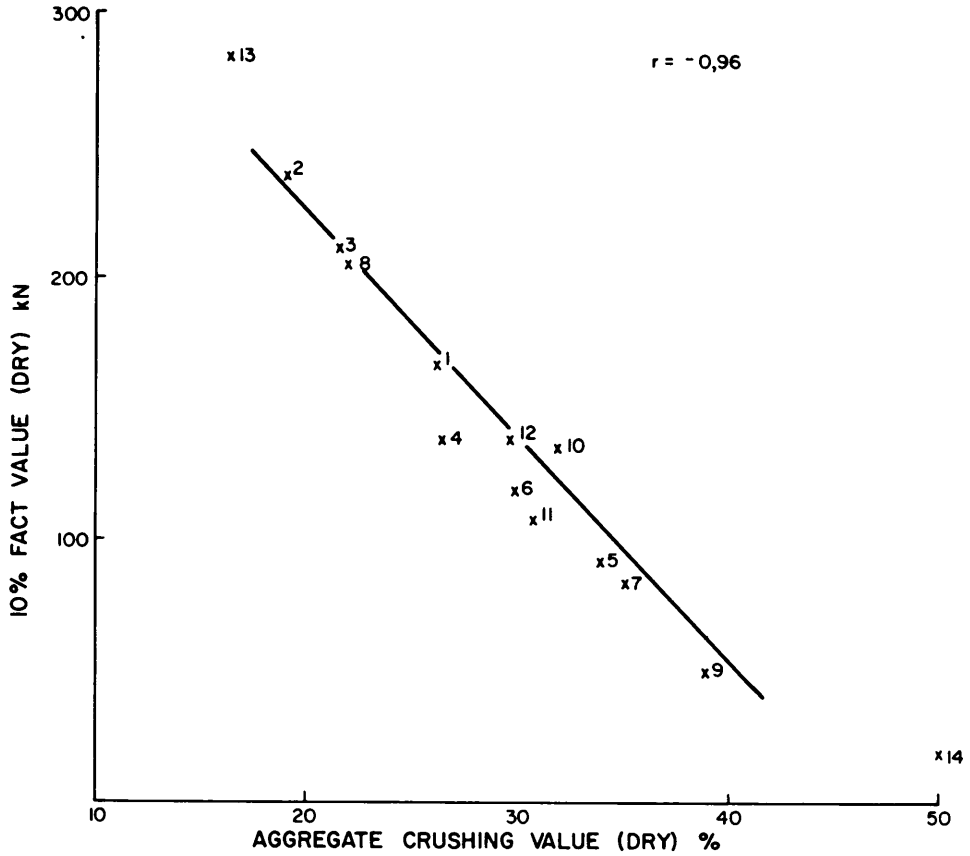


FIGURE 13.2

RELATION BETWEEN DRY ACV AND 10% FACT VALUES FOR THE MUDROCK SAMPLES.

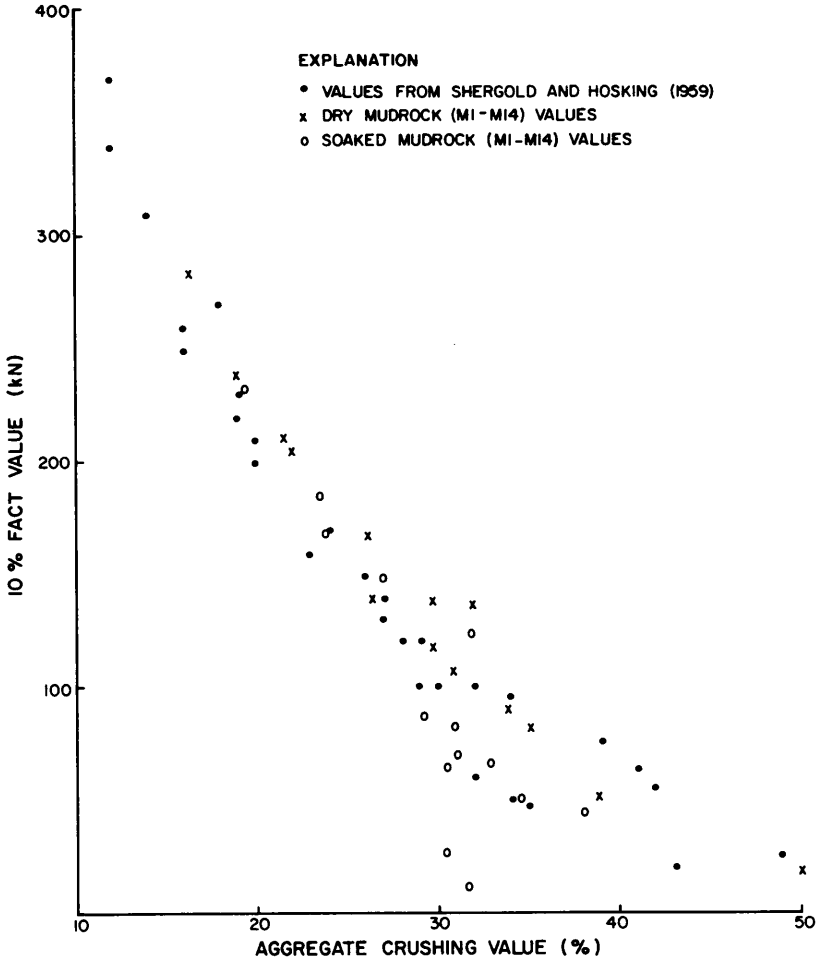


FIGURE 13.3

RELATION BETWEEN ACV AND 10% FACT VALUES FOR SOAKED AND DRY MUDROCK SAMPLES AND FROM OTHER PUBLISHED DATA

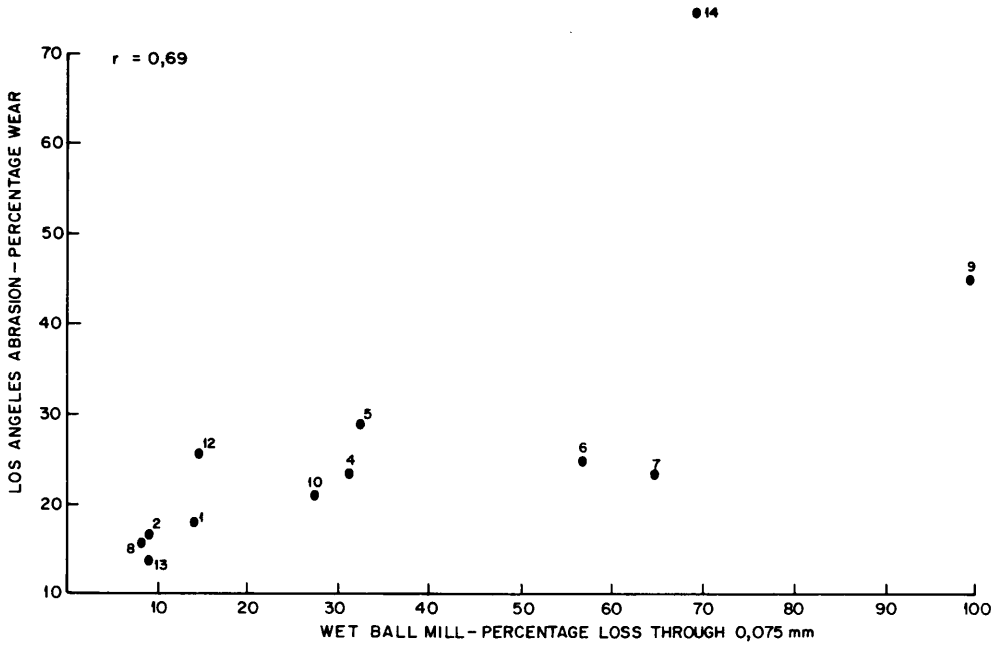


FIGURE 13.4

COMPARISON BETWEEN WET BALL MILL AND LOS ANGELES ABRASION TESTS

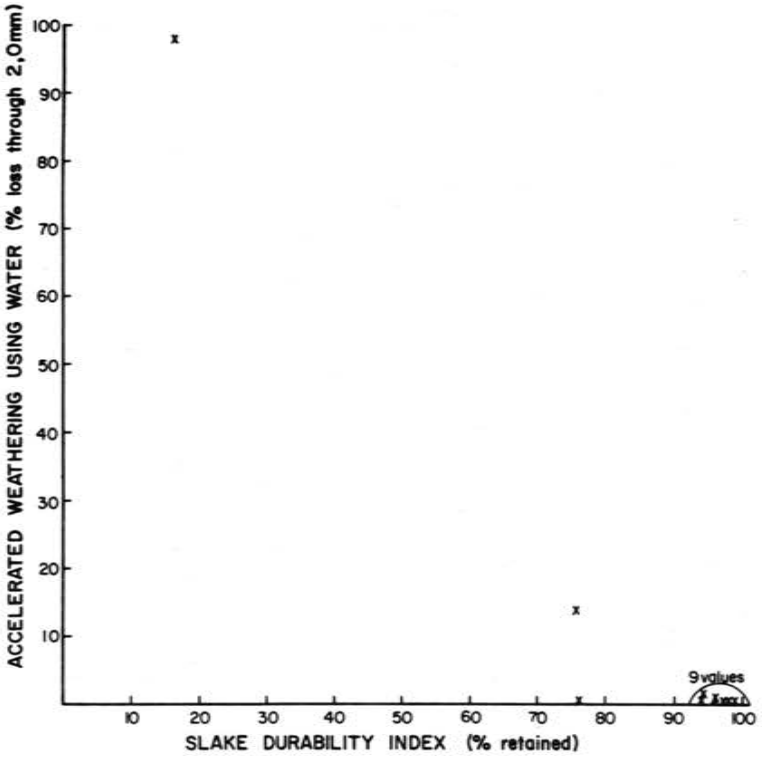


FIGURE 13.5

SHOWING THE LIMITED GENERAL QUANTITATIVE CLASSIFICATION ABILITIES OF THE SLAKE DURABILITY INDEX AND THE WET-DRY TEST USING WATER

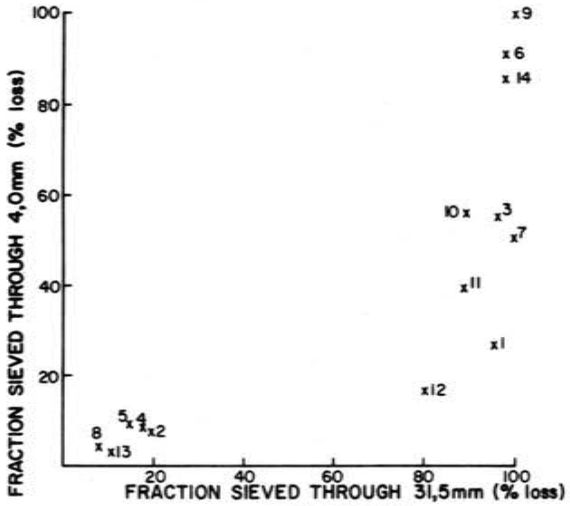


FIGURE 13.6

COMPARISON OF BREAK-DOWN IN TWO DIFFERENT FRACTIONS IN THE SODIUM SULPHATE SOUNDNESS TEST

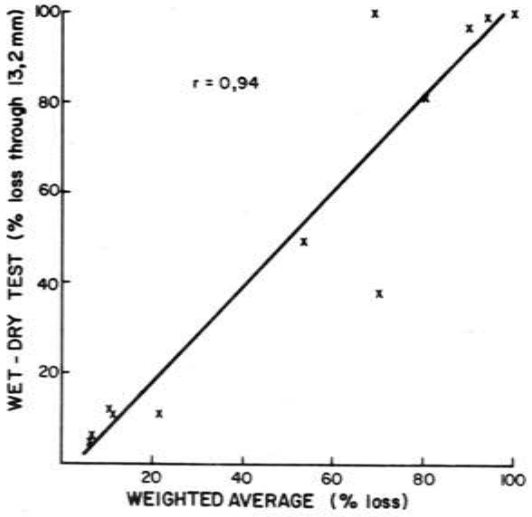


FIGURE 13.7

COMPARISON BETWEEN BREAK-DOWN IN SODIUM SULPHATE SOUNDNESS TEST AND BREAK-DOWN OF SIX LUMPS IN A MODIFIED TEST

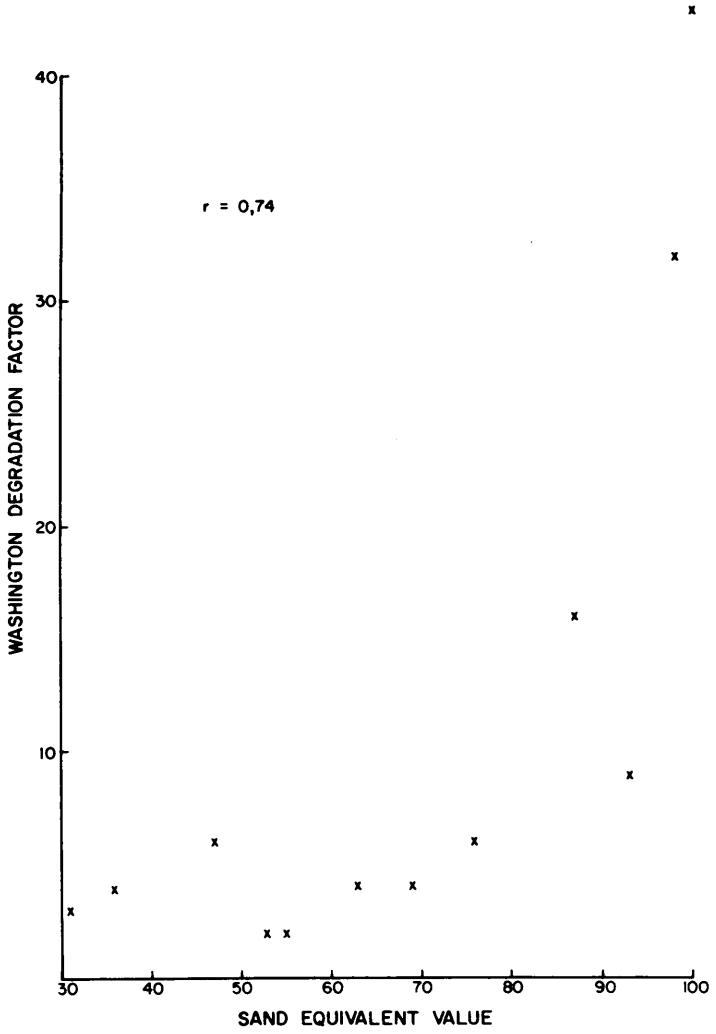


FIGURE 13.8
RELATION BETWEEN THE WASHINGTON DEGRADATION FACTOR AND THE SAND EQUIVALENT VALUE

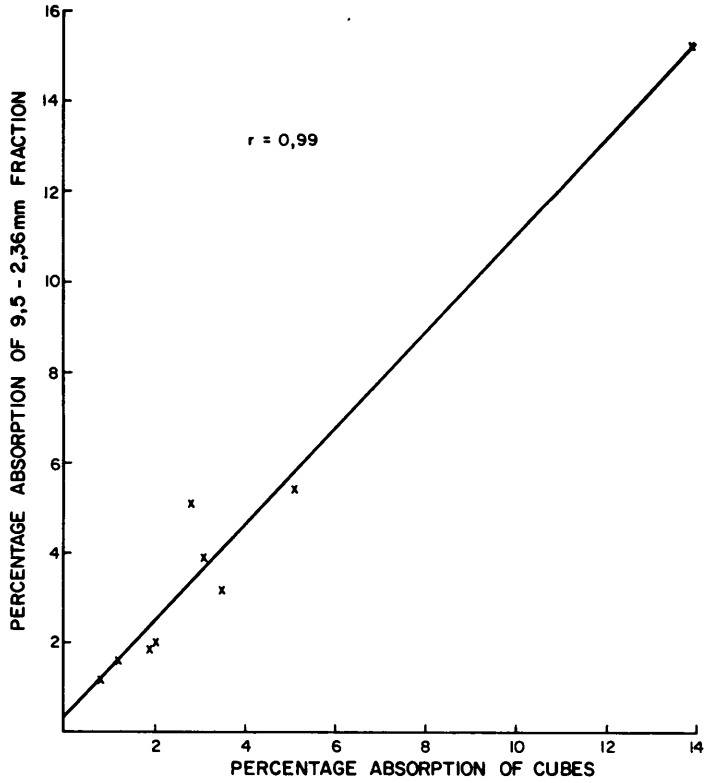


FIGURE 13.9
COMPARISON OF WATER ABSORPTION OF CUBES AND OF THE 9,5 - 2,36mm FRACTION

13.3 Comparison of "unrelated" tests

13.3.1 Uniaxial compressive and Brazilian tensile strength against aggregate crushing value and 10 per cent FACT

Figures 13.10 and 13.11 show that there are reasonable relationships between the results of the above tests. Estimates of compressive and tensile strengths can therefore be made if the crushing strengths are known. A comparison of Figures 13.10 and 13.11 indicates that the relationships for the compressive and tensile strengths are largely similar.

13.3.2 Treton impact value against aggregate crushing value and 10 per cent FACT

A good relationship between these tests was obtained as expected (Figure 13.12). It is considered that there cannot be major differences between the mechanisms of the break-up of a rock crushed by dropping a mass (impact), and in the break-up of a rock when it is crushed slowly using an applied load (crushing). The relationships obtained from the available points seem to be curvilinear. An advantage of the Treton test is that it does not require any sophisticated apparatus.

13.3.3 Wet ball mill test against ultrasonic disaggregation and sand equivalent tests

The good relationship between the ultrasonic disaggregation test and the wet ball mill test, shown in Figure 13.13, holds advantages for mudrock classification. The ultrasonic disaggregation-type test is a proven durability test but it requires expensive equipment. The good relationship between the above tests provides the possibility of replacing the ultrasonic test with a wet ball mill test. Unfortunately, no standard wet ball mill test is in use in southern Africa.

The figure also shows that the sand equivalent test gave results which are related to the other two tests.

13.3.4 Ultrasonic disaggregation test against aggregate crushing value and 10 per cent FACT tests

Figure 13.14 illustrates the above relationships. Although the correlation coefficients are quite high there is considerable scatter in the areas with the highest concentration of points. The use of these relationships is, therefore, limited.

13.3.5 Bulk specific gravity and absorption against the 10 per cent FACT

Figures 13.15 and 13.16 show good curvilinear relationships between the above-mentioned tests. A reasonable estimate of the 10 per cent FACT value can be made if the bulk specific gravities and absorptions of mudrock samples are known.

13.3.6 Maximum swell percentage against absorption of cubes

Figure 13.17 confirms the conclusions made in the free swell experiment and the temperature-humidity experiment that there is very little relation between the percentage moisture absorbed by mudrock samples and the maximum percentage swell which occurs when these samples are immersed in water.

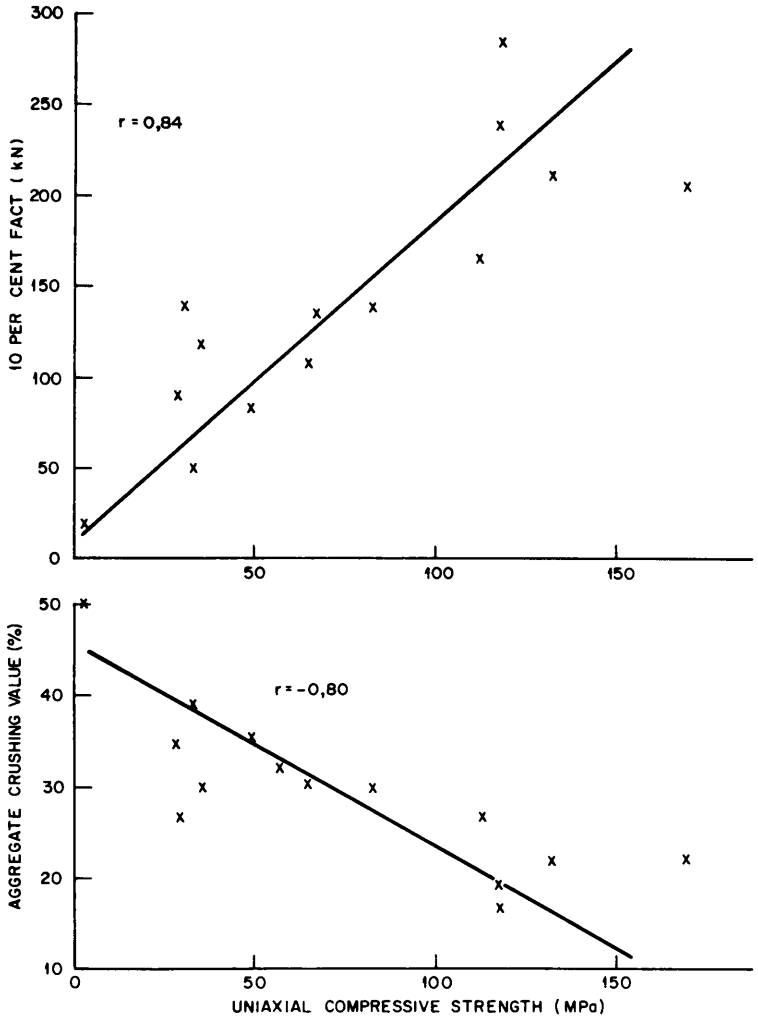


FIGURE 13.10

UNIAXIAL COMPRESSIVE STRENGTH AGAINST 10 PER CENT FACT AND AGGREGATE CRUSHING VALUE

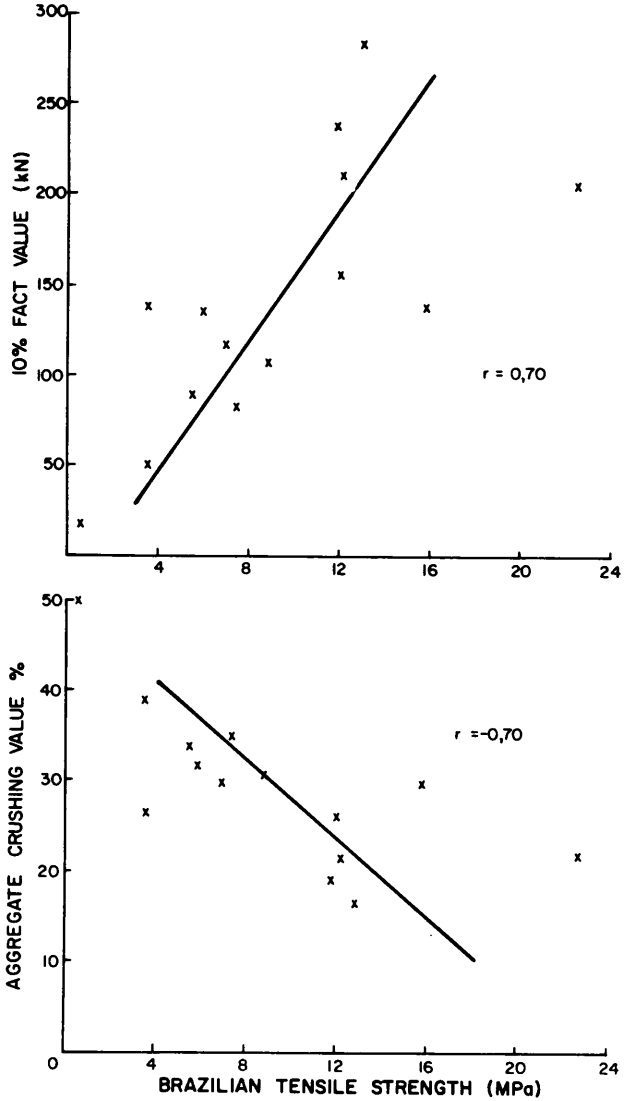


FIGURE 13.11

BRAZILIAN TENSILE STRENGTH AGAINST AGGREGATE CRUSHING VALUE AND 10 % FACT

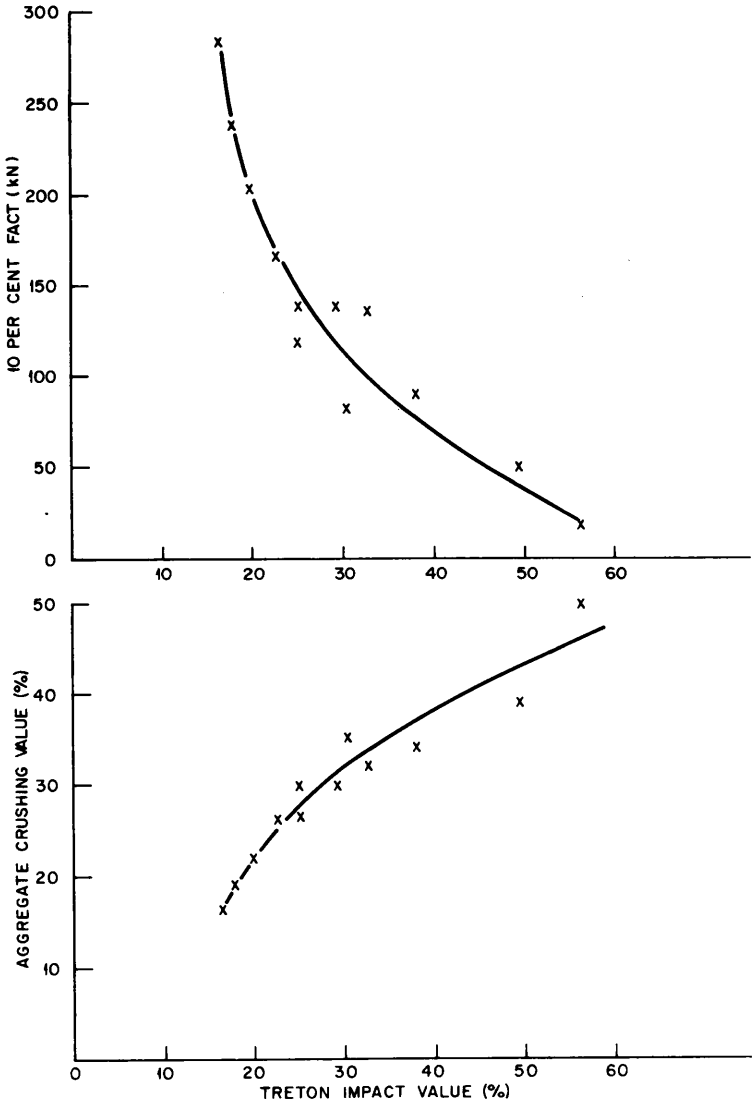


FIGURE 13.12

TRETON IMPACT VALUE AGAINST AGGREGATE CRUSHING VALUE AND 10 PER CENT FACT

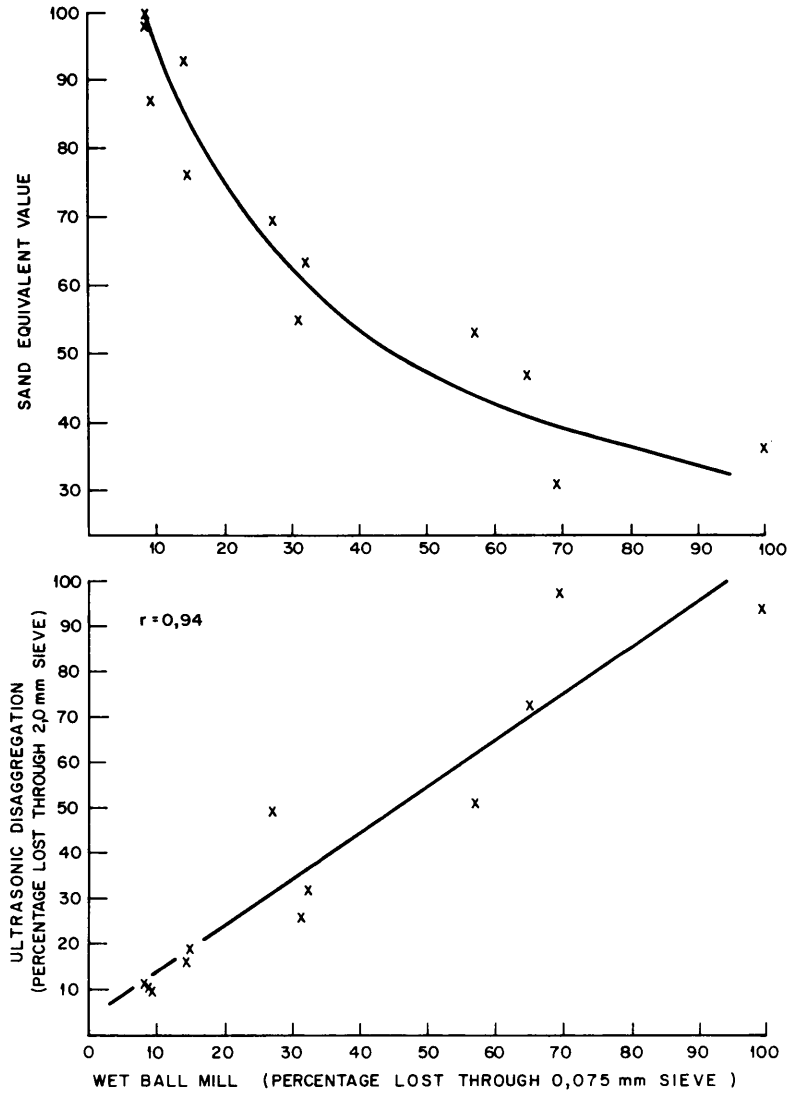


FIGURE 13.13

WET BALL MILL VALUE AGAINST SAND EQUIVALENT AND ULTRASONIC DISAGGREGATION VALUES

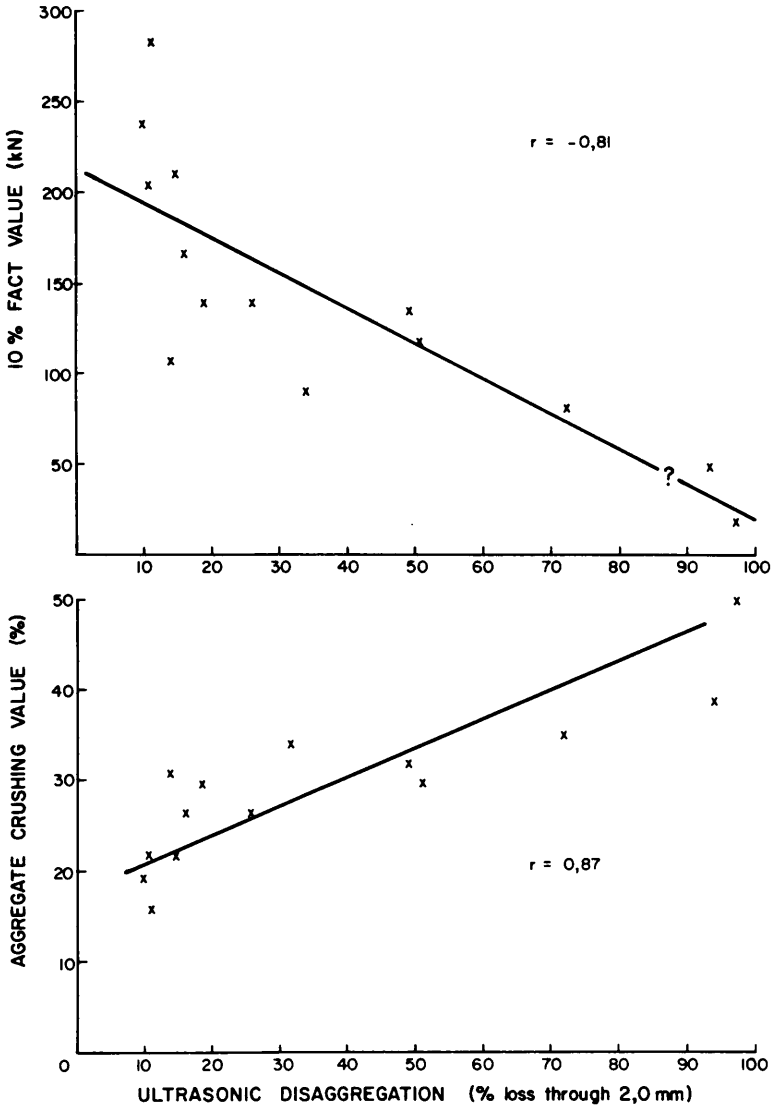


FIGURE 13.14

ULTRASONIC DISAGGREGATION AGAINST AGGREGATE CRUSHING VALUE AND 10 % FACT

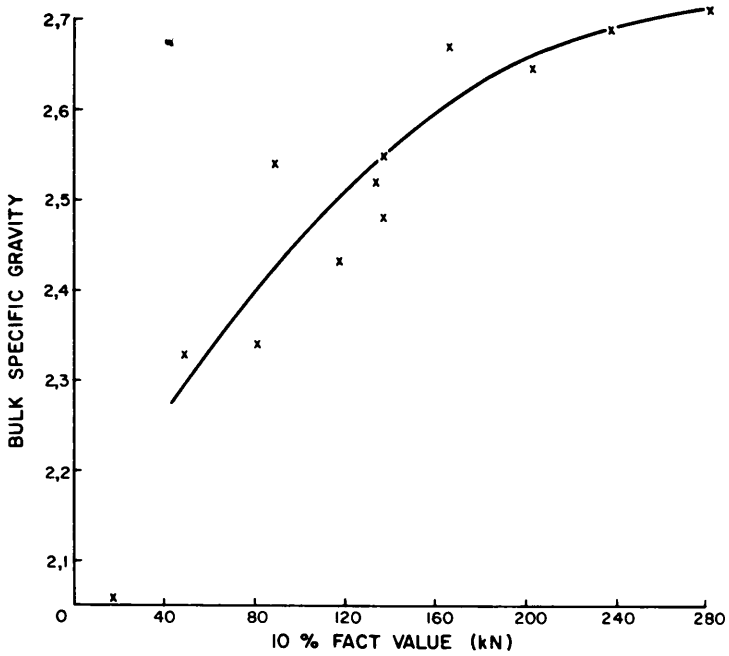


FIGURE 13.15

RELATIONSHIP BETWEEN 10 % FACT AND BULK SPECIFIC GRAVITY

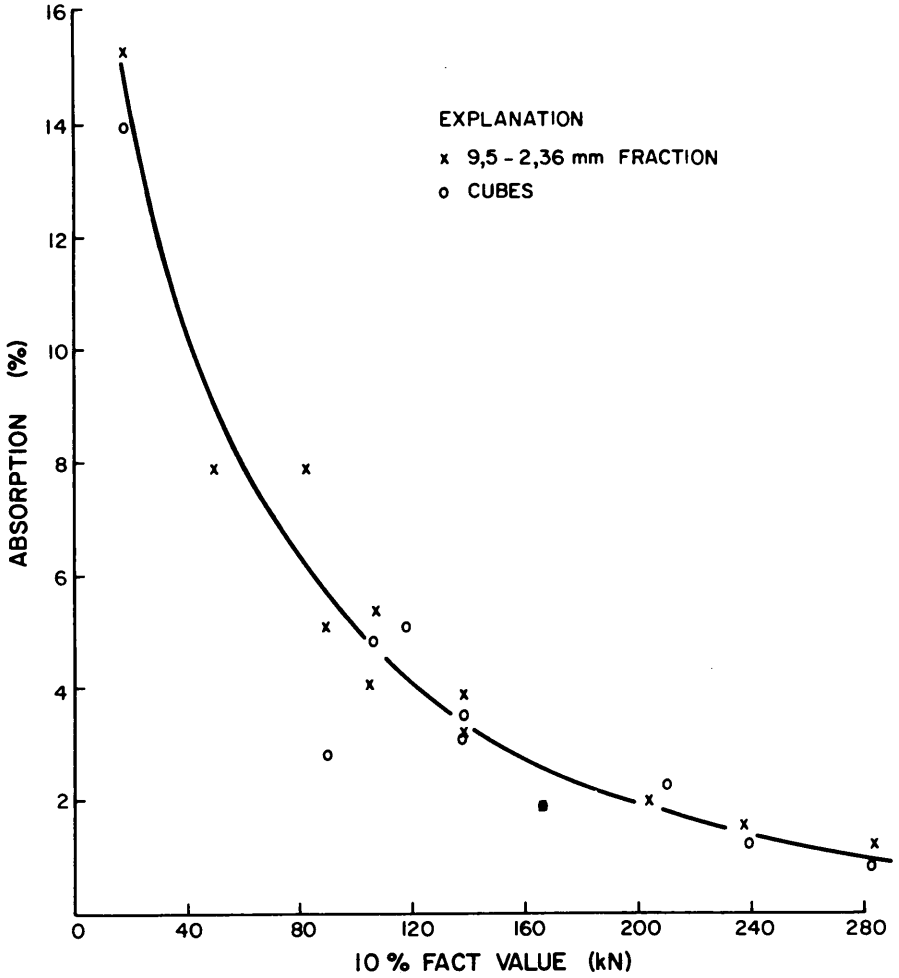


FIGURE 13.16

RELATIONSHIP BETWEEN 10 % FACT AND ABSORPTION OF 9,5 - 2,36 mm FRACTION AND CUBES

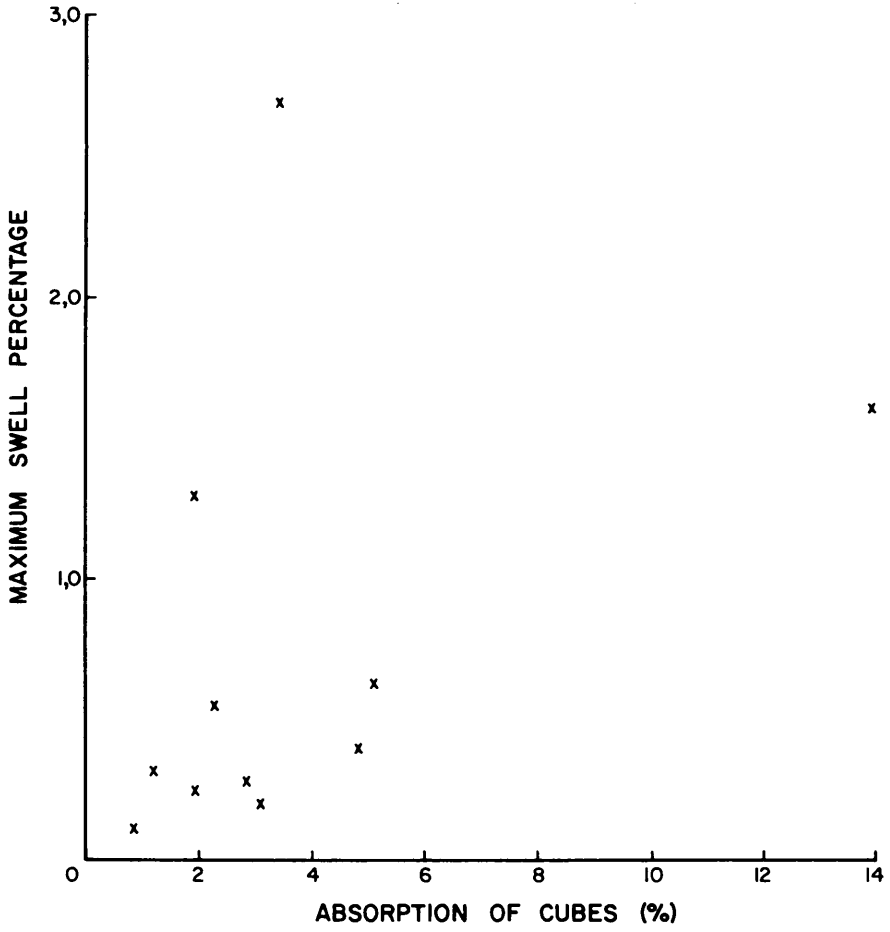


FIGURE 13.17

RELATIONSHIP BETWEEN ABSORPTION OF CUBES AND MAXIMUM PERCENTAGE SWELL

CHAPTER 14

SELECTION OF TESTS

14.1 Introduction

From the investigation of possible test methods, the comparison of results and the better understanding of the engineering-geological properties of mudrocks, it is possible to select certain classification tests. Fourteen sets of results are not sufficient to lay down final specifications but the work done provides a sound basis for narrowing down the number of tests applicable to the classification of southern African mudrocks.

14.2 Discussion of recommended tests

The tests recommended for further study can be broadly classified under four headings.

14.2.1 Tests to measure the durability of aggregate in a road pavement

An aggregate used in a road pavement requires basically three properties. These are:

(a) resistance against abrasion in a moist environment

(b) resistance against crushing during construction and to a lesser degree during service in the pavement

(c) resistance against chemical deterioration during its time of service in the pavement e.g. an increase in plasticity because of chemical decomposition.

The wet ball mill test developed in this study, should be used to test for (a). As the wet ball mill test is not a standard test, the Texas ball mill test, which utilizes a relatively small drum and a similar method, should be investigated. Its relationship with the wet ball mill test and the ultrasonic disaggregation test should be determined and if the results are satisfactory this test can possibly replace the wet ball mill test.

The 10 per cent FACT is recommended to test for (b). The test is preferred to the aggregate crushing value test for reasons mentioned in Section 12.19 and it also correlates reasonably well with compressive and tensile strengths and even better with bulk specific gravity and absorption. Dry and soaked tests should be performed to measure the degree of weakening in a moist environment.

It is difficult to test for (c), i.e. resistance against chemical deterioration. However, mudrocks are largely the end products of weathering and further deterioration of minerals is, although possible, not a major problem. The properties of the clay minerals which are present are of more importance and in this regard the sand equivalent test, which also proved to be a measure of durability (Section 13.3.3) can give an indication of their quality. X-ray diffraction should be used to identify the minerals and especially the clay minerals. From the available data it does not seem as if the clay minerals influence mudrock properties to any great degree but more information is needed on this aspect.

14.2.2 Tests to measure break-down

Special tests are required to classify the break-down properties of mudrocks as this property is not exposed by the durability tests mentioned above. Two types of break-down exist in mudrocks although there is a gradation from the one to the other. These are:

(a) break-down to constituent particles - called slaking, and

(b) break-down to flakes, plates etc. - called disintegration.

The slake durability index is recommended to test for (a). Unfortunately only one slaking sample (M9) was included among the 14 mudrock samples and it is, therefore, difficult to say how many cycles should be done. However, three slaking samples were present among the samples used for the pilot study on mesh sizes (Section 5.2.2) and for these, two cycles (or even one) were quite adequate. Sample M9 gave an index of 56,6 after two cycles. It is therefore recommended that the standard two-cycle test be used for the classification of slaking mudrocks. The quantitative classification of (b), i.e. disintegration, presents some problems. The wet-dry test using six lumps of 37,5 to 26,5 mm material and five cycles in

water is considered to be the most suitable but evaluation by means of a sieve analysis is not entirely satisfactory. Some mudrocks break into plates while others break into more equidimensional flakes. The latter may then pass a certain sieve, while most of the flat plates of the other sample are retained, thus misrepresenting the actual behaviour of the samples. The visual observation and the description of the behaviour in water is therefore considered to be the most important evaluation, although sieving through 13,2 and 2,0 mm mesh sieves should be done at the conclusion of the test to give some measure of disintegration and slaking respectively. Sieving through a 2,0 mm mesh sieve is quite adequate for rating slaking and this test can be used to replace the slake durability test in the field or if the apparatus is not available.

14.2.3 Standard tests

These tests include maximum dry density (MDD) - optimum moisture content (OMC), California bearing ratios (untreated and treated with lime), Atterberg limits, linear shrinkage, Treton and specific gravities and absorption tests. A point should be made of crushing the mudrocks in a standard way for the compaction tests otherwise the results are not comparable. The crushed material should also be subjected to one wet-dry cycle before compaction and CBR testing commences.

The influence of lime (and other stabilization agents) on the strength and more particularly on the volume change properties of mudrocks should be investigated further.

The Treton impact test should be continued. The test exhibited a good correlation with the 10 per cent FACT (and ACV) and may be used to replace this test in certain circumstances if further results confirm the good relationship. Bulk and apparent specific gravities and absorption tests should also be carried out as they seem to correlate with desirable durability properties such as crushing strength.

14.2.4 Other tests

Other tests which should be continued are the ultrasonic disaggregation test, which is a proven durability test providing a basis for comparison

with other tests, and the free swell test, about which more information is needed before it is discarded for classification purposes. Moreover, additional information is required about the expansiveness of southern African mudrocks.

The above recommendations are summarized in Table 14.1.

TABLE 14.1: SUMMARY OF TESTS RECOMMENDED FOR SOUTHERN AFRICAN MUDROCKS

Recommended test	Test method	Reason for selection
Wet ball mill	Author's method - described in Section 12.7	Tests resistance against abrasion in a wet environment - a condition important in a road pavement. Also correlates well with ultrasonic disaggregation, a proven durability test.
10 % FACT (dry and soaked)	Method B2 (Department of Transport, 1971)	Determines resistance against crushing - important in construction and in service in a pavement. Also gives measure of strength decrease when soaked.
Sand equivalent test	Method B19 (Department of Transport, 1971)	Gives measure of detrimental clay minerals present.
X-ray diffraction	Paige-Green, 1978	More information is needed, especially about types of clay mineral in southern African mudrocks.
Slake durability index	Test method in ISRM, 1979	To test for slaking properties i.e. break-down into constituent particles.
Wet-dry using water	Author's method - described in Section 12.10	To obtain mainly qualitative measure of disintegration (and slaking)
Maximum dry density - optimum moisture content	Method A7 (Department of Transport, 1971)	Standard road building test - material should be submitted to wet-dry cycle beforehand.
California bearing ratios - untreated and treated with lime	Methods A8 and A9 (Department of Transport, 1971)	As above - special attention should be paid to volume change properties of treated material.
Atterberg limits and linear shrinkage	Methods A1 to A5 (Department of Transport, 1971)	Standard road building tests which measure plasticity and volume change properties of fines.
Treton impact value	Method B7 (Department of Transport, 1971)	Test correlates well with crushing strength tests - may be able to replace them under certain conditions.
Bulk and apparent specific gravity and absorption	Method B14 (Department of Transport, 1971)	Tests correlate with strength properties - this relation should be investigated.
Ultrasonic disaggregation	Author's method - described in Section 12.12	A proven durability test with which other results can be compared.
Free swell	Author's method - described in Section 5.2.11 and with recommendations as in Section 9.4	More results are needed before test is discarded for classification purposes - more information is also needed about the expansiveness of southern African mudrocks.

CHAPTER 15

SUMMARY AND CONCLUSIONS

The objectives of this study, which were to investigate the engineering properties and classification of southern African mudrocks for road-building purposes, were accomplished by conducting a survey among users of the material; by investigating the engineering-geological properties of the rock material; and by studying tests which could be used for classification purposes.

The survey showed that mudrocks are very important materials for road-building in southern Africa, especially in the South African provinces of the Cape, Natal and the Orange Free State where large areas are underlain by these rocks. Mudrocks have been successfully used up to the subbase layer in both stabilized and unstabilized form. No particular problem caused by construction with mudrock appears to be of primary importance, but the spontaneous break-down of some mudrock types after exposure to the atmosphere gives rise to uncertainty about their quality. Users therefore feel that classification tests, in addition to the standard laboratory tests, are necessary to classify mudrocks for use in road construction.

The engineering-geological index properties were determined of fourteen mudrock samples, which were obtained from different geological formations and from various localities in South Africa. These were also submitted to different categories of classification tests. Although the samples chosen incorporated a wide range of engineering geological properties, the fact that they were limited in number means that they were not necessarily representative of the full range of southern African mudrocks.

Indicator, compaction and CBR tests were performed on material crushed according to a standardized procedure. The rocks were found to be of a variable quality, some rocks being of a subbase standard in the untreated condition. PIs were generally low and the harder rocks showed a lack of fine material. Almost all of the crushed rocks reacted very favourably to stabilization with lime.

An accelerated weathering test, in which CBR compactions were followed by wet-dry cycles, revealed the different rates of break-down exhibited by mudrocks. It was found advantageous to divide the break-down phenomenon into two types: slaking, i.e. a fairly rapid break-down into silt or clay, and disintegration, i.e. break-down at various rates into irregular fragments, flakes, plates or large grains.

Swell tests carried out on rock cubes treated differently beforehand, showed that exposure to the atmosphere (and oven-drying) has a marked effect on mudrock behaviour. The slaking and disintegrating rock types broke down to a greater extent when immersed in water after a period of exposure to the atmosphere than when being immersed at the natural (field) moisture content. This clearly showed that these mudrocks should not be allowed to lose excessive moisture if break-down is to be prevented or curtailed. Free swells were found to be generally low and only the slaking, disintegrating and weathered rock types expanded more than one per cent during immersion in water after initial oven-drying.

A test to monitor mudrock behaviour under varying temperature and humidity conditions showed mudrocks to be very sensitive to changes in humidity. It was, however, determined that even large variations in temperature and humidity did not cause any visible slaking or disintegration and it is therefore considered that free water is necessary to cause such deterioration.

A wide range of classification tests, selected from other relevant studies, was investigated. Some of the tests were carried out according to standard methods, while other tests were also devised. Most of the tests performed a dual function in that they also gave information on some basic rock material properties. It was found that tests, such as soaking in ethylene glycol, methylene blue adsorption, rate of slaking and the determination of porosity, did not show promise for general mudrock classification purposes. The Los Angeles abrasion and Washington degradation tests also did not succeed in separating the samples of a weaker quality. In a test where the effect of wet-dry cycles using in turn water, calgon and a sodium sulphate solution on lumps of mudrock was compared, it was established that the sodium sulphate solution was a more severe weathering agent and that it also affected some of the mudrocks in an "unnatural" way. This leaves doubt as to its use for testing accelerated weathering.

Other newly devised tests included a wet ball mill test, in which a ceramic container with porcelain balls was used, and an ultrasonic disaggregation test where a probe-type generator was employed to disaggregate crushed mudrock fractions. Both these tests gave a good range of values for the different samples.

A comparison was made of the quality ratings obtained from the different types of classification test. Certain mudrock samples were generally

given a good rating, while others were generally given a poor rating, but there was also a large degree of variation, mainly because the different types of test rated the samples according to different properties. Related tests were, therefore, compared graphically and statistically and a similar procedure was followed for "unrelated" tests when the rating sequences showed some similarity. In this way tests which were the most suitable for assessing certain rock properties, or which were capable of giving an indication of other relevant properties, could be selected.

It is considered that any rock requires three basic durability properties to perform satisfactorily during both the construction stage and the service period in a road pavement. These properties are: (i) resistance to crushing; (ii) resistance to abrasion; and (iii) resistance to decomposition. The 10 per cent FACT (soaked and dry) is preferred as a test to ascertain resistance to crushing. The results of this test also correlated reasonably well with those obtained from the rock strength tests i.e. the determination of uniaxial compressive strength and Brazilian tensile strength, the former being a test recommended by Olivier (1979a) for mudrock classification. It is recommended that the second rock durability property should be tested by means of the wet ball mill test, which measures abrasion in a wet environment, and which in the experiments showed a better spread of values than the Los Angeles abrasion test. The results also correlated well with those of the ultrasonic disaggregation test, a proven measure of durability. With respect to the third rock durability property, it is considered that since mudrocks are usually the end products of the decomposition processes, their mineralogical composition should not change rapidly. The sand equivalent test should, however, be carried out to avoid the use of rock materials with large amounts of deleterious clay minerals.

The mudrocks tested exhibited another characteristic which could unfortunately not be evaluated fully by the above tests, viz. break-down at different rates to various grain sizes and shapes on exposure to the atmosphere. The standard slake durability test was found to be suitable for the testing of slaking mudrock types but it could not differentiate between disintegrating mudrocks, even if more than two cycles were performed. For this purpose a five-cycle wet-dry test, which uses water and which evaluates disintegration on a qualitative basis, is preferred. This test can also, if necessary, be used to replace the slake durability test, by sieving the

material through a 2,0 mm mesh sieve after completion of the five wet-dry cycles.

Standard road specification tests, such as grading, Atterberg limits and linear shrinkage, compaction and CBR tests, should be performed on rock materials which have been subjected to a single wet-dry cycle after being crushed by means of the standard procedure. Other tests which should be continued are: (i) the Treton impact test, which correlates well with the 10 per cent FACT and which may replace it when the apparatus is unavailable, (ii) the determination of specific gravities and water absorption which correlate well with durability properties, (iii) the measurement of free swell to obtain more information about the expansiveness of southern African mudrocks, and (iv) ultrasonic disaggregation which is a proven measure of durability. The present study showed very little correlation between clay mineralogy and rock durability properties and X-ray diffraction analyses should therefore be continued on a greater variety of mudrocks to investigate this aspect further.

The results of the various studies conducted show that mudrocks can be used successfully for roadbuilding in southern Africa provided they are subjected to an adequate laboratory test programme and that sound construction techniques are used.

ACKNOWLEDGEMENTS

The author expresses his sincere thanks to the following people and institutions:

The promotor, Prof. C.P. Snyman, and co-promotor, Dr H.J. Olivier, for their able guidance and their contribution towards the improvement of the thesis, both technically and gramatically.

The Director of the NITRR, Dr S.H. Kühn, for his permission to use the work for a higher degree and Mr R.N. Walker, head of the Roads Branch for his support. The cooperation of Mr G.A. Jones and Dr F. Netterberg, past and present heads of the Soil Engineering Group, is also appreciated.

Mr J.L. Saunders for his highly competent assistance with laboratory work, calculations and checking of data. Special thanks are also due to my colleague Mr P. Paige-Green for many valuable discussions, assistance with the X-ray diffraction work and preliminary editing of the drafts.

Messrs D.J. Weston and F.J. Haupt of the NITRR for interesting discussions.

Mrs G.M. Hübener for the typing of the thesis.

NITRR Drawing Office for draughting the diagrams.

NITRR Routine Laboratory for carrying out some of the standard tests.

NMERI Geomechanics Division for doing the rock strength tests.

Mr J.J. de Jager of NIPR for a statistical formula to analyse duplicate results.

Dr R.E. Oberholster of the NBRI for checking the X-ray diffraction interpretation and Mrs C. Coetzee, formerly of NBRI, for her assistance with the microscope work.

Geological Survey for their assistance in the preparation of the thin sections and the major element analyses of the mudrock samples.

Sasol for the determination of the mudrock porosities.

Mrs J. Roché and Mrs B.M. Davies of the NITRR for their editing of the final draft.

The Roads Departments of the Cape Province, Natal, Orange Free State, Transvaal, Southwest Africa-Namibia and the Department of Transport for their cooperation in supplying information and also to the many civil engineers and engineering geologists who willingly participated in discussions with the author.

Finally to my wife, Marianne, for her constant support during the years of this study and to Almighty God who gave me the guidance and courage to complete the work.

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APPENDIX

FREE SWELL RESULTS: SAMPLE M1

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hrs	% of total swell after 6 hrs	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
1	Natural-dried at 50°C	0	0,053 0,214	0,108 0,245	0,453 1,269	21h30 22h00	58 38	113 65	72 45	0,054 0,054	11,9 4,3	0 0,006	0 0,5	1,09	1,45 1,64	
2	Natural - left open - dried at 105°C	1	0,096 0,147	0,002 0,212	0,561 1,045	22h40 22h45	70 122	0 130	85 52	0,070 0,085	12,5 8,1	0 0,002	0 0,2	1,35	1,69 1,79	0,22
3	Natural - left open - dried at 105°C	2	0,132 0,198	0,160 0,183	0,710 0,889	23h30 21h50	82 55	81 72	75 54	0,071 0,063	10,0 7,1	0,002 0,008	0,3 0,9	1,36	1,72 1,79	0,36
4	Oven dried - 3 days 105°C		0,182 0,147	0,166 0,145	1,305 0,589	22h45 22h30	202 61	280 148	75 28	0,150 0,041	11,5 6,9	0,020 0,002	1,6 0,3	1,29	1,67 1,90	
5	Oven dried - 4 days 50°C		0,197 0,095	0,230 0,213	1,556 0,832	22h00 22h15	63 15	73 21	85 11	0,138 0,053	8,9 6,4	0,016 0,006	1,0 0,7	0,98	1,52 1.76	
6	Natural-dried at 105°C	0			0,314 0,988 0,680 0,715 0,730	21h30 23h30 22h00 21h50 22h15			64 70 28 21 17	0,041 0,076 0,043 0,031 0,041	13,1 7,7 6,3 4,3 5,6	0,004 0,004 0,004 0,004 0,006	1,3 0,4 0,6 0,6 0,8	1,30	1,56 1,63 1,78 1,79 1,83	
7	Oven dried - 1 day 50°C				1,267 0,933 1,051 0,877	22h40 22h45 22h45 22h30			72 14 18 9	0,110 0,062 0,060 0,017	8,7 6,7 5,7 1,9	0,019 0,006 0,006 0,002	1,5 0,7 0,6 0,2	0,70	1,13 1,31 1,65 1,65	
8	Oven dried - 1 day 105°C				1,158 0,743 0,631 0,612	22h40 22h45 22h45 22h30			99 33 19 14	0,143 0,058 0,033 0,029	12,3 7,8 5,2 4,7	0,010 0,002 0,004 0,004	0,8 0,3 0,6 0,6	1,12	1,44 1,74 1,83 1,78	
9	Natural dried at 105°C	0			0,333 1,110 0,779	20h30 22h20 22h00			86 63 12	0,048 0,079 0,030	14,3 7,2 3,8	0,008 0,008 0,004	2,4 0,7 0,5	1,26	1,63 1,69 2,07	
10	Natural-dried at 50°C	0	0,079 0,164 0,191	0,077 0,230 0,156	0,433 1,300 0,738	20h30 22h50 22h35	122 47 12	198 51 20	78 58 13	0,070 0,114 0,044	1,62 8,8 6,0	0,010 0,010 0,004	2,3 0,8 0,5	1,07	1,43 1,63 1,83	
11	Oven dried - 1 day 50°C				1,054 0,837 0,957 0,815	22h00 22h45 22h50 22h45			46 19 15 7	0,113 0,042 0,052 0,018	10,7 5,1 5,5 2,2	0,014 0,004 0,006 0,002	1,3 0,5 0,6 0,2	0,67	1,14 1,34 0,97 0,67	
12	Natural-dried at 105°C	1	0,062 0,042 0,160	0,137 0,182 0,172	0,644 0,944 0,518	22h00 22h15 22h35	117 240 43	127 96 38	76 68 16	0,078 0,061 0,049	12,1 6,5 9,5	0,010 0,006 0,004	1,6 0,6 0,8	1,44	1,77 1,71 1,90	0,27

FREE SWELL RESULTS: SAMPLE M1 (continued)

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (Smax)			Total swell time (hours)	Time to reach half of maximum swell (min)			% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hours	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
			a	b	c		a	b	c							
13	Oven dried - 1 day 105°C				1,412	22h00			89	0,142	10,1	0,018	1,2	1,13	1,59	
					0,711	22h45			24	0,064	9,0	0,008	1,1		1,68	
					0,682	22h50			16	0,049	7,2	0,006	0,9		1,69	
					0,736	22h45			15	0,078	10,6	0,010	1,3		1,58	
14	Natural-dried at 105°C	2	0,068	0,149	0,908	22h30	60	79	67	0,088	9,7	0,010	1,1	1,47	1,88	0,69
			0,165	0,203	0,859	22h45	55	97	36	0,074	8,6	0,008	1,0		1,92	
			0,123	0,178	0,655	22h30	44	35	23	0,061	9,4	0,006	0,9		2,15	
15	Oven dried - 3 days 105°C		0,085	0,257	1,308	22h45	131	105	117	0,127	9,7	0,014	1,1	0,97	1,38	
			0,126	0,181	0,693	22h45	52	40	30	0,087	12,5	0,010	1,5		1,94	
			0,114	0,171	0,571	21h15	35	23	12	0,030	5,3	0,004	0,7		1,91	
16	Oven dried - 4 days 50°C		0,069	0,278	1,514	23h10	43	60	75	0,199	13,2	0,023	1,5	0,99	1,59	
			0,170	0,233	0,825	22h20	35	25	14	0,043	5,2	0,006	0,7		1,86	
			0,195	0,211	0,719	22h25	17	20	8	0,039	5,4	0,004	0,6		1,86	
17	Natural-dried at 105°C	7	0,142	0,157	1,230	22h00	41	66	38	0,066	5,3	0,008	0,6	1,42	1,96	0,48
			0,216	0,157	0,696	22h20	35	97	33	0,058	8,3	0,008	1,1		1,94	
18	Natural-dried at 105°C	14	0,177	0,182	1,201	23h10	71	60	57	0,105	8,8	0,011	1,0	*1,13*	*1,62*	*0,71*
			0,161	0,184	0,681	23h15	80	120	42	0,052	7,6	0,006	0,8		1,62	
19	Natural-dried at 105°C	30	0,175	0,101	0,906	24h20	61	150	67	0,074	8,2	0,008	0,9	*1,13*	*1,59*	*0,65*
20	Natural-dried at 105°C	63	0,189	0,171	1,181	22h55	82	82	40	0,060	5,1	0,006	0,5	*1,13*	*1,58*	*0,62*

FREE SWELL RESULTS: SAMPLE M2

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
7	Natural-dried at 105°C	0	0,049	0,035	0,056	18h10	150	90	190	0,016	29,6	0,002	3,7	1,17	1,28	
			0,190	0,091	0,254	24h00	450	1223	508	0,145	57,2	0,014	5,6		1,13	
			0,171	0,105	0,219	22h30	165	195	166	0,058	26,2	0,006	2,8		1,27	
8	Natural-dried at 105°C	1	0,045	0,046	0,134	22h30	109	150	107	0,029	21,7	0,004	2,9	1,20	1,31	0,11
			0,217	0,089	0,286	24h00	241	681	244	0,111	38,8	0,012	4,1		1,25	
			0,175	0,143	0,204	21h30	117	652	169	0,062	30,5	0,008	3,8		1,31	
9	Natural-dried at 105°C	0			0,092	18h10			62	0,011	12,5	0,002	2,1	0,98	1,17	
					0,496	21h45			60	0,063	12,7	0,002	0,4		1,25	
					0,345	22h00			60	0,069	19,9	0,004	1,1		1,62	
					0,341	20h50			40	0,042	12,4	0,008	2,2		1,57	
10	Oven dried - 1 day 50°C				0,276	22h30			61	0,034	12,2	0,004	1,4	0,44	0,56	
					0,269	21h45			90	0,053	19,9	0,002	0,7		0,96	
					0,256	22h00			120	0,069	27,1	0,004	1,6		1,13	
					0,266	21h10			95	0,061	23,1	0,002	0,7		0,99	
11	Oven dried - 2 days 105°C				0,272	23h10			382	0,143	52,4	0,015	5,4	1,05	1,08	
					0,248	21h45			124	0,061	24,6	0,007	3,0		1,25	
					0,246	22h00			115	0,061	25,0	0,004	1,5		1,30	
					0,246	20h50			99	0,063	23,8	0,007	2,8		1,16	
12	Natural-dried at 105°C	6	0,174	0,131	0,220	23h00	48	52	112	0,040	18,1	0,004	1,9	1,28	1,45	0,39
			0,202	0,108	0,279	22h30	68	89	115	0,061	21,8	0,006	2,3		1,36	
			0,178	0,131	0,214	21h55	66	166	94	0,053	24,5	0,006	2,9		1,29	
			0,171	0,122	0,282	23h05	66	99	65	0,053	18,7	0,006	2,2		1,39	
			0,133	0,122	0,250	21h25	82	105	53	0,036	14,3	0,004	1,7		1,39	
13	Natural-dried at 105°C	20	0,220	0,124	0,343	22h00	127	203	104	0,080	23,5	0,011	3,1	1,17	1,33	0,51
			0,185	0,132	0,263	21h10	108	124	122	0,066	25,0	0,008	3,2		1,30	
			0,163	0,115	0,205	23h15	116	189	148	0,049	23,7	0,004	2,1		1,32	
14	Natural-dried at 105°C	30	0,234	0,099	0,271	24h00	163	186	138	0,049	18,2	0,004	1,5	1,23	1,38	0,49
			0,202	0,105	0,206	23h05	94	100	99	0,049	24,0	0,002	1,0		1,35	
			0,181	0,108	0,224	21h25	60	83	93	0,051	22,8	0,006	2,6		1,39	
15	Oven dried - 7 days 50°C		0,259	0,136	0,267	21h45	220	240	177	0,071	26,5	0,008	3,0	0,90	1,12	
			0,227	0,117	0,242	22h10	99	126	198	0,041	16,8	0,004	1,7		1,31	
			0,218	0,122	0,253	22h40	74	95	41	0,043	16,8	0,004	1,6		0,97	
16	Natural-dried at 105°C	60	0,234	0,285	0,109	23h30	74	65	191	0,026	24,1	0,002	1,7	1,26	1,36	0,55
			0,208	0,182	0,110	23h00	103	111	148	0,030	27,1	0,004	3,4		1,35	
			0,205	0,161	0,110	22h45	96	88	139	0,030	27,1	0,004	3,4		1,36	
17	Natural-dried at 105°C	2	0,150	0,091	0,272	23h10	61	89	70	0,025	9,0	0,002	0,8	1,28	1,44	0,26
			0,189	0,109	0,276	20h25	111	365	109	0,064	23,0	0,010	3,7		1,35	
			0,190	0,110	0,267	21h30	80	183	74	0,047	17,7	0,006	2,3		1,42	
18	Oven dried - 6 days 105°C		0,215	0,105	0,364	23h00	325	585	203	0,123	33,7	0,004	1,1	1,18	1,26	
			0,196	0,105	0,247	20h25	96	141	99	0,055	20,7	0,004	1,5		1,36	
			0,167	0,096	0,257	22h10	108	236	112	0,055	21,5	0,006	2,3		1,39	

FREE SWELL RESULTS: SAMPLE M3

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (Hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
	Drying 105 C															
1	Natural	0	0,098	0,181	0,306	22h35	150	65	90	0,072	23,6	0	0	1,83	2,23	
			0,086	0,180	0,334	23h00	360	127	133	0,088	26,3	0,009	2,6		2,15	
			0,087	0,181	0,269	23h00	167	109	58	0,035	13,0	0,002	0,8		2,15	
3	Natural	29	0,074	0,149	0,207	23h30	336	184	355	0,066	32,0	0,009	4,1	1,52	1,85	0,37
			0,064	0,156	0,197	23h00	260	265	255	0,075	38,0	0,006	3,3		1,84	
			0,102	0,142	0,163	20h55	298	184	208	0,045	27,6	0,004	2,6		1,91	
4	Oven-dried - 4 days (long 1st swell)		0,173	0,197	0,393	71h00	349	338	329	0,165	41,9			1,58	2,04	
			0,137	0,173	0,250	23h00	138	283	212	0,061	24,5	0,002	0,9		2,06	
			0,114	0,160	0,205	21h55	120	110	129	0,040	19,5	0,002	1,1		2,17	
5	Natural	10	0,069	0,099	0,469	25h00	75	85	49	0,033	7,0	0,002	0,4	1,90	2,36	0,06
			0,079	0,167	0,492	22h00	120	96	72	0,055	11,2	0,002	0,4		2,30	
			0,073	0,173	0,377	22h00	73	53	32	0,027	7,1	0,012	3,3		2,32	
6	Natural	0	0,105	0,192	0,303	22h35	120	74	64	0,037	12,3	0,002	0,6	1,88	2,33	
			0,119	0,227	0,384	23h00	383	230	174	0,110	28,6	0,002	0,5		2,21	
			0,124	0,172	0,297	23h00	200	88	92	0,041	13,8	0,008	2,6		2,24	
7	Natural	3	0,098	0,208	0,569	20h55	49	34	32	0,033	5,8	0	0	1,13	1,68	0
			0,078	0,127	0,494	23h00	87	89	53	0,049	10,0	0	0		*2,46*	
			0,085	0,171	0,419	24h25	42	36	29	0,025	5,9	0	0		2,36	
8	Oven dried - 2 days		0,089	0,190	0,468	23h15	323	261	177	0,127	27,1	0	0	1,60	1,87	
			0,090	0,128	0,388	22h00	218	94	89	0,086	22,1	0,004	1,0		2,12	
			0,071	0,128	0,372	24h45	50	85	66	0,049	13,2	0	0		2,21	
9	Natural	1	0,089	0,206	0,479	21h00	111	115	46	0,037	7,7	0,002	0,4	1,79	2,24	0,03
			0,063	0,191	0,454	22h00	185	204	94	0,068	15,0	0,002	0,4		2,18	
			0,109	0,117	0,336	24h25	91	131	40	0,024	7,1	0	0		2,20	
10	Oven dried 2 days		0,135	0,325	0,621	23h15	?	321	237	0,223	36,0	0,004	0,7	1,59	1,36	
			0,129	0,213	0,482	22h00	178	118	163	0,079	16,3	0,004	0,9		2,25	
			0,054	0,233	0,454	24h45	40	116	48	0,049	10,7	0	0		2,41	

FREE SWELL RESULTS: SAMPLE M4

Cube No.	Sample Treatment	Left open for (days	Swell (%) (Smax)			Total swell time (hours)	Time to reach half of maximum swell (min)			% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
			a	b	c		a	b	c							
1	Natural	0	0,132	0,329	0,240	19h00	180	44	560	0,069	28,7	C,002	0,9	1,74	3,32	
			0,130	0,243	0,252	22h35	380	217	490	0,154	61,1	0,011	4,4		3,23	
			0,127	0,267	0,207	22h30	415	193	448	0,125	60,2	0,013	6,5		3,17	
2	Oven dried - 3 days (long 1st swell)		0,157	0,377	0,286	70h45	490	349	929	0,176	61,8	0	0	1,66	3,10	
			0,079	0,281	0,210	21h10	703	221	315	0,109	51,5	0,004	2,1		3,11	
			0,111	0,279	0,192	22h45	380	165	354	0,093	48,9	0,007	3,4		3,10	
3	Natural	0	0,108	0,281	0,216	20h00	367	130	298	0,066	30,6	0,004	1,9	1,63	2,88	
			0,099	0,262	0,163	22h35	643	353	603	0,108	66,7	0,010	6,2		2,61	
			0,096	0,251	0,183	22h30	638	281	727	0,128	70,3	0,004	2,2		2,62	
4	Natural	1	0,112	0,375	0,260	20h25	319	73	118	0,044	16,8	0,004	1,5	1,92	3,21	0,24
			0,120	0,174	0,205	21h10	713	270	465	0,125	60,6	0,008	3,8		3,07	
			0,126	0,293	0,196	22h45	419	169	320	0,083	42,4	0,004	2,0		3,05	
5	Natural	6	0,119	0,340	0,346	23h00	373	165	85	0,078	22,7	0,002	0,6	1,81	3,01	0,54
			0,074	0,206	0,214	23h50	553	220	238	0,084	39,6	0,006	2,8		2,90	
			0,050	0,235	0,167	23h30	225	120	360	0,084	50,6	0,008	4,8		2,86	
6	Oven dried - 2 days		0,092	0,382	0,213	22h48	293	119	544	0,137	63,9	0,008	3,7	1,61	2,98	
			0	0,296	0,205	22h35	0	68	449	0,121	58,7	0,008	3,8		3,03	
			0,057	0,214	0,189	23h00	190	51	368	0,097	51,0	0,004	2,1		3,05	
7	Oven dried - 2 days		0,094	0,184	0,214	22h50	601	611	217	0,072	33,9	0,005	2,5	1,60	2,50	
			0,068	0,175	0,175	22h35	691	653	195	0,063	36,1	0,005	3,1		2,56	
			0.047	0,177	0,185	23h00	?	495	224	0,078	42,2	0,007	3,9		2,62	
8	Natural	13	0,137	0,421	0,288	23h50	274	81	159	0,059	20,5	0	0	1,85	2,96	0,60
			0,093	0,232	0,181	23h00	410	212	220	0,054	29,6	0,004	2,0		2,81	
			0,104	0,246	0,185	23h30	350	144	174	0,046	25,0	0,004	2,0		2,78	
9	Natural	30	0,133	0,291	0,243	25h00	180	123	238	0,071	29,2	0	0	1,52	2,89	0,33
			0,079	0,226	0,176	22h10	570	277	420	0,101	57,4	0	0		2,73	
			0,104	0,168	0,157	23h40	375	210	320	0,071	45,2	0,002	1,2		2,76	
10	Natural	63	0,091	0,116	0,220	23h00	412	173	278	0,090	41,1	0	0	1,52	2,54	0,42
			0,077	0,127	0,157	23h40	748	420	595	0,102	65,0	0,006	3,8		2,40	
			0,086	0,130	0,157	23h25	658	324	500	0,092	58,8	0,004	2,5		2,36	

FREE SWELL RESULTS: SAMPLE M5

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (Smax) a	Swell (%) (Smax) b	Swell (%) (Smax) c	Total swell time (hours)	Time to reach half of maximum swell (min) a	Time to reach half of maximum swell (min) b	Time to reach half of maximum swell (min) c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
1	Natural	30	0,051	0,062	0,301	23h50	55	115	40	0,024	7,9	0	0	1,88	2,95	?
			0,040	0,061	0,248	23h30	237	190	94	0,032	12,8	0	0		2,93	
			0,022	0,087	0,266	23h20	300	160	78	0,038	14,2	0,004	1,5		2,90	
2	Oven dried - 1 day		0,041	0,084	0,262	24h50	404	290	148	0,058	22,2	0	0	2,09	2,92	
			0,019	0,088	0,233	22h55	420	245	154	0,055	23,5	0	0		2,99	
			0,041	0,075	0,248	23h15	388	286	158	0,057	22,8	0,006	2,4		2,99	
3	Natural	14	0,040	0,103	0,315	23h00	300	228	63	0,038	12,1	0,002	0,6	2,18	3,02	1,49
			0,031	0,087	0,220	22h00	350	233	151	0,065	29,6	0	0		2,94	
			0,059	0,081	0,265	23h20	258	280	136	0,063	23,7	0,004	1,4		2,97	
6	Natural	1	0	0,038	0,184	24h50	0	50	55	0,017	9,2	0,002	1,0	2,16	3,07	0,66
			0,042	0,073	0,262	22h55	336	310	231	0,090	34,5	0,002	0,7		3,00	
			0,020	0,074	0,276	23h15	330	295	221	0,090	32,7	0,002	0,7		3,00	
10	Natural	0	0,010	0,031	0,039	21h00	12	83	38	0,002	5,0	0	0	2,14	2,99	
			0,031	0,064	0,218	22h15	255	380	323	0,098	45,0	0	0		2,88	
			0,032	0,047	0,228	22h15	234	360	306	0,094	41,4	0	0		2,88	
11	Natural	0	0,006	0,030	0,069	21h00	62	43	49	0,006	8,3	0	0	2,24	3,16	
			0,040	0,036	0,241	22h15	315	148	310	0,101	41,7	0	0		3,07	
			0,037	0,085	0,260	22h15	317	319	293	0,105	40,4	0,002	0,7		3,09	
12	Natural	8	0,050	0,054	0,354	23h30	118	205	69	0,032	9,1	0,004	1,1	2,16	3,24	1,38
			0,046	0,043	0,261	22h00	273	314	145	0,056	21,5	0	C		3,17	
			0,051	0,060	0,292	23h15	335	306	154	0,056	19,3	0,002	0,7		3,14	
13	Natural	60	0,050	0,084	0,288	23h30	114	210	74	0,057	19,9			2,14	2,98	1,46
			0,036	0,075	0,261	21h10	195		160	0,077	29,5				2,96	
			0,049	0,121	0,271	23h10	152	208	166	0,077	28,5				2,95	
14	Oven dried - 2 days		0,033	0,052	0,265	24h00	729	420	240	0,105	39,7	0,008	3,1	2,07	4,08	
			0,032	0,051	0,254	23h20	599	360	199	0,065	25,6	0	0		2,90	
			0,032	0,060	0,248	23h00	480	237	155	0,055	22,1	0	0		2,91	
15	Natural	3	0,027	0,068	0,332	23h40	300	120	58	0,038	11,3	0,004	1,2	2,17	3,07	1,24
			0,016	0,046	0,269	23h45	689	325	176	0,083	30,9	0,004	1,5		3,04	
			0,032	0,043	0,306	23h20	300	220	168	0,085	27,7	0,004	1,3		3,01	
16	Oven dried - 3 days		0,047	0,083	0,315	23h40	321	256	173	0,071	22,6	0	0	2,21	2,99	
			0,040	0,057	0,279	23h45	300	340	171	0,061	21,9	0	0		3,14	
			0,048	0,082	0,298	23h15	280	285	179	0,061	20,4	0	0		3,12	
17	Natural	2	0,011	0,061	0,276	24h00	755	132	51	0,025	9,2	0	0	2,30	3,14	1,07
			0,036	0,064	0,279	23h20	285	289	193	0,086	30,8	0	0		3,12	
			0,036	0,066	0,298	23h00	255	208	170	0,068	22,9	0	0		3,15	

FREE SWELL RESULTS: SAMPLE M6

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max})			Total swell time (hours)	Time to reach half of maximum swell (min)			% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hours	% of total swell in last 2 hours	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
			a	b	c		a	b	c							
1	Oven dried - 4 days				0,785	71h40			240	0,267	34,0	0	0	3,94	4,97	
					0,665	24h00			95	0,114	17,1	0,002	0,3		5,25	
					0,648	21h35			60	0,073	11,2	0,009	1,4		5,50	
2	Natural	0	0,157	0,166	0,386	22h25	35	13	15	0,025	6,4	0,002	0,5	4,16	5,19	
			0,157	0,225	0,452	23h15	458	286	166	0,115	25,5	0,006	1,4		5,03	
			0,157	0,241	0,449	23h20	210	202	128	0,090	20,1	0	0		5,34	
			0,202	0,235	0,485	24h00	231	224	98	0,053	11,0	0,004	0,8		5,20	
3	Natural	0	0,154	0,173	0,417	22h25	101	21	83	0,070	16,9	0,006	1,4	4,22	5,04	
			0,225	0,103	0,554	23h15	161	144	228	0,189	34,2	0,006	1,1		5,00	
			0,213	0,246	0,576	23h20	198	162	116	0,129	22,4	0,002	0,3		5,01	
			0,245	0,263	0,533	24h00	86	142	144	0,093	17,4	0	0		5,09	
4	Natural	10	0,175	0,352	0,618	24h00	93	106	202	0,161	26,0	0,006	1,0	4,48	5,17	1,35
			0,208	0,266	0,623	25h00	154	164	136	0,179	28,7	0,006	1,0		5,13	
5	Oven dried - 1 day		0,209	0,342	0,627	23h45	583	344	263	0,232	36,9	0,022	3,5	3,72	4,23	
			0,230	0,218	0,485	22h40	193	180	184	0,150	30,9	0,004	0,8		5,01	
			0,224	0,102	0,540	23h20	145	?	74	0,068	12,7	0,002	0,4		5,08	
6	Oven dried - 1 day		0,058	0,180	0,609	23h45	779	675	226	0,175	28,7	0,024	4,0	3,74	4,06	
			0,205	0,249	0,486	23h40	220	286	114	0,141	28,9	0,014	2,9		3,36	
			0,219	0,255	0,557	23h20	147	166	104	0,133	23,8	0,004	0,7			
7	Natural	3	0,224	0,163	0,603	23h25	135	205	102	0,128	21,2	0,010	1,7	4,40	5,17	0,78
			0,204	0,071	0,440	23h05	335	?	228	0,136	30,9	0,006	1,4		5,09	
			0,235	0,210	0,461	21h35	172	184	147	0,132	28,6	0,014	3,0		5,31	

FREE SWELL RESULTS: SAMPLE M7

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
1	Natural	0	0,103 0,380	0,110 0,615	0,814 4,322	21h30 21h05	21 42	18 34	28 10	0,014 0,014	1,7 0,3	0,002 0	0,2 0	6,14	6,93	
2	Natural	3	0,399	0,435	3,268	23h30	14	14	8	0,020	0,6	0,002	0,1			*2,14*
3	Natural	1	0,225	0,220	2,455	21h40	12	15	9	0,022	0,9	0	0			*1,18*
4	Oven dried - 1 day		0,466	0,452	4,137	21h40	28	29	12	0,042	1,0	0	0	5,77		
5	Oven dried - 4 days		0,606	0,512	4,279	68h45	36	34	18	0,092	2,2	0	0	5,97		
6	Natural	0	0,097 0,455	0,099 0,541	0,758 3,668	21h30 21h05	6 47	11 39	21 10	0,017 0	2,2 0	0,006 0	0,8 0	6,31	7,13	
7	Natural	2	0,388	0,411	3,152	24h35	10	11	7	0,043	1,4	0,006	0,2			*2,18*
8	Oven dried - 2 days		0,641	0,568	4,308	24h35	42	44	21	0,034	0,8	0,002	0	6,04		
9	Natural	7	0,530	0,410	3,327	22h45	32	39	9	0,034	1,0	0	0			*2,83*
10	Natural	14	0,394	0,448	2,936	23h10	26	26	8	0,078	2,6	0,002	0,1			*2,87*
11	Natural	30	0,554	0,681	3,605	23h05	13	11	7	0,047	1,3	0	0			*3,03*

FREE SWELL RESULTS: SAMPLE M9

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
1	Oven dried - 2 days		3,833	1,976	3,864	05h20	2	2	2					5,11		
2	Oven dried - 2 days				1,967	05h20			3					5,19		
3	Natural	30	3,006	2,127	4,408	01h10	11	12	8							*2,72*
4	Natural	0	0,213	0,190	0,437	21h05	12	18	14					6,27		
			2,603	2,080	3,536	04h05	12	15	10					*5,15*		
5	Natural	0			0,618	21h05			2					5,97	6,45	
			2,888	2,547	3,115	04h04	9	11	6	None		None		*5,15*	*5,63*	
6	Natural	1	1,405 2,163(R)	1,221	2,515	22h30	10	13	9							*1,53*
7	Natural	16	4,158	2,309	2,340	00h22	4	7	4							*2,58*
8	Natural	3	1,162 3,703(R)	1,331	3,381	05h12	3	7	3							*1,94*
9	Natural	9	3,739	1,905	4,666	23h09	3	4	4							*2,20*

FREE SWELL RESULTS: SAMPLE M8

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (Smax)			Total swell time (hours)	Time to reach half of maximum swell (min)			% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
			a	b	c		a	b	c							
1	Natural	0	0,043	0	0,212	20h50	449	0	100	0,045	21,5	0,006	2,8	0,97	1,45	
			0,040	0,055	0,365	22h15	371	771	360	0,191	52,4	0,010	2,7		1,16	
			0,025	0,075	0,302	23h55	746	416	194	0,085	28,1	0,004	1,3		1,22	
2	Natural	7	0,030	0,024	0,143	24h50	420	450	463	0,061	42,9	0,006	4,3	1,08	1,38	0,18
			0,023	0,038	0,426	20h30	709	627	420	0,242	56,7	0,018	4,3		1,04	
			0,033	0,044	0,243	22h20	523	559	264	0,094	39,0	0,006	2,5		1,31	
3	Oven dried - 1 day		0,026	0,032	0,228	21h45	695	550	290	0,081	35,5	0,002	0,9	0,84	0,85	
			0,038	0,042	0,288	23h20	484	550	266	0,119	41,2	0	0		1,23	
			0	0,022	0,252	23h20	0	588	192	0,085	33,6	0,008	3,4		1,28	
4	Natural	0	0,047	0,043	0,207	20h50	165	150	120	0,056	26,8	0,006	2,7	1,16	1,68	
			0,054	0,032	0,363	22h15	341	706	147	0,113	31,1	0,009	2,6		1,17	
			0,032	0,046	0,293	23h55	408	495	182	0,100	34,2	0,007	2,5		1,21	
5	Natural	2	0,029	0,031	0,204	21h25	170	286	390	0,093	45,5	0,004	2,0	1,07	1,35	0,20
			0,042	0,040	0,292	24h50	480	480	310	0,131	45,1	0,004	1,4		1,05	
			0,026	0,026	0,221	22h20	792	464	160	0,079	35,8	0,010	4,6		1,06	
6	Natural	10	0,028	0,026	0,212	23h15	420	460	146	0,049	23,4	0	0	1,16	1,45	0,28
			0,051	0,036	0,321	20h30	630	732	190	0,118	36,8	0,012	3,7		1,07	
			0,029	0,048	0,273	25h45	923	555	263	0,116	42,8	0,014	5,1		1,39	
7	Natural	3	0,043	0,030	0,196	25h25	385	370	153	0,058	29,4	0,004	2,0	1,16	1,59	0,23
			0,038	0,068	0,309	23h15	759	573	174	0,137	44,4	0,008	2,5		1,16	
			0,036	0,040	0,265	22h25	569	585	80	0,066	24,8	0,006	2,2		1,18	
8	Oven dried - 4 days		0,072	0,069	0,488	70h25	1871	1960	405	0,280	57,5	0,008	1,7	1,13	1,52	
			0,052	0,045	0,322	24h15	512	623	225	0,121	37,7	0,004	1,3		1,26	
			0,061	0,049	0,318	22h20	377	405	279	0,140	44,1	0,017	5,3		1,37	
9	Oven dried - 1 day		0,026	0,046	0,250	21h45	790	656	300	0,083	33,1	0,012	4,7	0,93	0,93	
			0,057	0,047	0,281	23h20	334	350	296	0,126	44,8	0,006	2,1		1,20	
			0,053	0,066	0,237	23h20	390	331	147	0,067	28,3	0,006	2,5		1,17	
10	Natural	14	0,025	0,028	0,145	24h15	541	385	276	0,064	43,8	0,014	9,6	0,97	1,26	0,24
			0,043	0,025	0,206	23h55	624	747	246	0,082	39,4	0,008	3,8		1,04	
			0,041	0,036	0,298	25h45	530	800	293	0,117	39,3	0,006	2,0		1,22	

FREE SWELL RESULTS: SAMPLE M10

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
2	Natural	0	0,350	0,277	2,232	21h15	10	18	13	0,070	31,3	0,010	0,4	3,25 *2,53*	5,17 *4,43*	
3	Oven dried - 1 day		0,807	0,716	4,073	22h55	30	39	24	0,092	2,3	0,002	0	2,55		
4a	Natural	2	0,392	0,723	3,583	23h25	15	8	9	0,071	2,0	0	0			*0,69*
4b	Natural	22	0,832	0,827	4,605	23h00	12	8	10	0,064	1,4	0	0			*1,18*
5	Natural	7	0,580	0,745	3,215	23h10	23	19	15	0,103	3,2	0	0	3,06		*0,92*
6	Oven dried - 1 day		0,775	0,850	4,784	22h55	49	34	23	0,110	2,3	0	0	2,51		
7	Natural	35	0,697	0,442	4,002	22h00	43	42	21	0,080	2,0	0	0			*1,37*
8	Natural	0	0,362	0,365	2,508	21h15	11	10	9	0,080	3,2	0,015	0,6	3,23 *2,53*	5,36 *4,65*	
10	Oven dried - 4 days		0,784	1,351	5,191	71h15	49	37	40	0,094	1,8	0	0	3,06		

FREE SWELL RESULTS: SAMPLE M12

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hours	% of total swell in last 2 hours	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
1	Natural	2	0,112 0,191	0,161 0,159	1,369 2,318	24h50 22h20	120 125	67 83	57 27	0,115 0,095	8,4 4,1	0,004 0,012	0,3 0,5	2,26	3,19 3,55	0,37
2	Natural	0	0,096 0,205	0,076 0,234	1,017 2,100	22h15 22h40	164 113	136 114	26 84	0,065 0,087	6,4 4,1	0,002 0	0,2 0	2,21	3,02 3,27	
3	Oven dried - 1 day		0,150 0,148	0,149 0	2,205 1,487	22h00 22h15	158 61	160 0	56 20	0,147 0,066	6,7 4,5	0,008 0	0,4 0	1,70	2,73 3,04	
4	Natural	7	0,204 0,223	0,180 0,226	2,040 2,226	22h25 23h33	49 30	46 45	59 24	0,086 0,064	4,2 2,9	0 0	0 0	2,30	3,42 3,75	0,68
5	Natural	0	0,093 0,041	0,060 0,136	1,243 3,127	22h15 22h35	30 13	170 132	39 38	0,076 0,161	6,1 5,1	0,006 0	0,5 0	2,30	3,16 3,74	
6	Oven dried - 1 day		0,208 0,200	0,164 0,264	3,192 1,764	22h00 22h15	95 90	82 40	57 10	0,175 0,049	5,5 2,8	0,004 0,002	0,1 0,1	1,83	3,06 3,94	
8	Oven dried - 4 days		0,280	0,335	3,841	68h55	88	93	56	0,326	8,5	0,008	0,2	2,14	3,78	
10	Natural	38	0,248 0,170	0,216 0,184	2,240 1,719	23h10 24h05	82 23	48 40	45 18	0,140 0,066	6,2 3,8	0,006 0	0,3 0	2,26	3,34 3,51	1,17

FREE SWELL RESULTS: SAMPLE M11

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
1	Natural	68	0,112	0,134	0,518	22h45	42	234	122	0,111	21,5	0,002	0,4	1,48	2,35	0,72
			0,140	0,119	0,308	22h00	76	129	234	0,113	36,7	0	0		2,36	
2	Natural	30	0,159	0,126	0,576	24h05	672	669	196	0,160	27,7	0,002	0,3	1,47	2,15	0,74
			0,071	0,156	0,435	28h05	428	705	220	0,123	28,2	0,002	0,5		2,23	
			0,140	0,137	0,402	24h10	285	585	146	0,069	17,2	0,004	1,0		2,22	
3	Natural	97	0,188	0,179	0,674	24h40	75	110	113	0,119	17,7	0,009	1,3	1,48	2,58	0,60
			0,158	0,133	0,469	24h10	83	141	82	0,102	21,7	0,002	0,5		2,54	
4	Natural	14	0,145	0,063	0,528	24h35	420	820	206	0,170	32,2	0,002	0,4	1,44	2,08	0,65
			0	0,104	0,406	23h00	0	370	173	0,104	25,6	0,002	0,5		2,09	
5	Oven dried - 1 day		0,078	0,002	0,341	21h52	674	?	284	0,131	38,3	0,010	2,9	1,27	1,79	
			0,130	0,116	0,227	23h40	316	401	256	0,088	38,5	0	0		2,05	
			0,100	0	0,360	24h15	535	0	360	0,060	16,8	0,006	1,6		2,13	
6	Oven dried - 1 day		0,113	0,067	0,453	21h50	674	702	348	0,218	48,0	0,014	3,1	1,23	1,53	
			0,105	0,088	0,375	23h40	630	745	291	0,164	43,6	0,008	2,1		1,95	
			0,118	0,123	0,391	24h15	312	370	218	0,112	28,7	0,002	0,5		2,06	
7	Oven dried - 4 days		0,174	0,108	0,335	73h35	510	?	425	0,187	55,8	0	0	1,44	2,42	
			0,167	0,016	0,419	25h50	202	?	164	0,114	27,2	0,004	1,0		2,45	
8	Oven dried - 4 days		0,138	0,114	0,501	73h35	2480	2015	1808			0	0	1,40	1,97	
			0,137	0,121	0,404	25h50	823	640	365	0,167	41,3	0,004	1,0		1,99	
9	Natural	0	0,113	0,059	0,361	21h07	160	400	500	0,053	14,7	0,004	1,1	1,51	2,29	
			0,140	0	0,350	22h10	553	0	152	0,076	21,5	0,004	1,2		2,23	
			0,145	0,134	0,375	23h15	599	408	123	0,073	19,6	0	0		2,31	
10	Natural	0	0,112	0,100	0,385	21h05	409	225	96	0,109	28,4	0	0	1,50	2,12	
			0,138	0,116	0,384	22h10	586	540	381	0,192	49,8	0,004	1,0		1,86	
			0,141	0,058	0,408	23h15	395	?	236	0,142	34,7	0,006	1,4		2,13	
12	Natural	7	0,179	0,180	0,544	22h00	540	503	226	0,216	39,7	0	0	1,52	2,10	0,64
			0,128	0,153	0,408	24h35	286	264	181	0,110	26,9	0,004	1,0		2,18	
			0,132	0,166	0,420	23h00	225	206	135	0,090	21,5	0,002	0,5		2,22	

FREE SWELL RESULTS: SAMPLE M11a

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (mis) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
1a	Natural	0			1,376	23h05			19	0,087	6,3	0	0	2,68	4,40	
					3,007	22h10			17	0,054	1,8	0	0		4,98	
2a	Oven dried - 1 day				9,087	21h50			+40			0	0	2,07	6,13	

FREE SWELL RESULTS: SAMPLE M13

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
1	Oven dried - 2 days		0,099	0,058	0,124	23h30	669	0	278	0,054	43,8	0,004	3,1	0,56	0,61	
			0	0,064	0,102	24h00	0	563	388	0,054	52,8	0,002	1,9		0,73	
2	Natural	0	0,128	0,070	0,107	23h40	241	219	235	0,042	40,0	0	0	0,71	0,89	
			0,122	0,137	0,118	23h35	358	833	121	0,062	52,5	0,006	4,9		0,84	
3	Natural	14	0,133	0,189	0,098	28h05	282	239	400	0,068	69,7	0	0	0,67	0,90	0,13
			0,109	0,136	0,122	24h10	380	483	319	0,071	58,5	0,012	9,8		0,89	
4	Oven dried - 4 days		0,045	0,079	0,142	70h45	346	?	636	0,132	93,2	0,012	8,2	0,68	0,85	
			0,132	0,143	0,146	23h20	269	260	232	0,050	34,2	0,004	2,6		0,89	
5	Natural	2	0,143	0	0,177	23h30	242	0	159	0,040	22,6	0,004	2,2	0,79	1,01	0,09
			0,119	0,129	0,137	24h00	289	252	245	0,048	34,7	0,004	2,8		0,98	

FREE SWELL RESULTS: SAMPLE M14

Cube No.	Sample Treatment	Left open for (days)	Swell (%) (S_{max}) a	b	c	Total swell time (hours)	Time to reach half of maximum swell (min) a	b	c	% swell after 6 hours	% of total swell after 6 hours	% swell in last 2 hrs	% of total swell in last 2 hrs	Natural moisture content (%)	Moisture content after swell (%)	Moisture lost during air-drying (%)
1	Natural	0	0,030	0,054	0,192	20h35	2	2	1	0,004	2,0	0	0	11,93	14,01	
			0,149	0,192	1,456	24h25	5	6	2	0,027	1,9	0	0		13,98	
			0,208	0,175	1,340	21h25	1	3	1	0,018	1,3	0	0		14,03	
2	Natural	0	0,034	0,048	0,211	20h36	1	1	1	0,010	4,6	0	0	12,09	14,10	
			0,225	0,202	1,773	24h25	3	5	2	0,025	1,4	0	0		14,28	
			0,131	0,179	1,501	21h25	1	3	1	0,015	1,0	0	0		14,34	
3	Oven dried - 1 day		0,218	0,218	1,509	21h30	4	3	1	0,028	1,8	0	0	11,91	13,88	
4	Natural	7	0,520	0,174	1,172	24h30	1	2	1	0,008	0,6	0	0			*11,45*
5	Natural	2	0,181	0,150	1,265	22h50	1	3	1	0,006	0,5	0	0	12,84	14,47	10,68
			0,158	0,174	1,466	24h30	1	4	1	0,019	1,3	0	0		14,59	*10,65*
6	Oven dried - 1 day		0,266	0,201	1,696	21h30	2	4	2	0,028	1,6	0	0	12,31	14,10	
7	Natural	15	0,325	0,198	1,816	23h20	1	3	1	0,006	0,3	0	0		*14,67*	*11,36*
8	Oven dried - 4 days		0,190	0,193	1,433	71h34	8	7	6	0,059	4,1	0	0	12,61	14,50	
9	Natural	35	0,238	0,259	1,630	22h55	1	2	2	0,006	0,4	0	0		*14,73*	*11,13*

TEMPERATURE-HUMIDITY EXPERIMENT - PERCENTAGE SWELL RESULTS

Step no.	Cumulative time in days	Duration of cycle days	Temp. °C	Lambrecht relative humidity %	Thies relative humidity %	Percentage swell for samples												
						M1	M2	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
0	0	Original sample	20			0	0	0	0	0	0	0	0	0	0	0	0	0
1	3	3	20	88	96	0,18	0,12	0,06	0,09	0,15	0,36	0,24	0,21	0,74	0,41	0,30	0,03	-0,18
2	4	1	41	84	92	0,21	0,16	0,14	0,15	0,18	0,37	0,28	0,23	0,78	0,48	0,36	0,08	-0,56
3	5	1	20	89	98	0,20	0,14	0,13	0,13	0,16	0,37	0,26	0,22	0,75	0,43	0,32	0,04	-0,60
4	6	1	40	87	94	0,23	0,18	0,17	0,16	0,19	0,42	0,31	0,26	0,79	0,52	0,39	0,08	-0,56
5	7	1	20	88	97	0,20	0,15	0,14	0,14	0,17	0,39	0,28	0,23	0,75	0,45	0,32	0,04	-0,61
6	9	2	20	60	63	0,09	0,07	0,10	0,09	0,05	0,04	0,15	-0,07	0,57	0,16	0,32	0,02	-0,71
7	11	2	20	88	97	0,21	0,15	0,14	0,14	0,17	0,41	0,27	0,21	0,75	0,44	0,31	0,03	-0,61
8	13	2	20	59	62	0,09	0,07	0,10	0,08	0,05	0,09	0,15	-0,07	0,58	0,16	0,17	0,02	-0,72
9	15	2	20	87	97	0,21	0,15	0,14	0,13	0,18	0,43	0,27	0,21	0,75	0,44	0,31	0,03	-0,62
10	16	1	11	91	98	0,21	0,15	0,14	0,14	0,19	0,46	0,27	0,23	0,76	0,47	0,32	0,02	-0,63
11	17	1	51	81	86	0,22	0,18	0,19	0,17	0,18	0,39	0,29	0,18	0,75	0,46	0,33	0,08	-0,59
12	18	1	12	95	100	0,22	0,15	0,16	0,14	0,18	-0,02	0,28	0,23	0,75	0,45	0,31	0,02	-0,63
13	19	1	50	81	88	0,24	0,18	0,20	0,18	0,19	0,43	0,31	0,21	0,77	0,47	0,54	0,09	-0,55
14	21	2	20	90	98	0,23	0,16	0,18	0,15	0,19	0,45	0,30	0,22	0,77	0,48	0,41	0,04	-0,61
15	23	2	20	22	24	0,03	0,05	0,10	0,07	0,06	-0,04	0,06	-0,15	0,55	0,05		0	-0,82
16	25	2	20	89	98	0,22	0,15	0,16	0,14	0,20	0,42	0,28	+0,18	0,75	0,46	0,29	0,03	-0,63
17	27	2	20	23	25	0,03	0,05	0,10	0,07	0,07	0,36	0,06	-0,14	0,55	0,06	0,15	-0,01	-0,82
18	29	2	20	89	98	0,22	0,14	0,15	0,15	0,20	0,42	0,28	0,16	0,75	0,46	0,27	0,02	-0,64
19	30	1	40	84	93	0,25	0,17	0,19	0,18	0,23	0,46	0,31	0,18	0,78	0,49	0,37	0,08	-0,59
20	31	1	20	90	98	0,23	0,16	0,17	0,16	0,21	0,45	0,31	0,19	0,77	0,49	0,31	0,04	-0,61
21	33	2	20	63	67	0,14	0,10	0,14	0,11	0,13	0,34	0,19	-0,02	0,62	0,26	0,31	0,02	-0,72
22	35	2	20	88	98	0,23	0,16	0,17	0,16	0,21	0,44	0,30	0,18	0,77	0,49	0,31	0,04	-0,61
23	37	2	5	92	98	0,23	0,15	0,18	0,15	0,20	0,42	0,28	0,16	0,75	0,48	0,28	0,02	-0,65
24	39	2	50	21	23	0,05	0,10	0,12	0,09	0,08	-0,08	0,04	-0,15	0,58	0,05	0,50	0,04	-0,78
25	41	2	6	89	95	0,16	0,09	0,11	0,09	0,14	0,39	0,20	0,10	0,64	0,28	0,17	-0,02	-0,69
26	43	2	50	21	24	0,05	0,10	0,11	0,08	0,08	0	0,04	-0,13	0,58	0,04	0,22	0,04	-0,78
27	45	2	6	90	97	0,15	0,09	0,10	0,09	0,14	0,46	0,20	0,11	0,64	0,28	0,17	-0,02	-0,69
28	47	2	50	23	24	0,06	0,09	0,11	0,09	0,09	0,05	0,05	-0,13	0,58	0,09	0,16	0,04	-0,78
29	52	5	20	88	97	0,20	0,16	0,18	0,17	0,23	0,69	0,32	0,17	0,77	0,65	0,34	0,05	-0,62

TEMPERATURE-HUMIDITY EXPERIMENT - MOISTURE CHANGE RESULTS

Step no.	Cumulative time in days	Duration of cycles days	Temp. °C	Lambrecht relative humidity %	Thies relative humidity %	Percentage moisture change per sample													
						M1	M2	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	G
0	Original moisture contents		(%)			1,04	0,92	0,86	0,66	3,43	3,23	0,67	3,36	1,79	1,46	1,61	0,47	9,65	
1	3	3	20	88	96	0,26	0,19	0,49	0,42	0,75	0,59	0,42	0,34	0,55	0,47	0,43	0,19	-6,19	0
2	4	1	41	84	92	0,20	0,13	0,43	0,34	0,61	0,46	0,36	0,20	0,48	0,38	0,40	0,16	-6,29	0
3	5	1	20	89	98	0,26	0,18	0,52	0,41	0,73	0,59	0,37	0,34	0,57	0,49	0,46	0,19	-6,22	0
4	6	1	40	87	94	0,25	0,17	0,49	0,42	0,64	0,51	0,34	0,25	0,52	0,44	0,43	0,19	-6,32	0
5	7	1	20	88	97	0,26	0,19	0,52	0,45	0,78	0,63	0,40	0,37	0,61	0,50	0,49	0,20	-6,19	0
6	9	2	20	60	63	0,11	0,07	0,29	0,15	0,06	-0,08	0,20	-0,18	0,22	0,18	0,25	0,11	-6,61	0
7	11	2	20	88	97	0,26	0,18	0,49	0,39	0,72	0,53	0,38	0,29	0,57	0,47	0,44	0,19	-6,27	-0,01
8	13	2	20	59	62	0,09	0,04	0,20	0,14	0,01	-0,15	0,17	-0,23	0,19	0,14	0,23	0,10	-6,66	0
9	15	2	20	87	97	0,26	0,18	0,50	0,42	0,69	0,50	0,37	0,28	0,57	0,47	0,49	0,20	-6,27	0,01
10	16	1	11	91	98	0,26	0,19	0,54	0,45	0,81	0,62	0,40	0,36	0,60	0,51	0,50	0,10	-6,24	0,01
11	17	1	51	81	86	0,17	0,12	0,40	0,27	0,37	0,14	0,26	-0,03	0,38	0,30	0,33	0,14	-6,58	0
12	18	1	12	95	100	0,26	0,19	0,55	0,45	0,84	0,61	0,43	0,39	0,63	0,50	0,49	0,19	-6,19	0,01
13	19	1	50	81	88	0,20	0,13	0,42	0,31	0,42	0,16	0,27	-0,03	0,40	0,32	0,34	0,16	-6,58	0
14	21	2	20	90	98	0,23	0,16	0,48	0,39	0,65	0,44	0,36	0,24	0,58	0,46	0,47	0,20	-6,35	-0,01
15	23	2	20	22	24	-0,31	-0,31	-0,06	-0,20	-1,35	-1,37	-0,18	-1,58	-0,46	-0,41	-0,34	-0,06	-7,14	-0,02
16	25	2	20	89	98	0,13	0,05	0,42	0,35	0,40	0,11	0,35	0,11	0,52	0,44	0,41	0,19	-6,37	0
17	27	2	20	23	25	-0,36	-0,36	-0,07	-0,19	-1,41	-1,46	-0,19	-1,59	-0,46	-0,40	-0,36	-0,06	-7,15	-0,04
18	29	2	20	89	98	0,14	0,03	0,43	0,31	0,30	0,02	0,34	0,04	0,46	0,39	0,37	0,12	-6,43	-0,04
19	30	1	40	84	93	0,12	0,01	0,42	0,33	0,25	-0,06	0,30	0,07	0,40	0,33	0,33	0,14	-6,57	-0,02
20	31	1	20	90	98	0,14	0,03	0,49	0,36	0,46	0,14	0,35	0,11	0,55	0,46	0,43	0,19	-6,37	-0,03
21	33	2	20	63	67	0,02	-0,09	0,27	0,09	-0,26	-0,49	0,17	-0,40	0,21	0,17	0,22	0,11	-6,75	-0,02
22	35	2	20	88	98	0,12	0,02	0,45	0,37	0,41	0,12	0,36	0,10	0,55	0,45	0,43	0,19	-6,41	-0,02
23	37	2	5	92	98	0,15	0,03	0,48	0,36	0,47	0,16	0,38	0,12	0,57	0,47	0,46	0,21	-6,38	-0,02
24	39	2	50	21	23	-0,53	-0,52	-0,28	-0,34	-2,00	-1,96	-0,36	-2,09	-0,91	-0,72	-0,75	-0,17	-7,23	-0,04
25	41	2	6	89	95	-0,07	-0,13	0,18	0,14	-0,27	-0,42	0,14	-0,45	0,09	0,06	-0,12	0,05	-6,54	-0,04
26	43	2	50	21	24	-0,54	-0,54	-0,29	-0,35	-2,01	-1,96	-0,37	-2,10	-0,88	-0,74	-0,82	-0,19	-7,22	-0,05
27	45	2	6	90	97	-0,07	-0,14	0,17	0,11	-0,29	-0,43	0,15	-0,45	0,06	0,06	-0,20	0,04	-6,50	-0,03
28	47	2	50	23	24	-0,55	-0,54	-0,30	-0,35	-2,01	-1,97	-0,35	-2,09	-0,88	-0,74	-0,87	-0,17	-7,24	-0,05
29	52	5	20	88	97	0,12	0,01	0,45	0,35	0,39	0,08	0,34	0,02	0,52	0,43	0,33	0,17	-6,45	-0,04