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The effect of moisture content and composition on the compressive strength and rigidity of cob made from soil of the Breccia measures near Teignmouth, Devon

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THE EFFECT OF MOISTURE CONTENT AND COMPOSITION ON THE COMPRESSIVE STRENGTH AND RIGIDITY OF COB MADE FROM SOIL OF THE BRECCIA MEASURES NEAR TEIGNMOUTH, DEVON.

by

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in partial fulfilment for the degree of

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The effect of moisture content and composition on the compressive strength and rigidity of cob made from soil of the Breccia measures near Teignmouth, Devon.

Abstract

Earth has been used as a reliable building material for many thousands of years. Recently there has been a world wide renaissance in the use of earth as a building material due to its architectural versatility and environmental sustainability. However, in the United Kingdom it is regarded by the majority of building professionals as either obsolete or a novel historical material. The utilisation of earth as a modern building material and the repair of historic earth building structures is retarded by the uncertainty of the knowledge of the properties of the material.

This thesis considers earth building materials as composite materials containing a cohesive, low compression modulus binder fraction, a high compression modulus aggregate fraction, and a fibre fraction. The compression properties of a building material without fibre content (cob matrix material) are described in terms of the interaction between the binder and aggregate fractions, and moisture and the binder fraction. The effect of the moisture content of the material upon the compression failure mechanisms is described. Values of compression modulus predicted by a rule of mixtures equation are compared to experimental results for this material. The following mechanisms are proposed to account for the apparent discrepancy between the predicted and experimental results:

- the effect of pore size distribution and the proportions of binder and aggregate fractions upon strain magnification within the material
- the effect of an efficiency factor, primarily dependent upon the proportion of binder and aggregate fractions, which determines the degree to which the potential modulus of the material is realised.

Time Domain Reflectometry is employed for repeated, real time, non destructive measurement of the moisture content of an external cob wall. The results of these measurements are analysed and discussed.

This thesis proposes that consideration of cob as a composite material has developed a paradigm which will enhance the level of understanding of all earth building materials, enabling the manipulation and accurate prediction of their structural properties. This will be an important contribution to the realisation of the significant sustainable qualities of earth building materials by the current construction industry.

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[1] Note The following abbreviations have been used:'ts' for 'test series'; 'psd' for 'particle size distribution'; and 'm/c' for 'moisture content'. See 'Appendix C: variable glossary' for a complete list of abbreviations used in this thesis.

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Chapter 7) Discussion

Acknowledgements

Occasionally during this project I thought I would never reach the final stage of completion: writing the acknowledgements. The fact that I have is largely due to the influence of my supervisors. Collectively I owe them thanks for their confidence in my abilities. Individually, thanks to: **David Short**, for his perception (he is in fact so often right it can be irritating- but he is certainly no curmudgeon!); **Linda Watson**, for her encouragement and the concept of 'displacement activity', the thought of which has curtailed my time-wasting on many occasions; and **Bob Saxton**, for his enthusiasm about 'mud' and his practical experience of geotechnical engineering. I would also like to express my gratitude to the **School of Architecture** for generously continuing my funding. I enjoyed my time there.

It is cheering to consider the degree to which people I have encountered in my work at the University of Plymouth have been only too willing to offer help when asked ('I met someone researching earth as a *building material* today...'). First amongst these must be those who donated their physical labour and excellent company during the construction of the experimental wall used in this project. They are: **Andy Lewis**; **Joy Russell**; and **Ian Taylor**. I am also grateful for the help of: **Kenny Coventry** for assistance with statistical analysis (who deserves to be decorated for his patience- perhaps with tinsel?); **Richard Hartley** for assistance with characterisation techniques; **Nick Holden** for assistance with TDR measurement; and **Ian Taylor**, again, for redesigning and manufacturing the TDR probes used in the wall.

I am indebted to my examiners, **Bernard Lane** and **Steve Grove** for their many helpful suggestions about the first draft of this thesis. They had a great effect upon me.

My thanks to all at the **Devon Earth Building Association** whose concern for the well being of historic earth buildings initiated this project. I hope this work will be useful to them and others promoting the eminently sensible notion of building with earth.

Last, but not least (except in height), my wife **Heather** deserves praise for her endurance, support and honest encouragement.

Partly because he is far too young to object, this thesis is dedicated to our son, Jairus.

Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

Relevant seminars and conferences were attended at which work was presented; external visits were made for consultation purposes and papers prepared for publication. Practical experience of earth building was gained from working at Bowhill, an English Heritage property in Exeter. Consultancy work regarding the properties of an earth building material was undertaken for Paul Carpenter Associates, Consulting Engineers.

Presentations:
"The composition and properties of cob: a traditional West Country building material", Structural Repair and Maintenance of Historical Buildings III (STREMA), Bath, June 1993 (Joint presentation with Linda Watson, School of Architecture, University of Plymouth)
"Aspects of the Composite Behaviour of Cob", Out of Earth II, Dartington, May 1995

Conferences Attended:
Earth (Including: cob; pise; clay lump; and wattle and daub), York, March 1993
Earth Shelter Conference, Coventry, September 1993
Out of Earth, Dartington, May 1994
Out of Earth II, Dartington, May 1995

signed ______

date 18/2/97.

"It must be stressed that, contrary to common belief, building with earth is not a simple technology. The mere fact that natives of many countries have been building their houses with earth since thousands of years does not mean that the technology is sufficiently developed or known to everyone. It is indeed the lack of expertise that brings about poor construction, which in turn gives that material its ill reputation. However, with some guidance, virtually anyone can learn to build satisfactorily with earth, and thus renew confidence in one of the oldest and most versatile building materials."

Stulz and Mukerji, 'Appropriate Building Materials'.

Chapter 1: Introduction

This chapter introduces:

1.1) the demise of traditional earth building in the United Kingdom
1.2) the worldwide tradition and contemporary benefits of earth building
1.3) traditional and contemporary technology in earth building
1.4) approaches to the classification of earth building materials
1.5) project origin, aims and objectives.

1.1 The demise of traditional earth building in the United Kingdom

At the time of writing there are only a few builders, architects and engineers in Devon and Cornwall who are involved in the use of earth as a building material. The majority of these professionals concentrate on the maintenance, repair and alteration of traditional earth buildings using an earth construction technique and building material both of which are known as 'cob'. Traditional cob buildings are illustrated in plates 1.1 and 1.2. In the past however, the use of earth as a building material was commonplace in these counties, and in other regions of the United Kingdom, providing Devon with a population of earth buildings, "estimated in tens of thousands." (McCann 1983, pg. 17). The fact that some of these buildings are hundreds of years old illustrates that earth can be a robust, reliable building material if the quality of construction and maintainance is adequate. The discontinuation of the use of earth as building material in the United Kingdom is related to the demise of vernacular architecture. This demise was the result of a number of related factors including an increasing awareness of stylistic fashion, the mass production of building components, improved transportation of building materials, increasing urbanisation, and changing building practices (Clarke 1992). One example of the changes in the building practise which had a readily apparent impact on the use of earth as a building material is the development of building regulations dictating suitable materials and construction methods.

plate 1.1

Traditional cob building, Ringmore, South Devon

(courtesy of Linda Watson)

plate 1.2

Traditional cob building in poor repair,

South Molton, North Devon.

Building control in the United Kingdom originated to reduced fire hazard within heavily populated areas but slowly evolved to encompass other aspects of building construction (Ley 1995). During this evolution building control legislation neglected the use earth as a building material. This is described by Ley (1995), a Building Inspector of the North Devon District Council.

"Model building byelaws introduced after the Local Government Act 1858 required external and party walls of every new building to be constructed of brick, stone or other hard non combustible material. Clearly cob fell into that category, but in trying to clarify structural details amendments were introduced stating that walls be constructed of materials as set out in the schedule to the byelaws. The schedule described only walls of brick or stone defining thickness to height [ratios]. No such rules were introduced for cob and consequently the use of this material could not meet these specific requirements and was generally not permitted."

This situation was not rectified in later amendments to building control legislation until 1985. Ley continues, "Whilst the Approved document does not refer to the use of cob, the guidance notes to Regulation A7 (Materials) - (HMSO 1985), states that any material which, 'can be shown by experience such as in a building in use, to be capable of performing the function for which is is intended', is satisfactory. After a hundred and thirty five years of building control cob can now be considered as suitable."

As a direct result of this exclusion of earth from the building codes traditional earth building techniques were discouraged not only in Devon and Cornwall but in several other regions throughout the United Kingdom. Recently interest in these traditional earth buildings has increased resulting in the formation of a conservation based 'practitioner network', which is disseminating knowledge of conservation practice throughout the United Kingdom, and several 'regional earth building groups'[1] promoting the benefits of earth building materials in particular regions of the United Kingdom.

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[1] contact address for the regional earth building groups, and other useful addresses are in 'Appendix B: contact addresses'.

1.2 The worldwide tradition and contemporary benefits of earth building

The tradition of building with earth is not limited to the United Kingdom. In fact, "There is hardly an inhabited continent, and perhaps not even a country, which does not have a heritage of buildings in unbaked earth, and even nowadays more than a third of all humanity lives in a home built of earth." (Houben & Guillaud 1994, pg. 3) In many developing countries technology transfer projects are 'updating' the indigenous earth building techniques and educating the governments and populations about the economic and ecological benefits of earth as a building material. These benefits are described below (Houben & Guillaud 1994, pg. 3).

- Economic: the capital investment necessary for the production of construction materials of the developed world is high. Such investment is usually achieved in the form of a loan, the repayment of which in a foreign currency is a burden on the economy of a developing country. Particular earth building technologies are cheap, effective alternatives to the construction materials of the developed world.

- Environmental: earth as a building material does need to be fired to develop properties useful in construction. Therefore the energy requirement of unbaked earth building materials is low avoiding depletion of natural resources. Furthermore, the production of earth building materials, depending on the choice of technique, need not be centralised, resulting in reduced transportation costs.

1.3 Traditional and contemporary technology in earth building

There are two areas of development for earth building: new build using contemporary technology and the maintenance and repair of historic buildings predominantly using traditional technology. Dirk Bouwens, secretary and treasurer of a regional earth building group in the United Kingdom, EARTHA (The East Anglian Regional Telluric Houses

Association, established 21st November 1994), has linked the development of new build earth technology with the conservation of traditional earth buildings by commenting that, "Proper conservation can only occur by raising the status of the material by promoting new build." The successful development of both of these areas relies upon detailed knowledge of the performance of earth as a building material.

1.4 Approaches to the classification of earth building materials

An 'earth building material' is defined in this thesis as an earth based material which has been processed such that it is suitable for the construction of buildings. The production of the building material and the construction of the building may occur simultaneously or be discrete processes depending on the construction technique employed. This issue is discussed in Chapter 3, section 3.1. In order to investigate the properties of earth building materials the earth building literature adopts the following approach: the classification of materials according to how they are produced, subsequent investigation of the properties of the raw materials and those of the processed material in isolation from those of materials resulting from other production techniques. Examples of this approach are found in 'Earth Construction', Houben and Guillaud, and 'Building in Cob, Pise and Stabilised Earth', Williams- Ellis and Eastwick- Field. Such classification by production technique has the following disadvantages.

i) It overlooks the common aim of all production techniques of earth building materials: to produce a material with sufficient internal cohesion to withstand the forces it experiences and attack by the environment. Depending on the construction technique these forces may be the result of the weight of the material or a combination of the weight of the material and additional load applied to it by the structure.

ii) It overlooks general compositional similarities of all earth building: they are mostly comprised of mineral particles formed by the weathering of rocks ('earth' or 'soil') (Craig 1983, pg. 1).

iii) It requires a great amount of experimentation to determine the properties of earth building materials produced by different techniques.
iv) It does not enable information acquired from testing a material formed by one production technique to be used to predict the properties of material produced by a different technique.

An alternative approach to the classification of earth building materials is to examine the relationship between building function, material, shape, size and process. This is illustrated in figure 1.1 (Ashby 1992). This figure shows how the functions of a building are satisfied by a combination of the building material and the shape into which the building material is formed. Both the material properties and the shape of the building will be influenced by the production process employed.

This perspective on the use of earth building materials suggests the investigation of the effect of building material, shape and process, as individual elements satisfying the functional requirements of the building. The fact that all production techniques of earth building materials aim to produce a coherent material, and that all earth building materials have general compositional similarities (points (i) and (ii) above), suggest a range of mechanisms common to all earth building materials by which their properties are developed. Investigation of the properties of earth building materials, therefore, should concentrate upon the range and nature of these mechanisms. Examining the relationship between these 'property developing mechanisms', production processes, and particular attributes of the constituent materials will result in more effective use of earth as a building material. This approach also avoids the two disadvantages of classification by production technique, listed in points (iii) and (iv) above, by minimising the amount of experimentation necessary to predict the properties of different earth building materials. This is because an understanding of the mechanisms responsible for the development of the properties of earth building materials provides a framework to transfer behavioural knowledge of one type of earth building material to another.

How building requirements are satisfied by properties of material, shape and process

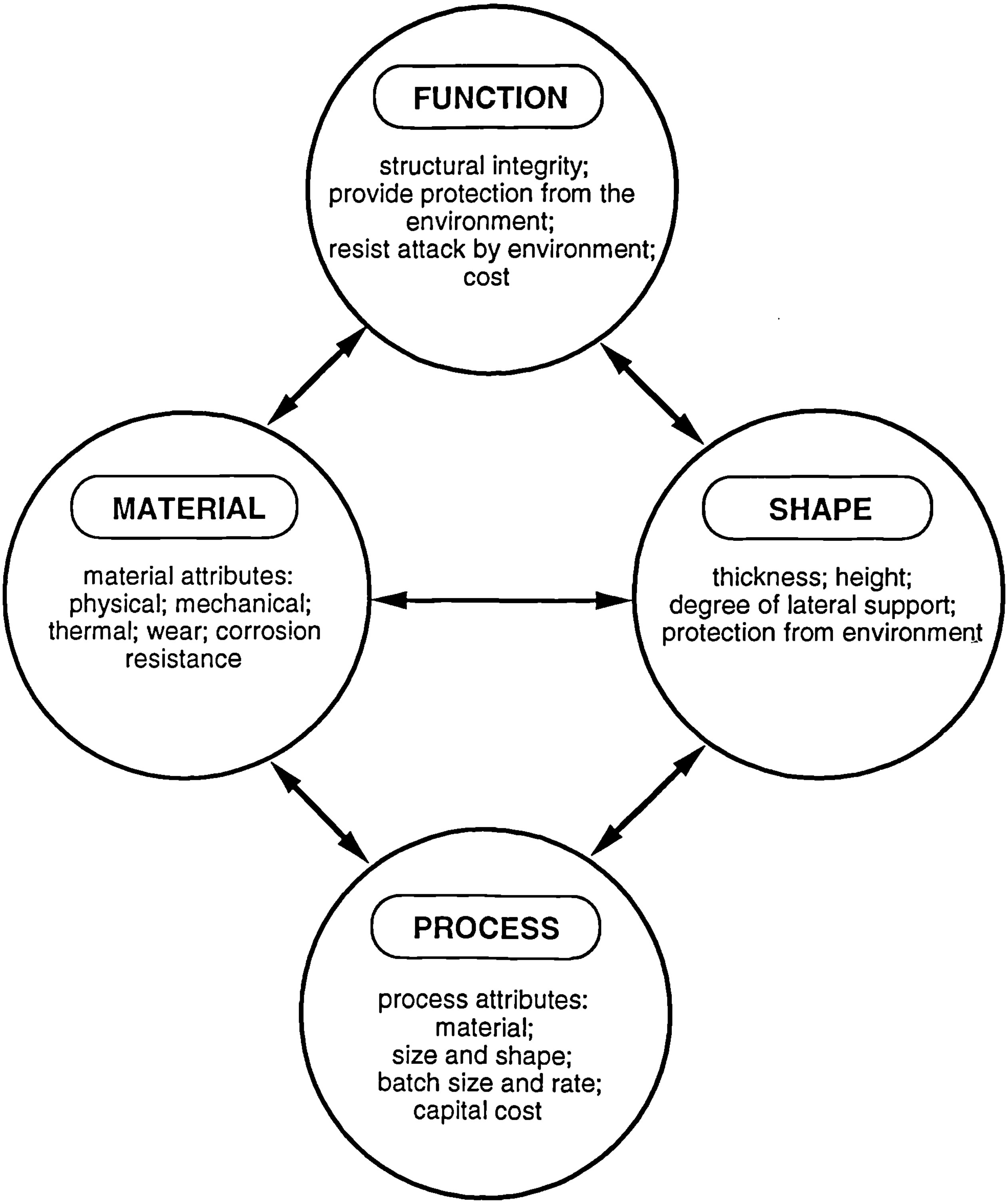

figure 1.1

Such knowledge can be used in conservation to develop repair and maintenance methods which are sympathetic to the building material. In new build this knowledge can be used to prove that the material meets building regulations, to persuade sceptical developers of its suitability, and to provide guidance for the manipulation of the earth material in order to maximise particular properties.

1.5 Project origin, aims and objectives

This project originated when the practitioners on the working group of the Devon Earth Building Association approached the University of Plymouth having identified a need for knowledge of the performance of cob in order to establish good practice procedures for the production and construction of cob.

The aim of the project is to enable the behaviour of a range of earth building materials, produced by the cob technique, to be predicted from knowledge of the properties and arrangement of their constituents.

This aim was to be achieved by:

- the analysis of the results of a series of compression tests on samples of earth building materials of different compositions; and
- the analysis of the results from the monitoring of the moisture content of an experimental cob wall.

Chapter 2: Context

This chapter will consider the background against which this project existed. It will discuss:

2.1) the different focuses of building in earth worldwide with emphasis upon the United Kingdom
    2.1.1) the maintenance and repair of existing buildings
    2.1.2) 'new build' construction
2.2) classification of earth building literature
    2.2.1) discussion of technical earth building literature
2.3) additional literature relevant to this project.

2.1) The different focuses of building in earth worldwide and in the United Kingdom

Present day use of earth as a building material is classified here into two groups: new build (completed since the Second World War); and the maintainance and repair of existing buildings. These categories are discussed below.

2.1.1) The maintenance and repair of existing buildings

Both worldwide and in the United Kingdom, there is a concentration of effort upon the maintenance and repair of existing buildings. International interest in this area is demonstrated by the conservation bias of the only international conference on earth building, organised by ICOMOS. ICOMOS defines itself as, "an international nongovernmental organisation composed of sixty national committees which form a world wide alliance for the preservation and protection of historic buildings, districts and sites." (ICOMOS promotional leaflet). This is a clear declaration of a conservation interest. The majority of papers contained in the ICOMOS conference publications focus upon building conservation. These conferences are:

- 5th International Meeting of Experts on the Conservation of Earthen Architecture, Italy 1987;
- 6th International Conference on the Conservation of Earthen Architecture, New Mexico 1990; and
- 7th International Conference on the Study and Conservation of Earthen Architecture, Portugal 1993.

Interest in the United Kingdom in the maintenance and repair of existing buildings is apparent from the following observations.

i) That national conferences and courses on earth building held in the United Kingdom during the last three years have had a building conservation biased content. Such events included 'Earth (including cob, pise, clay lump, wattle and daub)' a course held annually by the Institute of Advanced Architectural Studies which is at the University of York Centre for Conservation Studies; and 'Out of Earth I' (1994) and 'Out of Earth II' (1995) organised by the Centre for Earthen Architecture, University of Plymouth, in collaboration with ICOMOS (UK) Earth Structures Committee, English Heritage and Historic Scotland.

ii) That regional 'earth building groups' have been established in areas of the United Kingdom with populations of historic earth buildings. Three regional groups already in existence are the Devon Earth Building Association (DEBA), the East Anglian Regional Telluric Houses Association (EARTHA), and the East Midlands Earth Structures Society (EMESS). Although all of these groups have in their constitutions a commitment to the promotion of new build in earth, this is placed below commitments such as the aim to, "provide advice on the maintenance and repair of earth buildings" (DEBA and EARTHA).

iii) That the United Kingdom (ICOMOS) Earth Structures Committee was established in 1994. This is a sub committee of the International Council on Monuments and Sites (ICOMOS).

iv) The involvement of the University of Plymouth in the development of repairs standards as its contribution to the work of the European Earthen Architecture Research Network, established in 1995.

At present, the amount of repair and/ or maintenance work that is under taken in the United Kingdom is not recorded. However, the estimation of 40 000 earth buildings in Devon (Keefe 1992) can be taken as an indication of a considerable volume of on-going repair and maintenance of earth buildings.

Contact addresses for both regional building groups and the Earth Structures Committees are listed in 'Appendix B: contact addresses'.

2.1.2) 'New build' construction

This is the construction of new buildings using earth. This category includes the construction of extensions in earth to existing earth buildings. A distinction is drawn between the earth construction technique and the design of the form of the building. This is because new build may occur in any of the following combinations:

i) current construction technique with a contemporary form;
ii) current construction technique with a traditional form;
iii) historical construction technique with a contemporary form;
iv) historical construction technique with a traditional form.

'Historical' techniques are those with a significant traditional heritage. 'Current' techniques are those developed and practised since the Second World War.

Category (iv) above shows that new construction in earth need not necessarily take advantage of modern technology or knowledge but may represent an attempt to recreate the past.

Some countries have maintained a continuous tradition of building with earth, for example New Mexico, Australia and India. In other countries the tradition of building with earth was abandoned in favour of modern materials, such as concrete and fired brick, in the believe that this approach improved the quality of constructions. In such countries, for example France England and Germany, the use of the earth as a building material is being revived. The primary motivations for this change in materials are the current interest in the sustainable qualities of the earth building materials, and the notion that the 'user friendly' attributes of earth can facilitate self build construction.

World wide there is a significant amount of new build occurring in earth materials. This is apparent from the following examples of new construction (Houben 1995):

i) in California in 1980 new build houses made of sun dried earth bricks numbered nearly 200 000 and the use of this material was steadily increasing;

ii) in Mexico 850 earthen houses have recently been built in the state of Zasatecas; and

iii) at least 8 000 000 units of urban and peri- urban housing of African countries will be built in earth over the next ten years.

In contrast to this global perspective, interest in new build construction in the United Kingdom using earth materials has been, until very recently, limited. In Devon , for example, new build in earth materials has been restricted to a very small number of houses (for example Tricombe in Honiton, Devon, constructed by Kevin McCabe) and extensions to existing earth houses (for example Bushells Cottage, Down Saint Mary, Devon constructed by Alfie Howard). These examples are of construction using a traditional form and technique, cob. However, currently interest in new build construction is growing in the United Kingdom. This is apparent from:

i) the Millennium funded Sustainable Earth Centre, Doncaster, which, although at the developmental currently, is planned to include significant amounts of earth walling;

ii) the interest of undergraduate students at the Plymouth School of Architecture, University of Plymouth, in a module about construction, design and environmental implications of earth building; and

iii) inquires to the Centre for Earthen Architecture for information on new earth building.

2.2) Classification of earth building literature

The texts considered in detail in this chapter are classified according to thier content and intended readership.

a) **Earth building manuals**: these are intended as guides for construction using earth building materials. There are three types of earth building manual.

i) 'Specification texts' written for those who wish to specify or manage construction using earth building materials. The texts examined here are:
'Building with Earth' (Doat et al 1985);
'Building with Earth a Handbook' (Norton 1986); and
'Earth Construction', (Houben & Guillaud 1994).

All of these texts are aimed at enabling earth construction in developing countries: their content is, therefore, similar. All of these texts consider:

- soil evolution, composition and types together with its characterisation by 'field tests' and standard geotechnical techniques including particle size distribution and material 'limits' (these 'limits' are considered in chapter 5 of this thesis)
- stabilisation of soil by the inclusion of additives to improve its properties
- rammed earth, direct shaping, adobe and compressed block production and construction techniques (these techniques are illustrated in chapter 3 of this thesis)

- quality assurance tests
- use of finishes or renders on earth walls.

In addition, Doet and Houben & Guillud both consider the implications of seismic activity upon the use of earth building materials.

Of these texts, the most comprehensive is Houben & Guillaud, it considers materials not included in the others (for example, clay straw blocks and extruded earth). However, none of these texts investigate, beyond the fundamental observation that the cohesive properties of soil are related to there clay content, the mechanisms by which earth building materials develop their properties.

ii) 'Design texts' written for building professionals, architects and engineers, wishing to employ earth building materials in their designs. Many examples of this type of earth building manual are written for and by architects, typically such books will include commentary on the aesthetic possibilities of these materials. Examples considered here are:
'Building in Cob, Pise and Stabilised Earth' (Williams- Ellis et al 1947) and 'The Rammed Earth House' (Easton 1996).

Williams- Ellis et al attempted the first comprehensive survey of earth, both historic and current, building techniques appropriate for use in the United Kingdom. The initial motivation for this was the scarcity of construction materials following the First World War. The hoped for revival of earth building materials failed to emerge. This book was republished after the Second World War, when construction materials were scarce again. The book considers in detail the techniques of rammed earth, adobe, stabilised earth, and cob and chalk mud: some example designs and constructions are discussed. The material qualities demand by each technique are considered in isolation from the other techniques. There is a failure to recognise that the brief descriptions of suitable materials are similar. There is very little discussion of classification processes, material 'limits' are only briefly mentioned, and particle size distribution ignored completely. There is no mention or discussion of the mechanisms by which earth buildings materials fail under load. Although this book is nearly fifty years old, it is still an often cited text and is the earliest example found during this project of a methodology often adopted elsewhere, even to the present day. This is the methodology of the classification of earth building materials by their construction technique.

The Rammed Earth House (Easton 1996), is considered a modern equivalent of the Williams- Ellis text, although this book only considers the construction technique of rammed earth. As with Williams- Ellis, there is discussion of architectural plans and example constructions. Analysis of the raw material, soil, is more detailed than that of Williams- Ellis; even so the soil characterisation, selection, testing and stabilisation are all considered briefly in just one 18 page chapter.

iii) 'Self build texts' written for the construction workers.
The example of an owner builder text considered here is 'Dirt Cheap the Mud Brick Book' (Archer & Archer 1976).
This text, concentrating exclusively on the production and construction using hand moulded earth block ('adobe'), contains some content included in the manuals described in (i) above. However, there is no discussion of the testing of building blocks, or even of the requirements of any building code, and the techniques of soil selection consist only of field tests.

b) **Earth building codes**: these will certainly contain acceptance criteria for particular tests, including definition of the required structural properties of the earth building material(s). Earth building codes may also contain advice on: the selection of suitable soils and stabilisers; production and construction techniques; and design criteria. Currently there are no internationally recognised earth building codes; instead codes are being written for individual countries or regions of countries. The following variables may limit the usefulness of a building code outside the area for which it was written: the type of raw material available for earth construction, the environment that the earth structures must withstand (for example monsoons or earth quakes), and the degree of legislation involved in the construction process. It is common for building codes to only consider earth building material resulting from one particular construction technique.

Examples considered here are:
'Notes on the Science of Building' numbers 13, 18, 20 and 22, (Commonwealth Experimental Building Station 1950, 1964, 1951, 1964)
The New Mexico Building Code for Adobe 1982, partly reproduced in 'Adobe and Rammed Earth Buildings, Design and Construction' (McHenry 1984)
'Rammed Earth Structures: a code of practice' (Keable 1996)
The series of 'Notes on the Science of Building' collectively addresses rammed earth and adobe construction techniques. These 'notes' consider the selection of suitable soils, the foundations, finishes, and damp proofing methods appropriate to these techniques. There are no criteria for the physical testing of these materials.

The content of all of these guides is referenced to 'Earth Wall Construction Bulletin 5', Middleton (1949). This 'bulletin' has recently been updated (Middleton 1987) but was not available for review.

The 1982 New Mexico Building Code for Unburned Clay Masonry considers not only hand adobe, but also 'hydraulically pressed units' ('compressed block'), cut sod blocks, and low temperature kiln fired blocks. The term 'stabilised' is reserved for blocks treated to improve their water resistant properties. From the section of this reproduced by McHenry, it is clear that other sections of the code consider rammed earth construction. The other sections of this code have not been available for review.

Funded by the Overseas Development Agency, Keable has recently published a code of practice which exclusively considers rammed earth structures. The document is primarily written to provide quality assurance of structures built in developing countries. The code considers materials selection, using both field tests and laboratory tests, as well as formwork, foundations, stability and openings in walls, finishes, and the installations of services. This text also introduces a novel, non destructive method of assessing the compressive strength of walls. The method uses hand held apparatus which produces an indentation on the surface of walls of sub standard compressive strength.

c) **Earth building research:** this is current in the areas of new build and building conservation. Much of the current building conservation research is field based and is presented in conference papers, indeed the 7th International Conference on the Study of Earthen Architecture, Portugal 1993, included an entire section of 22 papers presenting the results of 'Field Research in Conservation'. There is also research interest into the impregnation of chemicals, for example acrylic copolymers and siloxanes (Sramek & Losos 1990), to 'stabilise' historic earth materials in uninhabited monuments. This thesis is concerned with the relationship between the composition of cob and its properties. Therefore, only papers investigating the properties of earth as a building material will be considered in this chapter. These are:

'Structural, heat- transfer, and water- permeability properties of five earth-wall constructions' (Whittemore 1941)
'Influence of different parameters on the resistance of earth used as a building material' (Olivier & Mesbah 1987)
'The influence of the mixing and the type of press on the making of compacted earth bricks' (Olivier et al 1989)
'Technological Properties of Earth Based Construction Materials Treated with Hydraulic Cement or Acrylic Polymer' (Atzeni et al 1933).

Whittermore's research paper, although dated, typifies an approaches still adopted currently. Whittermore studied the behaviour of a range of earth building materials, including stabilised and unstabilised adobe and rammed earth, under compressive, transverse, concentrated, impact and racking load (it is not apparent from this paper what is meant by the term 'racking'). However, the discussion of soil type is limited to a numerical description of the particle size. No consideration is given to the effect that the nature of the raw material might have upon the properties of the building materials studied.

Like Whittemore's paper, the paper titled the 'Influence of different parameters on the resistance of earth, used as a building material' (Olivier & Mesbah), considers the mechanical properties of earth as a building material. In this the mechanical property is the compressive strength of compacted clay bricks, which is measured for a series of specimens produced by various manufacturing and curing parameters. This experiment is conducted upon six different soils and their granulometry ('particle size distribution') is reported. The effect of their particle size distribution upon the efficacy of the production process, and the efficacy of the production process upon the compression strength is considered. However, how the particle size distribution of the materials affects the compression strength of the test samples is not considered: the 'internal structure' and failure mechanisms of the materials are not discussed.

The only example of literature found to investigate the effect of internal structure upon earth building materials, (Atzeni et al 1933), does so for only one type of soil, the particle size distribution of which is not reported. Here the materials under investigation are stabilised by the addition of cement or latex. The effect of the inclusion of varying amounts of these stabilisers upon the internal structure of the soil, investigated through measurement of pore size distribution, is discussed. It appears that more useful results would be generated from investigating the affect of the particle size distribution of the soil on the pore size distribution of the earth building material.

d) Practical conservation guides: these texts are written for conservators, either professional or amateur, wishing to carry out repair and maintenance upon earth buildings. The following examples, considered here, are written for conservators working in the United Kingdom.
'Practical Building Conservation Volume 2: Brick, Terracotta, and Earth' (Ashurt & Ashurst 1988)
'The Conservation of Clay and Chalk Buildings' (Pearson 1992).

'Practical Building Conservation Volume 2...' evolved through the author's work on a technical report for English Heritage. This book is the second volume in a series of five volumes examining the conservation of the following building materials stone masonry; mortars, plasters and renders; wood, glass and resins; and metals. Of the 126 pages of Volume 2, only 39 pages consider the repair and maintenance of earth building materials. However, a section at the beginning of this volume which considers causes and control mechanisms of 'damp' in buildings, is also relevant to earth building materials. The earth building materials discussed are cob, chalk mud, rammed earth, clay lump and daub. These are historical techniques, all of which, except rammed earth, have a significant tradition in the United Kingdom. For all these materials there is discussion of history and distribution; the selection, via field tests, of suitable soil for repair material; decay mechanisms; and appropriate repair techniques.

Pearson (1995) was motivated to write a practical conservation guide by his professional involvement as a Chartered Surveyor practising in and around Hampshire. He writes, 'This book is the culmination of many years of research, examination and experimentation... ...I have brought together much of what has been written on the subject, to which I have added repair and conservation techniques which I have noted in my sketch book as having been particularly successful.' The book includes a similar content to that of Ashurst & Ashurst (1988), but typically in greater detail, for example there is discussion of thermal performance of earth walling. An exception to this is the limited discussion devoted to the repair and maintenance of daub material. The author makes several contentious statements, for example: it is stated that 'it could take up to two years' for an earth wall to dry out (pg. 46), and 'In a clay wall constructed by the traditional method, and average compressive strength of approximately 1000 kN/ m^2 can be obtained if a sample is taken, dried and tested. In practice, the wall would not be completely dry and this would raise the compressive strength slightly.' (pg. 59). However no source for such information is given by the author. Given the scope of the content of this book, it is surprising that there is no practical advice given about consideration of new build construction.

One of the aims stated by all of the regional earth building groups, identified above, is to disseminate methods of 'good practice' guides for maintenance, repair and new build procedures within their regions. Examples of these guides, in Devon, are leaflets published by the Devon Historic Buildings Trust, 'The cob buildings of Devon' produced in two parts (Keefe 1992 and 1993), and 'Appropriate plasters, renders and finishes for cob and random stone walls in Devon' and 'Cob and the Building Regulations (DEBA 1993 and 1996).

Given the worldwide research interest, identified above into conservation techniques it is very likely that texts of category exist in other countries. However, no such examples have been available for this review.

e) Historical texts: there is a significant amount of archival information on the the indigenous earth construction techniques of the United Kingdom, but no authoritative review of this literature exists. However, 'Clay and Cob Buildings', (McCann 1983) contains descriptions of historical earth construction techniques, discussion of their history and origins and their regional distribution within the United Kingdom. Harrison (1989) also considers the history of earth building in the United Kingdom in his dissertation. Houben & Guillaud (1994) consider that the history of earth building is not well documented (pg. 8), but this observation appears to apply to the worldwide history and development of earth building. These authors include a brief historical summary of earth construction in the opening chapter of their book. As the focus of this thesis is the relationship between the behaviour of cob and its composition, literature addressing the history of earth building will not be discussed further.

When this project began, little information was available in this country. The University of Plymouth has consequently developed its own documentation centre accumulating international texts on the subject of earth building. However, availability has hindered this literature review together with the fact that many texts being published in languages other than English.

2.2.1) Discussion of earth building literature

Further discussion of the literature will concentrate on: the earth building manuals and codes, the practical conservation guides, and current research into earth building. This literature aims to address the three related areas necessary for successful earth construction listed below.

i) Knowledge of materials

This area is sub divided into knowledge of raw material properties, raw material selection criteria, and the mechanisms by which the properties of the earth building material are developed. The sum of this knowledge must be at such a level as to provide the designer with information about properties that will influence the design and performance of a building. For example: structural and thermal properties, the effect of moisture content on the performance of the building material, and necessary protection from the environment.

ii) Building material production and construction techniques

This describes the processes which convert the raw materials into the building material, and the building material into part of the fabric of the building. Suitable processes will maximise the properties of the building and the building material within economic and ethical boundaries established in the design brief. Examples of economic limitations are high capital costs of sophisticated manufacturing machinery, or the high labour costs of a labour intensive manufacturing system. Ethical limitations may be imposed if the brief stresses the importance of, for example, minimising the impact of the construction on the environment, or the involvement of the local population in the production and construction processes.

iii) Design

This will consider the requirements specified in the brief whilst operating within any limitations imposed by the material behaviour, the production of the earth mix, and the construction technique employed.

For both new build, and the maintenance and repair of existing buildings in earth, a potentially important source of empirical knowledge is the transfer of experience from generation to generation. Traditionally knowledge was transferred through observation and practical involvement and only infrequently documented. In many cultures this source of knowledge has been eliminated due to a break in the tradition of building in earth. Where this has happened and there is a renewed interest in building with earth, as in France and the United Kingdom, new sources of information have been developed such as literature and training programmes delivered by organisations like CRATerre- EAG (the International Centre for Earth Construction- Ecole d'Architecture de Grenoble, Grenoble, France), ENTPE (the Ecole Nationale des Travaux Publics de l'Etat, Lyon, France), and CEA (the Centre for Earthen Architecture, University of Plymouth, Devon). Even in cultures where there is a continuous tradition of building in earth new knowledge has evolved traditional techniques to improve their suitability for new build projects.

World wide there are numerous research projects examining different aspects of building with earth. During the course of this project recent research literature has been found relating to building with earth in France, Germany, Finland, Hungary, America, Mexico, Australia, India and China. Indeed 151 individuals and institutions actively engaged, in 1992, in research into 'the conservation and preservation of earthen architecture' were revealed by the 'Gaia Project'. The Gaia Project, initiated in 1992, was the result of collaboration between ICCROM (The International Centre for the Study of the Preservation and the Restoration of Cultural Property) and CRATerre- EAG in response to the need for organised activity in the conservation and preservation of eathern architecture (Teutonico 1994).

The techniques of the maintenance and repair of earth buildings are being developed by academic research; architects, engineers, and surveyors; and practitioners working with earth buildings through out the United Kingdom. This growing knowledge base is now being collected through the developing 'practitioners network' represented by the ICOMOS (UK) Earth Structures Committees and the regional groups mentioned above (DEBA, EARTHA and EMESS). In addition to the practitioners network knowledge of earth building is also being developed by English Heritage, Historic Scotland, and the Building Research Establishment. English Heritage and Historic Scotland are sponsored by the government Department of National Heritage and have a responsibility to proffer advice to the government and planning authorities where historic sites or buildings are involved. It is this responsibility which has heightened interest in earth building by these organisations, resulting in a number of major earth building repair projects for example, at Bowhill, Exeter. Peter Trottman at the Building Research Establishment, has investigated some aspects of earth building through consultancy projects with which he has been involved. Although this work is unpublished, Peter Trottman has spoken about his experience with earth as a building material at seminars and conferences held by DEBA and the University of Plymouth.

Currently the earth building movement relies heavily upon the field of 'geotechnical engineering' for the selection of soil for earth building materials and the prediction of their properties. Geotechnical engineering is also influencing current research into earth building materials. These observations are apparent from the classification of the earth building literature, above. Geotechnical engineers are interested in the behaviour of soil as the material supporting the foundations of buildings and roads; and as the fabric of dams, cuttings and embankments. There is a difference in the knowledge required for the effective geotechnical engineering of soil and the effective use of soil as a constituent of a building material.

When geotechnical engineers investigate a soil it is done acknowledging the fact that the inherent material properties are largely beyond their control. This is because the volume of soil in projects involving geotechnical engineers is so massive that there are few methods of modifying the properties of the soil which are economically viable[1]. In this situation the soil is not a raw material of a manufacturing process.

During the production of an earth building material, however, the soil is a raw material for a manufacturing process: the properties and structure of the soil will be modified by the manufacturing process. It may now be economically viable to modify the nature of the soil if, by doing so, the properties of the building material, and therefore the building, can be enhanced. It is this difference between geotechnical engineering and the

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[1] some methods do exist, for example, drainage or grouting of soil foundations (Bell 1975), or stabilisation of slopes by reinforcing materials (Jones 1985)

earth building movement that dictates a more detailed knowledge of the materials behaviour of earth building materials than the geotechnical industry can supply.

Geotechnical engineers predict the behaviour of soil by a process of 'characterisation' and 'classification'. Characterisation processes describe the soil in terms of physical composition and the response of the soil to particular tests. Examples of characterisation processes are particle size distribution, moisture content and the limit tests. These tests are discussed in chapter 5. Classification processes allocate a soil to one of a number of groups on the bases of the characterisation results. Once classified the behaviour of the soil can be predicted from the accumulated knowledge of the behaviour of similar soils. The prediction of the behaviour of the soil maybe augmented by tests on samples of the soil.

This approach of prediction by characterisation and classification, and verification by the testing samples of the building material has been adopted by the earth building movement. Consequently earth building manuals and codes contain material recommendations by characterisation and classification. Classification and characterisation processes which are not laboratory based are sometimes described as 'field tests'. For maintenance and repair of existing buildings field tests are often used simply to match the repair material with that of the original structure (Ashurst & Ashurst 1988, pg. 96): it is assumed that the material is suitable for construction or repair because of the survival of the original structure. For new build projects classification is used in an attempt to determine whether the proposed material is suitable for construction. Some classification and characterisation processes are defined in chapter 5.

The disadvantage of the characterisation and classification approach is that no knowledge is acquired about the mechanisms by which earth building materials develop their properties. This knowledge is crucial to the expansion of the practice of building in earth because the structural use of any material is limited by the mechanisms which cause it to fail. The mechanisms developing the properties of earth building materials will be influenced by the constituents of the earth mix and the 'internal structure' of the building material: the arrangement of these constituents. Internal structure is determined by the production process and the composition of the earth mix of the building material. The current lack of understanding of the behaviour of earth building materials means that there is insufficient knowledge to clearly define the most suitable production process for a particular earth mix, modifications to improve the performance of earth building materials, or acceptance criteria for their raw ingredients.

There is, therefore, a requirement for the understanding about soil developed by the geotechnical engineering industry to be augmented to include knowledge of:

- the internal structure of earth building materials;
- the influence of the nature of the constituents on the internal structure;
- the influence of the manufacturing process on the internal structure; and
- the influence of internal structure on the properties of the building material.

In order to gain knowledge of the variables governing the development of the properties of earth building materials further research is required. The nature of this research can be clarified by comparing the knowledge about earth building materials and another construction material, concrete. (Some areas of concrete science, applicable to the study of earth building materials, are discussed in chapter 7). The authors of the earth building manual 'Earth Construction' (Houben & Guillaud 1994) consider it to be 'above all a technology survey'. This book, the most comprehensive guide to earth building current available, is therefore suitable for such a comparison.

Earth Construction contains chapters with the following titles: 'soil', 'soil identification', 'soil stabilisation', 'soil suitability', 'tests', 'characteristics', 'construction methods', 'production methods', 'design guidelines', 'disaster-resistant construction', and 'earth wall finishes'. These chapters have been categorised below.

i) Knowledge of materials discussed in the chapters titled: 'soil', 'soil identification', 'soil stabilisation', and 'soil suitability'
ii) Material production and construction techniques discussed in the chapters titled: 'construction methods', and 'production methods'
iii) Design discussed in the chapters titled: 'tests'; 'characteristics', 'design guidelines', 'disaster- resistant construction', and 'earth wall finishes'

Of the section addressing knowledge of materials only one chapter, 'soil', briefly discusses some of the mechanisms developing the properties of earth building materials. The remaining chapters in this section consider identification, stabilisation and suitability of the soil in terms of characterisation and classification techniques. In stark contrast to this the development of the properties of concrete is well researched and documented. Example text books are 'Concrete: structure; properties and materials' (Mehta 1986) and 'Concrete Technology' (Neville & Brooks 1987). Both of these texts have chapters addressing particular properties of concrete, for example strength, dimensional stability, and durability. In these texts the derivation of these properties is directly related to the composition of the concrete, and the mechanisms responsible for these properties are investigated and described.

Even research papers investigating earth as a building material do not follow the 'causal' approach adopted by the concrete research community. For example the paper 'Influence of different parameters on the resistance of earth, used as a building material' (Olivier & Mesbah 1987), appears from the title to be an attempt at achieving this type of knowledge. However the abstract states that, "This article presents the static compressive test which enables the optimising of the compressive strength of compacted clay bricks according to various manufacturing or curing parameters.": the paper primarily considers the effect of processing variables on the properties of earth building material, there is no consideration of internal structure or failure mechanisms. Another paper investigating the properties of earth as a building material is 'Properties of soil- cement blocks for walls' (Venkatarama Reddy 1991) in which the compressive strength of soil cement blocks of different composition was found ('soil- cement blocks' are mechanically compressed earth blocks stabilised with a small cement content). This paper states, "The studies carried out in this investigation clearly indicate the role of density and soil composition on the strength and durability characteristics of soil- cement blocks." However, without discussing the mechanisms which develop strength and durability the results can not be applied to different soils: the paper reinforces the characterisation and classification approach.

The difference in the level of knowledge of materials behaviour of concrete and earth as a building material is not merely a result of approach but also of funding and time. Detailed knowledge of the materials behaviour of concrete has commercial value as it can, for example, improve the properties or broaden the market of concrete. Currently, knowledge of the materials behaviour of earth as a building material has little commercial value, limiting available funding for research into this subject. The investigation of the materials behaviour of concrete is many decades old: the Abram's water/ cement ratio, first used in 1918 to predict the strength of concrete, is still discussed in contemporary texts. It is arguable that investigation into materials behaviour of earth as a building material has only begun in the last twenty years as a result of the previously mentioned technology transfer initiatives.

It appears that research into earth as a raw material for building, as opposed to a geotechnical construction material, has been underway for 18 years at the University of Kassel. Gernot Minke from the University of Kassel has named the following goals of his research: "to determine the structural and physical properties of different earth mixtures and to investigate optimal types and quantities of aggregates and additives in order to improve the weather resistance, to minimise the shrinkage ratio, to increase the binding force and to reduce the thermal conductivity." (Minke 1994). Details of Minke's work are unclear because only brief descriptions have been published in English.

In addition to providing knowledge about the most suitable production process for a particular earth mix, modifications to improve the performance of earth building materials, and acceptance criteria for their raw ingredients, research into the internal structure of earth building materials will have another important benefit: the description of the properties of earth building materials in similar terms to other construction materials. This would encourage the broader acceptance of the material in the existing building industries of developed countries.

2.4) Additional literature relevant to this project

In investigating the 'knowledge gap' described above this project has utilised literature from a wide range of disciplines. Specialised literature about earth building has already been discussed. In addition to these texts literature from the following areas will be cited in this thesis: materials science, engineering materials, soil science and geotechnical engineering, and statistics.

Chapter 3: Building with Earth

This chapter considers:

3.1) earth building materials, production and construction techniques
3.2) the physically distinct materials that are the constituents of cob
3.3) the influence of the binder fraction on the properties of cob
  3.3.1) the effect of water on clay
  3.3.2) the structure of clay and the cohesion of the binder fraction
  3.3.3) the apparent cohesion of the binder fraction
  3.3.4) shrinkage
3.4) the influence of the aggregate fraction on the properties of cob
3.5) the influence of the particle size distribution on the properties of cob
  3.5.1) the compression modulus of cob matrix material
  3.5.2) strain magnification and void content- the effect of internal structure of cob matrix material
3.6) the influence of the fibre fraction on the properties of cob
  3.6.1) during compression testing
  3.6.2) during production and construction
  3.6.3) during the drying process
3.7) cob production and construction.

3.1) Earth building materials, production, and construction techniques

The raw material for a process producing an earth building material is described in this thesis as an 'earth mix'. The principal component of an earth mix is subsoil. Subsoil occurs naturally between the layers of topsoil, which contains large quantities of organic material, and parent rock material (Norton 1986, pg. 7). Both topsoil and subsoil layers are decomposing. However, due to its organic content, the rate of decomposition of topsoil is several orders of magnitude greater than that of subsoil. For this reason topsoil is considered too unstable for inclusion in an earth mix. The subsoil component of an earth mix provides a 'binder fraction' and an 'aggregate fraction' (Note: the definition of 'aggregate' used in this project differs from that used in soil science and soil physics texts. In this project 'aggregate' is used to describe particles non technically referred to as 'gravel' or 'stones'. In soil science and soil physics texts 'aggregates' describes loose agglomerates of soil.) The binder fraction consists of the fine material of the soil. It is the cohesive properties of the binder fraction which will bind the earth mix together. The aggregate fraction consists of the remainder of the soil material, excluding any organic content. The binder fraction encases the aggregate fraction and any 'stabilising' components of the earth mix. Stabilisers are described below.

Most subsoils naturally contain binder and aggregate fractions. The suitability of a particular subsoil as a component for an earth mix, and whether any stabilisation is necessary, is dependent upon the nature and proportion of these fractions. The proportion of these fractions are measured by a standard geotechnical characterisation process, 'particle size distribution', described in chapter 5. The effect of these fractions on the performance of cob is discussed below.

Subsoil suitable for use as a building material is readily available throughout much of the world. As a result many cultures have utilised the material to fulfil a broad range of roles using numerous manufacturing techniques. Figure 3.1 (Houben & Guillaud 1994, pg. 165) illustrates eighteen different earth building techniques classified according to the role that the earth plays in the building: it is either load bearing, non load bearing or used in conjunction with a load bearing structure.

Load bearing earth structures can either be formed simultaneously as the building itself, or from units moulded before the construction process: the former is monolithic construction, the latter unfired 'blockwork' construction. In construction techniques using unfired blockwork, the production of the building material is completed before the construction process begins. This is not true for the monolithic construction processes: there is no clear distinction between the end of the production of the building material and the beginning of the construction of the building.

This is an important difference as the properties of the monolithic building material will develop in situ. The rate of monolithic construction is therefore determined by how quickly the properties of the building material develop. This is not the case with unfired blockwork, as their properties are already fully developed at the time of construction. Furthermore, the production of unfired blocks is easily sheltered, making it possible for the manufacture of this type of building material to be independent of weather conditions.

'Historic' and 'current' construction techniques were defined in chapter 2, section 2.1.2. Examples of earth building materials produced by historic techniques are cob (resulting in a monolithic, load bearing material), and wattle and daub (resulting in a material used in conjunction with a load bearing structure) (Harrison 1979). Typical examples of earth building material resulting from current building techniques are extruded earth (Houben & Guillaud, pg. 182) and compressed block (Doat et al 1985, pg. 140) which are produced by mechanised techniques. Some current techniques, however, are the result of the 'up dating' of traditional techniques, for example current rammed earth production.

The production of earth building material can be categorised additionally into 'solid, unmodified soil' production techniques and 'liquid', 'plastic' or 'dry modified soil' production techniques (Jeanne- Marie Teutonico lecture at the University of Plymouth February 23rd 1995). Examples of the solid unmodified soil forms of production in figure 3.1 are the excavation of dug outs, and the cutting of sods or earth blocks for use as a building material.

The descriptions 'liquid', 'plastic' and 'dry' refer to the consistency of the earth mix at the time that the building material is produced. This consistency is dependent upon the moisture content of the earth mix. Of these three consistencies only in the plastic state can the material keep its shape without moulds or shuttering before its properties are fully developed. Examples of plastic production techniques in figure 3.1 are hand shaped adobe, direct shaping and cob. The property of plasticity is discussed in section 3.3. The liquid production techniques require moulds or shuttering to support the building material whilst its properties develop as it dries. Poured earth in figure 3.1 is an example of this technique of production. The dry production techniques require moulds or shuttering to confine the material whilst it is compacted sufficiently to become a coherent whole, thus developing the properties of the material. Examples in figure 3.1 are rammed earth, tamped blocks and pressed blocks.

It is possible for the same soil to be used successfully in different production processes by controlling the moisture content of the material at production (private conversation with Miriam Oliver, University of Plymouth, May 1995). In order to be successful the liquid and plastic production techniques rely upon the addition of the correct amount of water to the production material. The material of the liquid, plastic and dry techniques is described as modified because the structure of the original soil has been altered by the production technique.

The modified soil production techniques are divided into the following four processes.

i) Preparation of the soil: the removal of ‘over size’ aggregate particles and organic material, and the breaking up of the soil into fine agglomerates.

ii) Addition of stabilisers: these are added as they are believed to enhance the properties of the material either during production or after construction. Stabilisers may be manufactured, for example, lime, cement, or bitumen; or naturally occurring, for example plant fibres or juices, or animal products. For a discussion on soil stabilisers see Stulz and Mykerji (1993, pg. 29 et seq.) or Houben and Guillaud (1994, chapter 4).

iii) Mixing: this distributes the components of the earth mix evenly throughout the material. This ensures more uniform cohesion within the material than if it was unmixed, and improves the homogeneity of the material.

iv) Forming: a consolidation process eliminating trapped air in the material. This improves the structural properties of the material after construction.

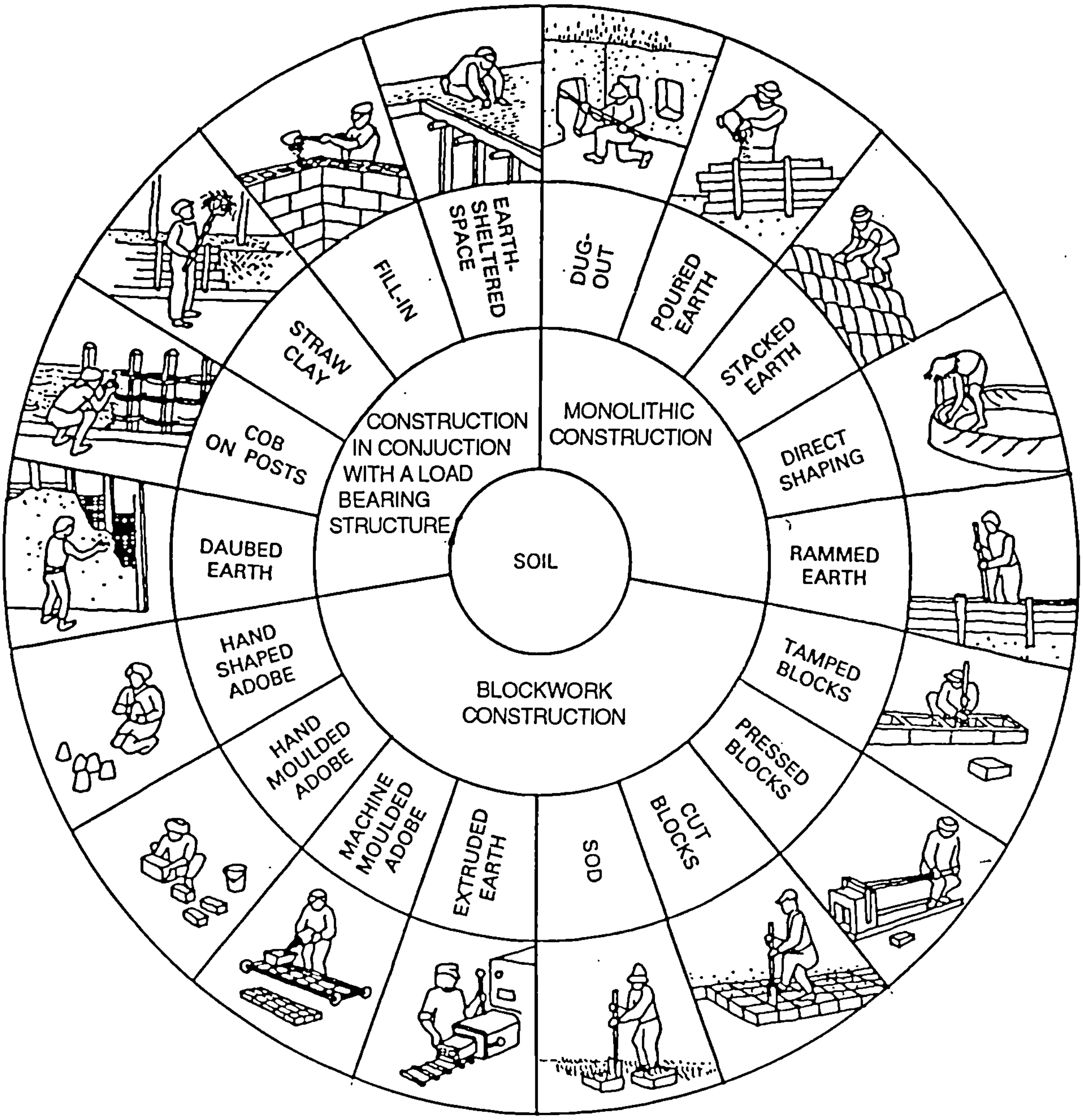


figure 3.1

Earth building techniques

The addition of water to the earth mix is necessary for the success of the liquid and plastic production techniques. However, the addition of water to the earth mix causes shrinkage as it dries and may create voids within the building material by inhibiting the consolidation process.

It may be necessary to apply a finish to an earth building material either to meet aesthetic requirements, or to protect the material from environmental degradation. The process necessary to finish the surfaces of earth building material after it is constructed is dependent upon the construction technique employed. A surface ready for the application of render or plaster can be achieved in the monolithic construction process by trimming the building material before it is fully dry or by using shuttering during construction. Unfired blockwork can be produced with finished quality surfaces or finished with a plaster or render. The face of earth material used in conjunction with a load bearing structure is typically smoothed flat before it is fully dry: it can then be finished with a plaster or render. Examples of finishes traditionally used on earth buildings in the United Kingdom are earth based plasters and renders; lime based plasters and renders; and coal tar.

This chapter will only discuss further the production of cob and construction using cob. Further information about the regional materials and techniques using earth within the United Kingdom can be found from appropriate books listed in the bibliography and the sources given in 'Appendix B: regional groups'.

3.2) The physically distinct materials that are the *constituents of* cob

Cob is considered here as a 'composite material' consisting of a 'fibre', straw, reinforcing a 'matrix material', subsoil. Both the subsoil and the straw are also composite materials. A composite material can be defined (Hull 1981, pg. 3) as a material which:

i) consists of two or more physically distinct and separable materials;
ii) can be made by mixing the separate materials in such a way that the dispersion of one material in the other can be achieved in a controlled way to give optimum properties; and
iii) has some superior properties in comparison with those of its individual components.

The matrix material consists of an agglomeration of small cohesive particles, the 'binder fraction', reinforced by much larger solid particles, the 'aggregate fraction'. The straw 'fibre fraction' is made up of natural cellulose fibres in a matrix of hemicellulose and lignin. In this project the constituents of the 'cob matrix material' are classified as either 'aggregate' or 'binder', according to the particle size such that: aggregate > 0.0063 mm, and binder < 0.0063 mm.

Aggregate and binder fractions are further classified in this project according to particle size. The size ranges used in this project and the labels applied to them are given below in table 3.1. (These size ranges were dictated by the availability of sieve sizes at the University. These size ranges are non standard.)

The particles of gravel, sand and silt size are the products of mechanical weathering of parent rock. Although the particle size is reduced by mechanical weathering, the structure of the particles is not affected. The particles produced by mechanical weathering are referred to as particles of 'primary mineral'. Clay minerals, however, are the product of chemical weathering in the presence of air and water over a long period of time. Chemical weathering not only changes the particle size but also the structure of the material. Clay minerals are referred to as 'secondary minerals' (Jury et al 1991, pg. 4). The differences in the material properties of the aggregate and binder fractions are the result of different particle size and structure.

fine GRAVEL	5- 2 mm	part of aggregate fraction
coarse SAND	2- 0.6 mm	"
medium SAND	0.6- 0.212 mm	"
fine SAND	0.212- 0.0063	"
CLAY/ SILT	≤ 0.0063 mm	binder fraction

table 3.1
Particle names and their size ranges.

The consistency during the production process, resistance to deformation during construction and shrinkage of cob during the drying process are the result of the properties of the binder fraction. These properties are largely the result of the interaction between the particles of clay mineral in the binder fraction and water. Particles in the binder fraction other than those of clay minerals may also contribute to binder properties, albeit to a lesser extent. The structure of clays and the effect of water on their behaviour is described in the next section.

3.3) The influence of the binder fraction on the properties of cob

3.3.1) The effect of water upon clay

The addition of water to a dry earth mix with a significant clay content will result in the earth mix having the property of 'plasticity'. Plasticity may be defined as the property which, "allows the earth mix to be deformed (or shaped) without cracking or breaking under the influence of an applied force, and to retain its new shape when the deforming force is removed, or reduced below a certain value" (Ryan 1978, pg. 13). Plasticity results from the 'adsorbtion' of water molecules to the surface of the clay particles in the earth mix. Adsorbtion is defined in the following extract: "The atoms or ions at the surface of a solid are subject to a different net force from those in the interior, because at the surface there are atoms or ions on one side only. Accordingly, surfaces in general have a greater activity than the interior and are prone to attract other molecules or ions: this phenomenon is known as adsorbtion. The effect of such adsorbtion is to reduce the free energy of the surface." (Worrall 1975, pg. 101). The phenomena of adsorbtion has a marked affect on the properties of the clay fraction due to the large specific surface energy of clay particles. Table 3.2 below (Bell 1981, pg. 51) illustrates the relationship between particle size and 'specific surface area' (a measure of surface area per unit weight of material):

soil particle	size (mm)	specific surface area (m^2/g)
sand grain	1	0.002
kaolinite	d= 0.3 to 0.003	
	thickness= 0.3 to 0.1 d	10- 20
illite	d= 0.1 to 0.002	
	thickness= 0.1 d	80- 100
montmorillonite	d= 0.1 to 0.001	
	thickness= 0.1 d	800

table 3.2
Relationship between particle size and specific surface area.

This table shows the calculated specific surface area of the clay particles as being between 5 000 and 400 000 times that of the sand particles, depending on the species of the clay mineral. The increase in specific surface area of the clay particles is not only a result of size but also of the shape of the particles. Clay particles have a thin plate-like structure. As the specific surface area of individual particles increases, the effect that the surface properties of these particles have upon the behaviour of the mass to which they belong, increases also. In the particular example of clay mineral particles, the large specific surface area determines that the attraction of water and other materials onto the surface of the clay particles will dominate the behaviour of the clay mass.

The adsorbtion of water onto the surface of clay particles occurs either due to hydrogen bonding or Van der Waals forces (Askeland 1996, pg. 23 et seq.). The potential for hydrogen bonding exists when a hydrogen atom forms a primary bond with an oxygen atom, such as in the formation of a water molecule. The overall charge on a molecule of water is zero: there is as much negative charge on the electrons as positive charge on the nucleus in the molecule. However, the locations of the negative and positive charge in the water molecules are displaced from one another: the oxygen atom becomes relatively negatively charged whilst the hydrogen atom becomes relatively positively charged. The water molecule is therefore described as being 'dipolar': it has two differently charged 'ends'. Hydrogen bonding between water molecules and the surface of clay particles occurs due to the attraction of the positively charged hydrogen atom of the water molecule to the negatively charged surface of the clay particle.

The Van der Waals forces may result in the adsorbtion of water molecules onto the surface of clay particles by any of three mechanisms. These arise from: attraction between the oppositely charged ends of permanent dipoles; the attractive force between permanent dipoles and dipoles induced by those in adjacent, originally non- polar, molecules; and interaction between instantaneous, fluctuating dipoles due to the constant oscillation of the electrons.

Water molecules are not the only particles to become adsorbed onto the surface of the clay minerals: charged particles called 'ions' do as well. When this adsorbtion of ions contributes to the bonding between clay particles it is known as 'ion bridging'. Ion bridging is discussed below. As more water is added to the clay more water becomes adsorbed to the surface of the clay particles. This process continues until the surface of the clay can no longer attract water molecules. Once this degree of saturation of the clay has been reached the water will begin to occupy void space between the clay particles. The orientation of these 'free' water molecules may still be affected by the distribution of charge on the surface of the clay particles. Although the existence of a layer of adsorbed water at the clay surfaces is not questioned the nature of any long range structure of water (greater than 1- 4 nano meters) is still under investigation (Selby 1993, page 19). The two models proposed to describe the distribution of ions and water molecules around clay particles are the Gouy- Chapman model and the Stern model. The Gouy- Chapman model describes a film of water around the clay particles in which the concentration of cations decreases from a high concentration at the mineral surface to a lower concentration further away. The Stern model incorporates a layer of cations adsorbed directly onto the clay surface and a Gouy- Chapman diffuse layer of electrostatically retained ions further away from the clay surfaces.

Despite this dispute about the long range structure of water around clay particles it is clear that water fulfils the role of a boundary lubricant, easing the movement of clay particles past one another. As the viscosity of adsorbed water and water subject to polar orientation is higher than that of bulk liquid water, the lubricating effect of non orientated free water is greater than that of adsorbed or orientated water (Kezdi 1980, pg. 85). Particles of sand or alumina, of a similar size as clay particles, will also adsorb water at their surfaces. However, since these particles are not plate-like they cannot slide easily over one another and little plasticity results (Ryan 1978, pg. 23).

The further addition of water to the earth mix causes it to become increasingly less viscous until a state is reached where it can no longer retain its shape against the force of gravity. Once this stage has been reached the earth mix behaves as a liquid and will flow. Plasticity, therefore, occurs within a range of moisture content where there is sufficient boundary lubrication for the particles to move relative to each other, but the cohesive force between the particles is great enough for the earth mix to resist flow due to the force of gravity. In the geotechnical classification of soils the range of moisture content over which the material exhibits plastic behaviour is known as the 'plasticity index'. The upper and lower boundaries of the plasticity index are defined by the 'liquid limit' and the 'plastic limit' respectively. These tests are discussed in chapter 5. The magnitude of the plasticity index is determined by the amount of charge available on the surface of the clay particles, this is affected by the adsorbtion of cations onto the surfaces. 'It has been found that material which are highly plastic [that is have a high plasticity index] usually also show high dry strength and a high moisture content at their optimum working consistency' (Ryan 1978, pg. 21).

The 'plasticising' effect that water has upon the binder fraction makes the earthen mixture easy to mix and hence facilitates the improvement of the homogeneity of the material.

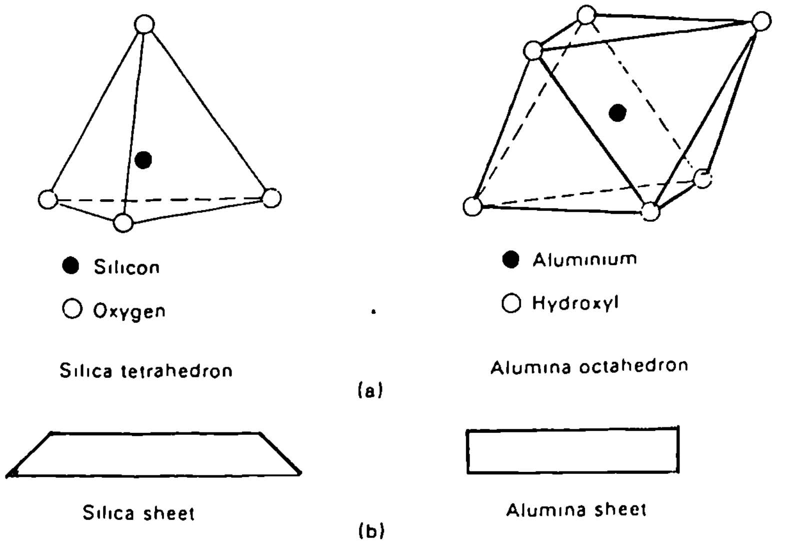
3.3.2) The structure of clays and the cohesion of the binder fraction

Clay particles are formed by the 'bonding' of atoms and molecules. There are two principal forms of bonding: primary and secondary (Askeland 1996, pg. 23 et sq.).

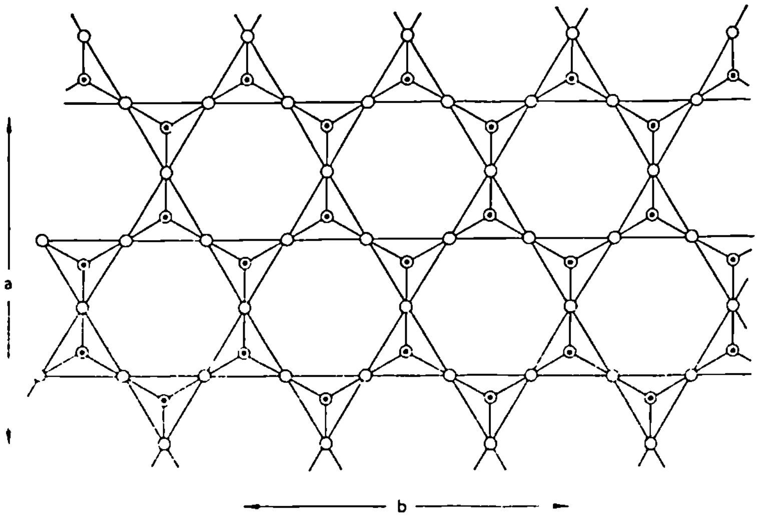
Primary bonding is either ionic, covalent, a combination of ionic and covalent bonding, or metallic. The nature of the primary bond is determined by the electrical charges, or 'valency', carried by the atoms or molecules of material which are bonded together. Ionic bonds are formed between atoms carrying opposite charges. If a primary bond is formed between two neutral atoms it will be a covalent bond. The bonding within the layers of clay material is primary bonding.

Secondary bonding has already been discussed in the adsorbtion of water molecules and charged particles to the surface of clay particles. Secondary bonding also occurs between 'layers' of clay material within the structure of a clay particle across a space called an 'interlayer'. Secondary bonds are due to either Van der Waals forces or hydrogen bonds.

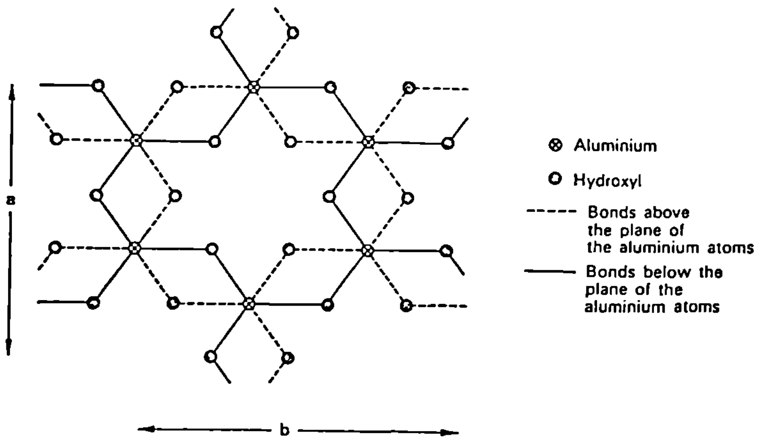
The three major clay minerals are kaolinite, illite and montmorillonite (Bell 1981, pg. 50). These three minerals are formed from different arrangements of two structural 'sheets'. These crystalline sheets are formed by the ionic bonding of many silica tetrahedra and alumina octahedra. The structure of the silica tetrahedra and alumina octahedra; and the silica and alumina sheets is shown in figure 3.2 ((Ryan 1978, pgs. 45 and 47) and (Craig 1983, pg. 2)).



the basic units of clay minerals



the silica tetrahedral layer viewed from above



the alumina octahedral layer viewed from above

figure 3.2

Structure of sheets of clay minerals

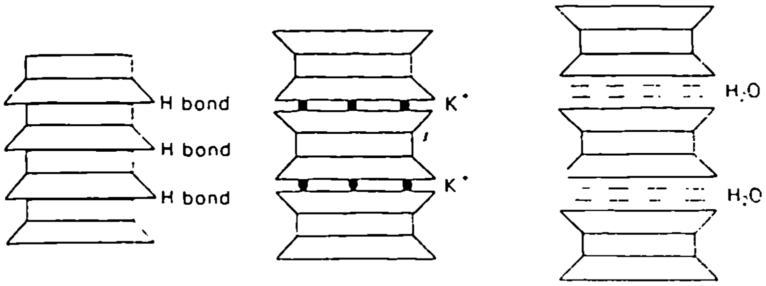
The silicon atom in the centre of the tetrahedra carries four positive valencies and each oxygen atom carries two negative valencies. Therefore, each tetrahedron carries a net charge of minus four. These tetrahedra are able to bond together, sharing oxygen atoms, and forming sheet structures. The silica sheet in figure 3.3 is capable of infinite extension in the a and b directions by the bonding of further silica tetrahedra. Three of the four oxygen atoms in every tetrahedron are now valency satisfied, receiving one valency from each of the two silicons to which they are linked. The fourth oxygen atom, at the apex of the tetrahedron, is bonded to only one silicon atom and therefore has one valency unsatisfied. It is through these valency unsatisfied oxygen atoms that the silicon sheet can bond with other sheet structures: for example sheets formed from alumina tetrahedra.

Like the silicon sheet, the alumina sheet is formed by the bonding of many units. The unit of the alumina sheet is an alumina octahedron consisting of an aluminium atom surrounded by four hydroxyl groups. When the alumina octahedrons ionically bond together, every hydroxyl group is shared by two aluminium atoms: each hydroxyl group receiving half a valency share from the two trivalent aluminium atoms. As the hydroxyl groups are monovalent they are all valency satisfied in this arrangement and there are no unsatisfied valencies in the structure. The alumina sheet in figure 3.3 is capable of infinite extension in the a and b directions by the bonding of further alumina octahedra.

These silica and alumina sheet structures can become ionically bonded together to form layers of clay material. This is possible because the dimensions of the hexagonal rings in the silica and alumina sheets are very similar. Bonding occurs by the elimination of hydroxyl groups in the alumina sheet, their places being taken by the valency unsatisfied oxygen atoms at the apex of each tetrahedron of the silica sheet. This arrangement requires each valency unsatisfied oxygen atom to combine with two aluminium atoms: the oxygen atom receiving half a valency share from each aluminium atom. The clay mineral kaolinite is formed from layers of material consisting of silica and alumina sheets bonded in this manner. Consecutive layers of kaolinite material are held together by hydrogen bonds and Van der Waals forces, as shown in figure 3.3 (Craig 1983, pg. 3), to form a particle of kaolinite. Figure 3.3 also shows how the clay minerals illite and montmorillonite are formed from different combinations of sheets of silica and alumina.

The accumulation of many layers of clay material constitutes a clay particle. Some kaolinites may have as many as 100 repetitions of layer material and interlayer in a particle. Maximum particle thicknesses vary from about 2 nm to 2 μm, but most are in the range of 10 nm to 0.2 μm (Selby 1993, pg. 15).

The type of bonding between the layers of clay material has a significant affect on the behaviour of the clay. The layers of kaolinite material are bonded firmly enough to prevent the structure expanding when the particle is hydrated. This is not the case for montmorillonite particles. Layers of montmorillonite material are held together by very weak Van der Waals forces: this is the only form of bonding possible due to their valency satisfied structure. This weak bond between the layers is not strong enough to resist forces resulting from the attraction of water molecules to the montmorillonite material. This leads to the characteristic swelling of montmorillonites in water. The available surface area of particles of kaolin material is simply the external surface. However, as the individual layers within a particle of montmorillonite can be separated, the surface area of a particle includes the external area and an internal surface area. This source of additional surface area in conjunction with the small size of montmorillonite particles gives them a much greater overall surface areas than that of kaolin particles.



(a) (b) (c)

Clay minerals: (a) kaolinite, (b) illite, (c) montmorillonite.

construction of clay minerals form combinations of silica and alumina sheets

figure 3.3

Arrangement of sheets to form clay particles

Figure 3.3 shows the structure of the layers of illite particles as identical to that of the layers of montmorillonite particles. In fact some of the aluminium atoms in the alumina sheet have been substituted by atoms of magnesium and iron, and some of the molecules of silica in the silica sheet have been substituted by aluminium atoms. This partial 'isomorphous substitution' results in the layers of illite material carrying additional negative charge which allows the layers to be bonded together by potassium ions. Like the bonding between layers of kaolin material, the bonding between layers of illite is strong enough to prevent expansion of the structure when a particle of illite is hydrated. Isomorphous substitution therefore has a marked affect upon the properties of clay minerals.

The relative strengths of primary and secondary bonds is given in table 3.3 below (Kezdi 1980, pg. 74).

Van der Waals forces	1- 10
hydrogen bond	10- 20
ionic and covalent bonds	40- 400

table 3.3

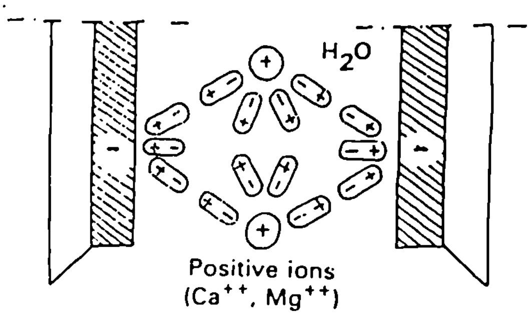
Relative strength of primary and secondary bonding.

(Note: these values are relative to each other and have no units.)

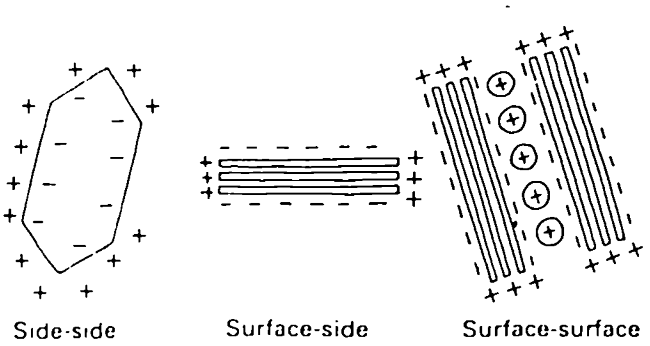
The crystalline structure of the clay particles and the internal structure of particles of the aggregate fraction are maintained by primary bonds. However, bonding between particles of the binder fraction are maintained by weaker secondary bonds. The practical consequences of the difference in bonding strength shown in table 3.3 is that failure of the cob will not be related to failure of the 'internal' primary bonds of the aggregate or clay particles but to the failure of cohesion between particles of clay in the binder fraction or between clay and aggregate particles. Once cohesion has failed it can be re established by recycling the earth mix through an appropriate production process.

The cohesion of the binder fraction has real and apparent components. The real component is due to secondary bonding between clay mineral particles, and clay mineral particles and silt particles. The mechanisms which develop apparent cohesion are discussed below. The real component of the cohesion in the binder fraction may be due to Van der Waals forces, electrostatic forces, or a combination of the two bonding mechanisms. The electrostatic forces are the result of interaction between the charged surfaces of the clay minerals, and ions and the charged surfaces of the clay minerals. The charge on the surface of a clay particle will be affected by the isomorphous substitution of ions in to the crystal structure of the mineral. Valency differences may occur between the edges and surfaces of clay particles due to unsatisfied charges at the edges of the silica and alumina sheets. These valency differences may result in electrostatic bonding between clay particles. Electrostatic bonding may also occur due to 'ion bridging' between clay particles. Electrostatic bonding due to ion bridging and valency differences of adjacent clay particles are shown in figure 3.4 (Houben & Guillaud 1994, pg. 29). "The attractions and repulsions between the charged surfaces of [separate] clay particles are much weaker than those forces operating between clay surfaces and ions. This emphasises the importance of ions as links between particles. As the concentration of ions in adsorbed water increases so does the strength of bonding. Ionic attractive forces [attraction between particles due to adsorbed ions on thier surface] are therefore at a maximum in dry soils." (Selby 1993, pg. 52).

The strength of secondary bonding between clay particles is also affected by the surface area and proximity of the clay particles. The proximity of the particles increases as their capacity to repeal each other is reduced by neutralising their surface charge. A close packing of clay particles due to the neutralising of their surface charge is called a 'deflocculated structure'. According to Ryan (1978, pg. 22) the dry strength of a material with such a structure, "will increase perhaps by as much as 100%" in comparison with the same material with a loosely packed 'flocculated structure' (In this case the 'dry strength' of the material is established by a three point bend test.).



electrostatic bonding between clay particles due to ion bridging



electrostatic bonding due to valency

differences between clay particle surfaces

figure 3.4

Electrostatic bonding

3.3.3) The apparent cohesion of the binder fraction

The component of apparent cohesion of the binder fraction is produced by surface tension in water films between particles, and by the interlocking of particles at a microscopic level as a result of surface roughness ('internal friction') (Selby 1993, pg. 54). 'Internal friction' may enable cob matrix material to resist deformation depending upon the degree of boundary lubrication due to adsorbed water in the binder fraction.

Coulomb's law of friction states that the frictional resistance to motion of a body on a nominally smooth surface is described by:

$$F = \mu P$$

where F is the frictional force, P is the force normal to the contact surface and μ is the coefficient of friction. The resistance due to friction is independent of the nominal area of surface contact. Theoretically, friction is primarily dependent upon the force pushing the contact surfaces together. This is due to the nature of surfaces when examined at a microscopic scale. No matter how carefully they are machined and polished, all surfaces appear rough at a microscopic scale. Therefore, when two surfaces are brought into contact they will be supported on the 'summits' of the high points ('asperities') of the surfaces. The area of contact between the asperities of each material is dependent on the force pushing the surfaces together as the area of contact is related to the degree of deformation of the asperities. If a force is applied parallel to the surfaces, shear stresses are established in the materials. These shear stresses are a maximum in the asperities of each material which are in contact. For the two surfaces to move relative to each other it is necessary for material in the contact asperities to deform or fracture. The resistance of the asperities to deformation or fracture will be dependent upon the area of contact between them, which is dependent on the degree of deformation of the contact asperities. It is for this reason that the degree of frictional resistance is not dependent on the nominal area of surface contact.

Description of the development of internal friction in a mass of aggregate and binder particles must take account of the layer of adsorbed water molecules that both types of particles have on their surface (Kezdi 1980, pg. 191). When aggregate particles are touching the the actual area of contact due to surface asperities is less than the nominal area of contact. Because the number of contact points between the particles is limited the layer of adsorbed water on the contacting asperities is highly compressed. However, the layers of adsorbed water surrounding clay particles which are touching are not highly compressed. This is because the very small size of clay particles increases the number of contact points in a mass of the particles.

From the above discussion of real and apparent cohesion due to the internal friction the following conclusions can be drawn.

i) When load is applied to an assemblage of aggregate particles, the adsorbed water between the contact asperities is highly compressed. Internal friction is therefore the primary source of resistance to deformation of the assemblage. In such a case the effect of cohesion mechanisms due to secondary bonding between particles are negligible.

ii) When load is applied to an assemblage of binder particles, the adsorbed water around the particles is not highly compressed. The development of internal friction in such an assemblage is therefore restricted by the layer of adsorbed water. However, in an assemblage of binder particles the cohesion mechanisms due to secondary bonding between particles are significant.

iii) In a mix containing both aggregate and binder fractions clay particles may become attached to aggregate particles by secondary bonds.

Apparent cohesion can also occur in an assemblage of particles due to 'capillary attraction'. 'Capillary attraction' describes the attraction between particles covered with a film of water due to the surface tension of the film pulling the particles together. The magnitude of the attractive force is inversely proportional to the radius of curvature of the water between the soil particles: the smaller the radius the greater the capillary stress. In a saturated soil the surface tension is completely eliminated as there is no water surface in the mix to develop capillary attraction between particles.

The occurrence of apparent cohesion due to capillary attraction is dependent upon the particle size distribution of the earthen mix, the 'wettability' of the particle surfaces, and the degree of saturation of the mix.

In the case of an earth mix containing both aggregate and binder particles the degree of actual and apparent cohesion is dependent upon:

i) the proportions each fraction in the mix;
ii) the internal structure of the mix;
iii) the mineralogical nature of the clay in the binder fraction;
iv) the charge on ions in solution in the moisture content of the mix; and
v) the moisture content of the mix.

3.3.4) Shrinkage

'Shrinkage' describes the decrease in volume of cob as water is removed from it. This is due to the contraction of the binder fraction as it dries. It is only at very high moisture contents that liquid water can flow under gravity out of cob. The principal drying mechanism of cob, therefore, is the removal of water by evaporation. The contraction of the binder fraction is the result of surface tension and secondary bonding forces acting on the clay particles. These forces increase as the water evaporates resulting in the clay particles being pulled closer together. The shrinkage ceases when the internal structure of the cob is such that it can resist these contraction forces. This state is reached when the 'free water' (water not adsorbed to particle surfaces) in the material has evaporated.

The contraction of an earth mix during shrinkage will occur around different centres within its volume. This causes regions of tensile loading which results in cracking of the binder fraction as it dries. The degree of cracking of the binder fraction is related to the amount of contraction that it experiences, the quantity and quality of aggregate in the mix, and the distribution of the particle sizes of this aggregate. The presence of a fibre fraction in the earth mix will also influence the cracking processes. These topics are discussed in more detail below. The amount of contraction of the earth mix is related to the type of clay which it contains. This is primarily due to the ability of some clay particles to attract water between the sheets from which they are made, as well as attract water on to the particle surfaces. This causes them to swell more then if they only attracted water onto the particle surfaces. The binder content and aggregate content of cob are inversely proportional. Therefore, one effect of increasing the amount of aggregate is to decrease the degree of shrinkage simply because the amount of dimensionally unstable binder fraction in the cob has been reduced.

The point at which shrinkage due to moisture loss ceases in a mix with a significant clay content is termed the 'critical moisture content' in the ceramic processing industry, or the 'shrinkage limit' in geotechnical engineering. Fluctuations of moisture content below this value will not result in changes in volume of the material. The degree of shrinkage that the mix experiences during drying is proportional to the difference between the moisture content of the material at production and the moisture content of the material at the shrinkage limit. The change in volume of the mix during drying from the moisture content at production to one at or below the critical moisture content will be equal to the volume of this amount of water. Because the moisture content of the earth mix depends upon the production process employed, different production processes have differing degrees of shrinkage associated with them.

3.4) The influence of the aggregate on the properties of cob

The aggregate fraction contributes to the development of the properties of cob. These contributions are the result of the difference in some of the properties of the material of the aggregate particles compared to those of the binder fraction. Differences between the properties of the binder and aggregate fractions which are important in the development of the properties of cob are listed below.

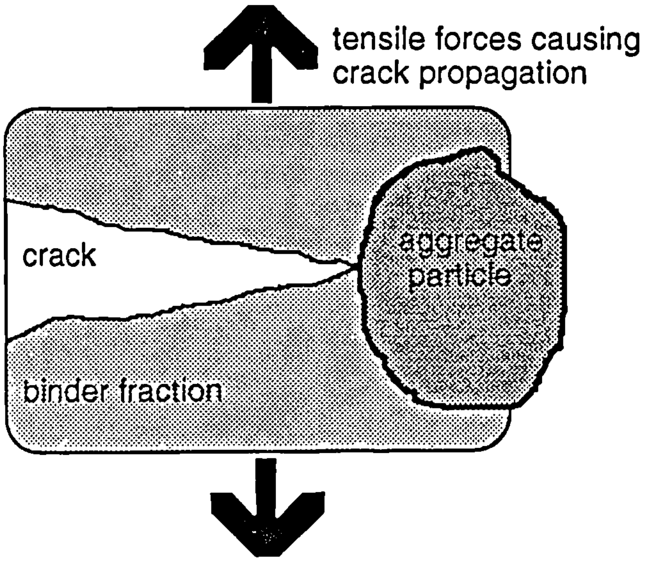
i) The particles of the aggregate material do not experience significant secondary bonding between them and are chemically inert within cob.
ii) The aggregate material has a greater resistance to deformation than that of the binder fraction of cob.
iii) The resistance to deformation of the aggregate material is unaffected by moisture content.
iv) The volume of the aggregate fraction is independent of moisture content: the volume of the binder fraction increases at moisture contents greater than the shrinkage limit.

Two important contributions made by the aggregate fraction are: to increase the 'potential' resistance to deformation of the material; and to impede the growth of cracks through the binder fraction by a process known as 'crack stopping'. The increase in potential resistance to deformation of the cob offered by the aggregate fraction is the due to (ii) above. The process of crack stopping is explained below.

The propagation of a crack through a material is related to how much energy is absorbed per unit area of new surfaces produced by the cracking process, and the magnitude of surface area which must be created by the crack for it to progress. These factors determine the amount of energy necessary for a crack to propagate (Ashby & Jones 1980, pg. 121 et seq.). This energy can be provided either by external loading, for example during a compression test, or by shrinkage stresses. Figure 3.5 shows a crack propagating through the binder fraction which has encountered a particle of aggregate material. The same figure also illustrates the only two cases by which that crack can continue to propagate: either through the aggregate particle or around the aggregate particle. Propagation through the aggregate particle can only occur if the bond between the binder and aggregate particle is strong enough to allow the development of shear forces great enough to split the aggregate particle. Propagation around the aggregate particle can only occur if there is enough energy available to overcome the greater resistance to crack propagation due to the increased surface area that must be created during this process. In practice the secondary bonding between the aggregate particles and the binder fraction will not be able to resist the shear forces required to split the aggregate particle. Therefore, if the energy required to create the surface necessary to propagate the crack around the aggregate particle is not available, the crack will stop propagating.

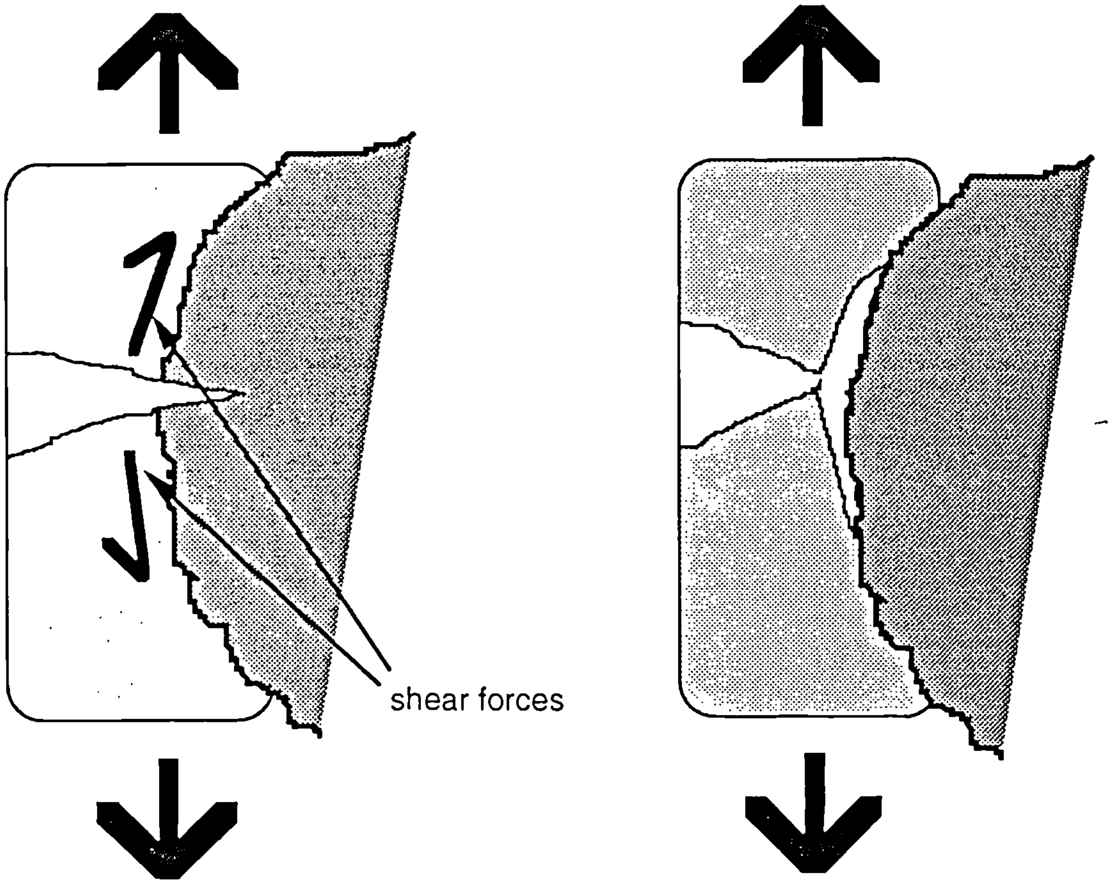
Both of the contributions of the aggregate fractions to the properties of cob described above will affect the performance of the material when it is shrinking and when it is under load. It should noted that although aggregate particles can inhibit crack growth they may also cause it via 'strain magnification'. Strain magnification is described in the next section of this chapter.

Crack stopping in cob matrix material by an aggregate particle



A crack propagating through binder material encounters an aggregate particle. Further propagation is possible either by the crack propergating:

a) through the particle
or
b) around the particle



a) Propagation through the aggregate particle ...

... can only occur if the bond between the binder and aggregate particle is strong enough to allow shear forces great enough to split the aggregate particle

b) Propagation around the aggregate particle ...

... can only occur if there is enough energy available to overcome the greater resistance to crack propagation due to the increased surface area that must be created during this process

figure 3.5

Table 3.4, below, summarises the important differences in properties of the binder and aggregate fractions of cob together with the behaviour of the interface between binder and aggregate particles.

component	property	
	cohesion	resistance to deformation
binder fraction	inversely proportional to moisture content	inversely proportional to moisture content
aggregate fraction	independent of moisture content	independent of moisture content
binder/ aggregate interface	inversely proportional to moisture content	inversely proportional to moisture content

table 3.4
Summary of the properties of the binder and aggregate fractions.

3.5) The influence of the particle size distribution on the properties of cob

3.5.1) The compression modulus of cob matrix material

Measurement of the particle size distribution of an earth mix enables the proportion of binder and aggregate fractions in the mix and the surface area of each fraction to be estimated. These proportions are important in the development of the properties of the earth building material constructed from the earth mix. If the relative volume of the binder and aggregate fractions in an earth mix can be calculated then a 'rule of mixtures' equation can be used to predict the 'modulus' of the mix. The 'modulus' (E) measures the resistance of a material to recoverable ('elastic') deformation

(Ashby & Jones 1980, pg. 25). In this thesis the modulus measured and discussed is that resulting from compression tests of samples of cob material: this modulus is therefore called the 'compression modulus'.

The 'rule of mixtures' equation presumes that the modulus of a composite material is the result of the proportion and moduli of the components of the composite. This equation is used to predict the modulus of other composite materials, for example concrete (Ashby & Jones 1986, pg. 195; Neville & Brooks, 1987, pg. 4). Concrete is as an approximation of an ideal 'composite soft material', which consists of particles with a high modulus (the aggregate), embedded in a continuous matrix phase with a lower modulus (the hardened cement paste). The modulus of a composite soft material can be calculated using the following equation:

$$\frac{1}{\text{compression modulus composite}} = \frac{\text{Vf matrix}}{\text{compression modulus matrix}} + \frac{\text{Vf particle}}{\text{compression modulus particle}}$$

'Vf' is a measure of the 'volume fraction' of the composite component such that:
volume fraction of binder + volume fraction of aggregate = 1.

The application of this equation assumes that:
i) the stress/ strain response of the composite is elastic and linear;
ii) the stress in the sample resulting from its compression is constant throughout the material;
iii) both aggregate and binder fractions of the material exhibit linear elastic behaviour in the region of the stress/ strain curve where the compression modulus of the composite is measured; and
iv) the material has no entrapped air within it.

Warren (1982) suggests that the first assumption is not unreasonable as it is commonly made, "In recent years, in estimating deformations in stiff soils, increasing use has been made of models depicting the soil as a linearly elastic cross- anisotropic medium [the properties of the soil at any point are approximately the same in any horizontal direction but are different in the vertical direction]".

Stock, Hannat and Williams (1979) presented data some of which attempted to illustrate how the volume fractions of aggregate and cement paste affected the compression modulus of concrete. This data is given in table 3.5. Figure 3.6 compares the measured modulus of the concrete with that predicted by the rule of mixtures for a composite soft material. This figure includes values of compression modulus calculated from:

average compression modulus +/ - confidence interval.

The calculation of such 'confidence intervals' is discussed in chapter 6, section 6.1.

From figure 3.6 it is clear that that the rule of mixtures, whilst not modelling the measured data exactly, provides a good indication of the relationship between the modulus of concrete, and the moduli and the volume fraction of the constituents.

aggregate volume fraction	number of tests	average compression modulus +/ - confidence interval (GPa)
0	5	13.4 +/- 0.30
0.2	5	15.8 +/ - 0.93
0.4	4	23.2 +/ - 3.04
0.6	2	30.7 +/ - (unreported)
0.8	4	39.1 +/- 2.42

table 3.5

Experimental data of the effect of aggregate fraction upon the compression modulus of concrete

Experimental data and rule of mixtures prediction of the effect of aggregate v‹
fractions upon the compressive modulus (E) of concrete

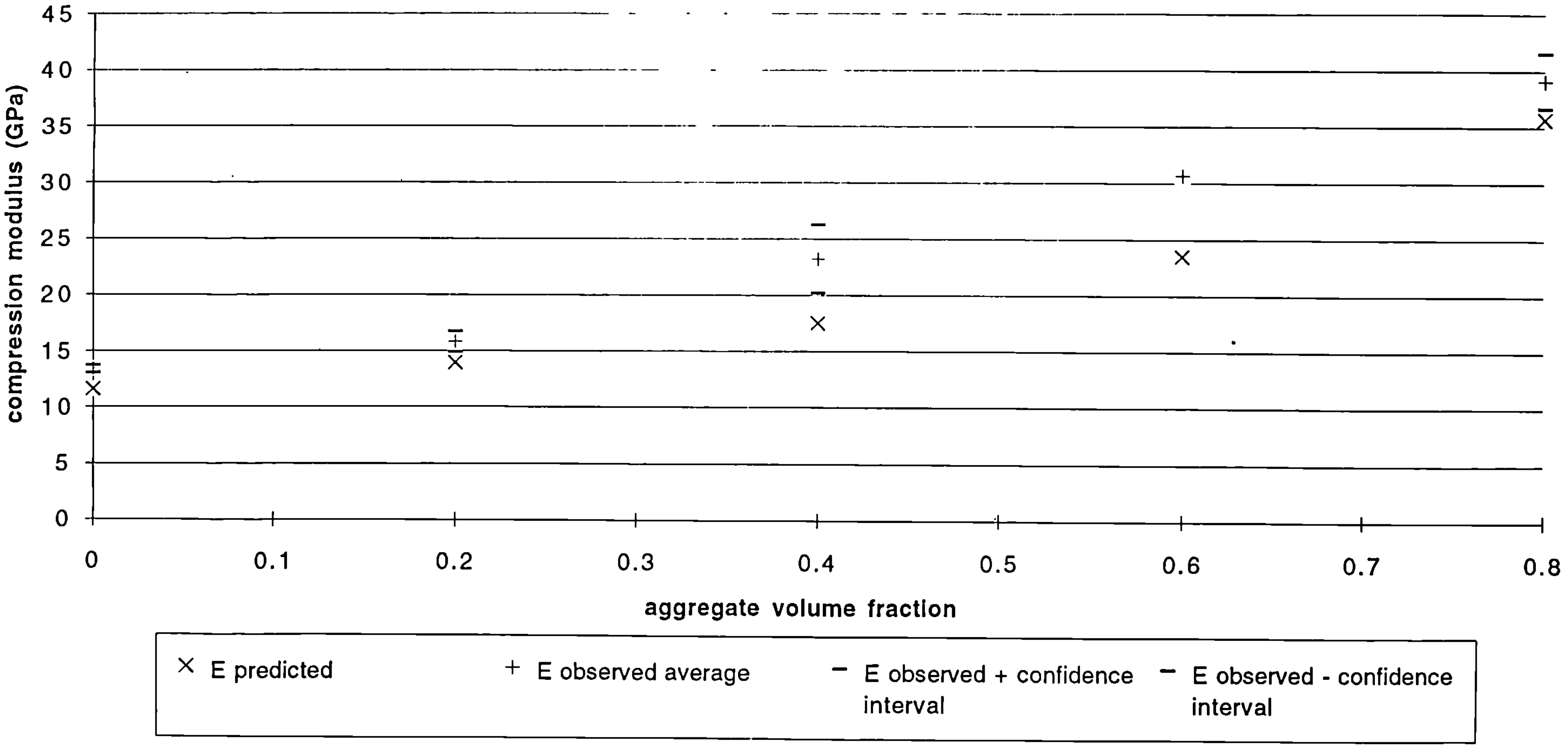


figure 3.6

Given the similarities between cob matrix material and concrete it is reasonable to assume that cob matrix material may also be considered as an approximation of an ideal composite soft material, consisting of high modulus aggregate particles, embedded in a continuous matrix of low modulus binder fraction. Therefore the compression modulus of a void free earth building material consisting entirely of binder and aggregate fractions may be calculated using the rule of mixtures.

In section 3.5 the concept that the aggregate fraction brought to an earth mix the 'potential' for the material to develope a large compression modulus was introduced. In order for this potential to be realised there must be enough binder fraction in the material to restrain the aggregate so that aggregate particles are deformed instead of displaced within the material by any applied load. That is the degree to which the compression modulus potential of the aggregate fraction is realised is determined by an 'efficiency factor' which is related to the proportions of binder and aggregate fractions in the material. Figure 3.7 illustrates the effect of varying volume fractions of aggregate upon the modulus of cob matrix material, as calculated by the rule of mixtures of an ideal composite soft material, and the proposed effect of the efficiency factor. This efficiency factor will be discussed in chapter 7.

3.5.2) Strain magnification and void content- the effect of internal structure on cob matrix material

The properties of cob matrix material is not only affected by the nature of the binder and aggregate materials but also by their distribution ('internal structure').

One effect resulting form the effect of water upon clay, discussed in section 3.3.1, is a reduction in the resistance to deformation ('stiffness') of the binder fraction.

Graph illustrating proposed effect of efficency factor upon the compressive modulus of cob matrix material

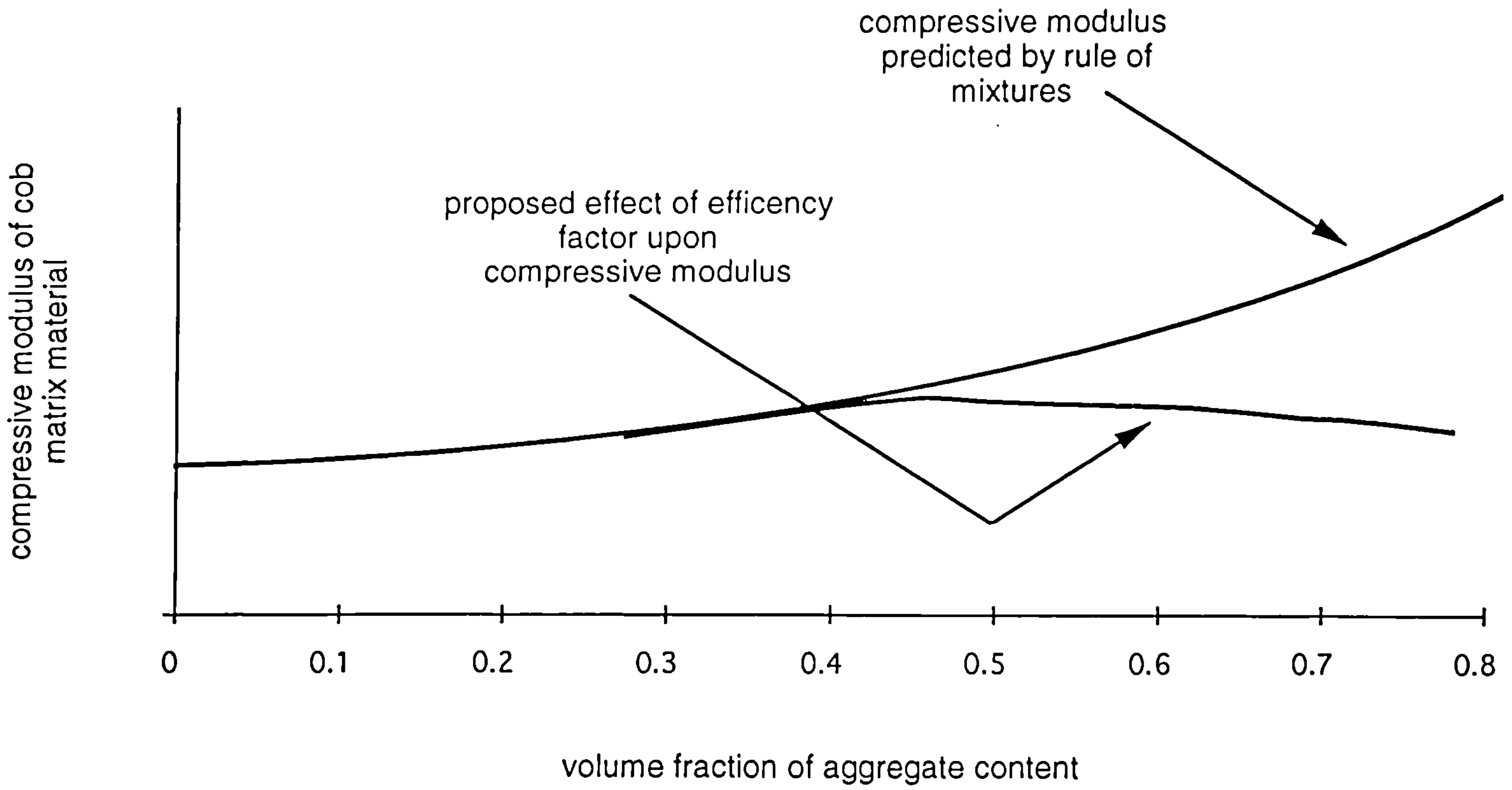


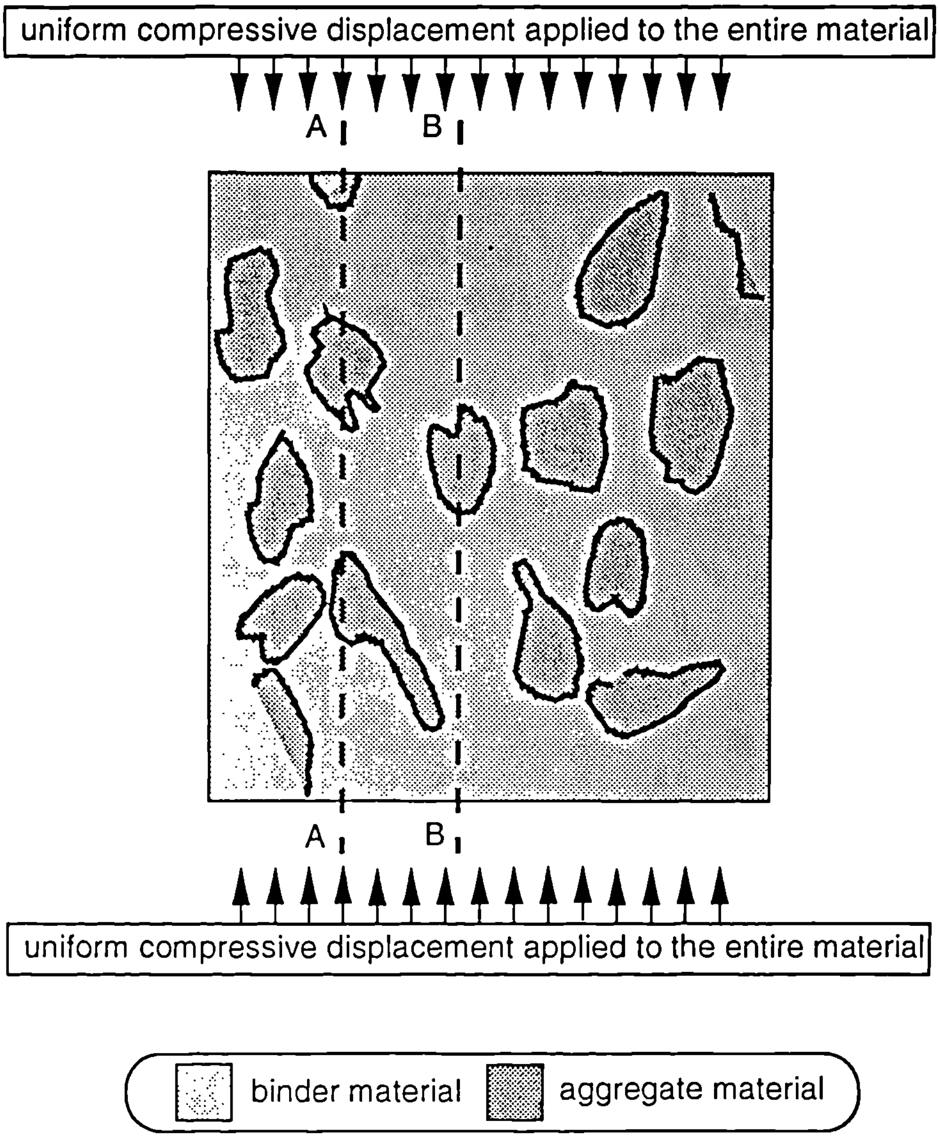
figure 3.7

It is in the nature of composite materials to combine elements with different mechanical properties. The large differences in the stiffness of the components of cob matrix material will have an effect when the material is under compression load. Both components will respond to the load by deforming, or 'straining'. The amount which the constituents will deform is related to their stiffness: the aggregate fraction with the greater stiffness will deform less than the binder fraction which has a lower stiffness. The result of these different deformations is to introduce a relative strain between the constituents. The magnitude of this relative strain will vary within the material according to the distribution of the binder and aggregate fractions relative to each other: aggregate rich volumes will deform less than binder rich volumes. The increase in relative strain in a material is known as 'strain magnification' (figure 3.8). Strain magnification will cause an additional stress on the bonding between the aggregate and binder fractions and within the binder fraction.

In practice, cob matrix material does not only consist of aggregate and binder particles, but will contain space occupied by air known as 'voids'. Because voids have no stiffness, their presence in the cob matrix material will contribute to strain magnification.

In considering the influence of voids within cob matrix material it is useful to refer to the well funded and thorough research into concrete material. Concrete, like cob matrix material, can be considered as a composite consisting of particles with a high compression modulus (the aggregate fraction), embedded in a continuous matrix phase with a lower compression modulus (the binder fraction). The aggregate fraction in concrete, like that in cob matrix material, comprises particles of primary mineral material. The binder fraction is a mixture of the hydration products of cement powder and finer particles of primary mineral.

Strain magnification in cob matrix material



- The proportions of binder and aggregate material along sections A-A and B-B are different.
- The aggregate material has a much greater resistance to deformation than the binder material.

- Therefore, in order for the total strain along both sections to be the same, the binder material along section A-A will have a greater strain imposed on it than that along section B-B.

This effect is called ‘strain magnification’.

figure 3.8

"... Portland cement is made primarily from a combination of a calcareous material, such as limestone or chalk, and of silica and alumina found as clay or shale. The process of manufacture consists essentially of grinding the raw materials into a very fine powder, mixing them intimately in predetermined proportions and burning in a large rotary kiln at a temperature of about 1400 °C when the material sinters and partially fuses into clinker. The clinker is cooled and ground to a fine powder, with some gypsum added, and the resulting product is commercial Portland cement used throughout the world. ... set cement paste is the product of reaction of cement with water. What happens is that, in the presence of water, the silicates and aluminates of Portland cement form products of hydration or hydrates, which in time produce a firm and hard mass- the hardened cement paste." (Neville & Brooks 1987, pgs. 8 and 12).

"Strength, as well as durability and volume changes of hardened cement paste appears to depend not so much on the chemical composition as on the physical structure of the products of hydration of cement and on their relative volumetric proportions. In particular, it is the presence of flaws, discontinuities and pores [voids] which is of significance..." (Neville & Brooks 1987, pg. 95).

The size range of the voids in hardened cement paste and their effect on the properties of hardened cement paste are described below
(Mehta 1986, pgs. 26 and 27).

i) Interlayer space in calcium silicate hydrate. Values for the the width of the interlayer space within the calcium silicate hydrate structure (one of the products of the chemical reaction between cement powder and water) have been variously reported in the range of 0.5 to 2.5 nano meters (nm: 1 nm = 10^{-9} m). This void size is too small to have an adverse effect on strength an permeability of the hardened cement paste.

ii) Capillary voids. These represent space not filled by solid components of hardened cement paste. In well hydrated, low water/ cement ratio pastes, the capillary voids may range in size from 10 to 50 nm. In high water/ cement ratio pastes, at early ages of hydration the capillary voids my be as large as 3 to 5 μm (1 μm = 10^{-6} m). Capillary voids larger than 50 nm are assumed to detrimental to strength and impermeability. Capillary voids smaller than 50 nm are assumed to be more important to drying shrinkage and creep.

iii) Air voids. Whilst capillary voids are irregular in shape, air voids are generally spherical. On occasion very small air voids my be added to concrete purposely ('entrainment').[1] 'Entrapped' air voids (voids not purposely included in the material) may be as large as 3 millimetres. Entrained air voids usually range from 50 to 200 μm. Both entrained and entrapped air voids are much bigger than capillary voids and are capable of adversely affecting the strength and impermeability of hardened cement paste.

Given the similarities between cob matrix material and concrete it is highly likely that the presence of voids will affect the physical properties of cob matrix material; and that the void size distribution within the material will determine the nature and magnitude of these effects.

It is proposed that cob matrix material will contain 'macro' and 'micro' voids. 'Micro voids' describe the space between particles of the binder fraction. Micro voids result from:

i) any repulsive or attractive force between the particles due to charges on the surface of either particle; and

ii) the presence of adsorbed water and ions on the surfaces of either particles.

Micro voids will be of a similar size to the capillary voids of hardened

---

[1] The most important application of air- entraining admixtures is for concrete mixtures designed to resist freezing and thawing cycles. With increasing air entrainment the tendency of saturated cement paste to expand on freezing decreases as the entrained air voids provide escape boundaries for the hydraulic pressure (Mehta (1986) and Neville & Brooks (1987)).

cement paste (10 to 50 nm) described above.
The degree of micro voidage is determined by:

i) the magnitude of unsatisfied charge available on the surface of the clay particles in the binder fraction;
ii) the concentration and charge on ions in solution in the moisture content of the cob matrix material; and
iii) the moisture content in the cob matrix material.

The quantity of micro voids will be a maximum in a 'flocculated structure'.

If there is no variation in the distribution of these elements then the distribution of micro voids will be uniform throughout the binder fraction. In this way micro voids will be responsible for the bulk of the 'porosity' of the binder fraction. As micro voids increase the distance over which any inter particular bonding must operate, they have the effect of reducing the compression properties of cob matrix material.

Macro voids will be larger than entrained air voids in hardened cement paste but of a similar size to entrapped air voids in this material (200 to 3 000 μm). The frequency of macro voids in cob matrix material depends upon the interaction of the following:

i) the degree and uniformity of the compaction process during the production of the material;
ii) the packing density of the mix; and
iii) the proportion of binder fraction in the mix.

The maximum packing density of the cob matrix material is related to the particle size distribution and is the maximum density that the earth mix can achieve without its constituent particles being deformed. Because of the difference in distribution of these two types of voids, macro voids will promote more strain magnification than micro voids.

During the production of concrete both the chemistry and physical structure of the cement paste changes. In contrast, the chemistry of cob remains constant throughout production. From the above discussion it is apparent that the physical structure of cob matrix material is influenced by:

i) the proportions each fraction in the mix;
ii) the mineralogical nature of the clay in the binder fraction;
iii) the charge on ions in solution in the moisture content of the mix;
iv) the moisture content of the binder fraction; and
v) the degree and uniformity of compaction applied during the production process.

If it is assumed that there is no void content and that there is a uniform distribution of aggregate and binder fractions, then the degree of strain magnification of a cob matrix material can be described by the index:

$$\text{strain magnification index} = \frac{\text{total particle volume}}{\text{total particle surface area}} \quad \text{m}$$

The value of this index decreases with increasing fineness of the particles which make up the aggregate fraction of an earth mix. A low value of this index indicates low strain magnification in the earth mix. This index is considered in chapter 7.

The degree of strain magnification in an earth mix is determined by the uniformity of the distribution of aggregate fraction, binder fraction, and void content; and the size distribution of the aggregate particles and voids.

From this discussion of strain magnification and voidage within cob matrix material, it is apparent that the degree of strain magnification within the material is minimised by the following processes.

a) The affect of micro voids can be reduced by:
    i) adopting a production process producing high compaction of the material;
    ii) consistent compaction in the production process; and
    iii) changing the particle size distribution of the earth mix to maximise the packing density.
b) Promoting a deflocculated structure of the clay particles in the binder fraction.

c) Reducing the maximum particle size of the aggregate fraction.

d) Ensuring that the aggregate fraction is evenly distributed throughout the binder fraction by the production process: 'maximising the homogeneity of the material'.

e) Maximising the stiffness of the binder fraction by keeping the earth building material dry when it is in service.

3.6) The influence of the fibre fraction on the properties of cob

3.6.1) During compression testing

Fibre within cob matrix material can act as a crack stopper as a result of two mechanisms:

i) by increasing the surface area that the crack must create as it propagates through the binder fraction, this situation is similar to the particulate crack stopping mechanism illustrated in figure 3.5; and

ii) by decreasing the stress at a crack tip by transferring tensile load across cracks, inhibiting propagation.

By these mechanisms the fibre in the blocks of test series 1 and 2 prevented sudden changes in the stress/ strain relationship of the test like those exhibited by the cylinders of test series 4 and 5.

Observation of failed samples in test series 1 and 2 reveals that fibres are pulled out of the matrix material as it fails ('fibre pull- out') rather than breaking and remaining embedded in the matrix material. This showed that the shear strength of the bond between the surface of the fibres and the binder fraction is less than the tensile strength of the fibres. Fibre pull- out is illustrated in plate 3.1.

plate 3.1

Fibre pull- out

(courtesy of Robert Saxton)

3.6.2) During production and construction

The inclusion of fibre in cob enables it to adhere together in large agglomerates during the production and construction processes. This facilitates the turning of the cob during the mixing process and the transfer of the cob to the wall under construction.

3.6.3) During the drying process

During the drying process of cob, the fibre fraction enables the distribution of shrinkage throughout the entire volume of the material. Without a fibre fraction there is a possibility of shrinkage becoming concentrated in a few locations throughout the material resulting in large cracks. The effect of fibre fraction upon the shrinkage behaviour of a wet earth mix is illustrated in the sequence of plates shown in plates 3.2- 3.5.

3.7) Cob production and construction

The building material 'cob' is the result of processing an earth mix (consisting of subsoil, fibre and water) in a plastic state. Construction with cob is a monolithic process using the building material whilst it is still in a plastic state. The author has been taught cob production and construction techniques by:

- English Heritage craftspeople working on Bowhill manor in Exeter (traditional manual production technique and mechanised production technique using a cement mixer); and
- Larry Keefe, until recently Conservation Officer at Teignbridge District Council, Devon, and now investigating the pathology of cob buildings at the University of Plymouth (traditional manual production technique only).

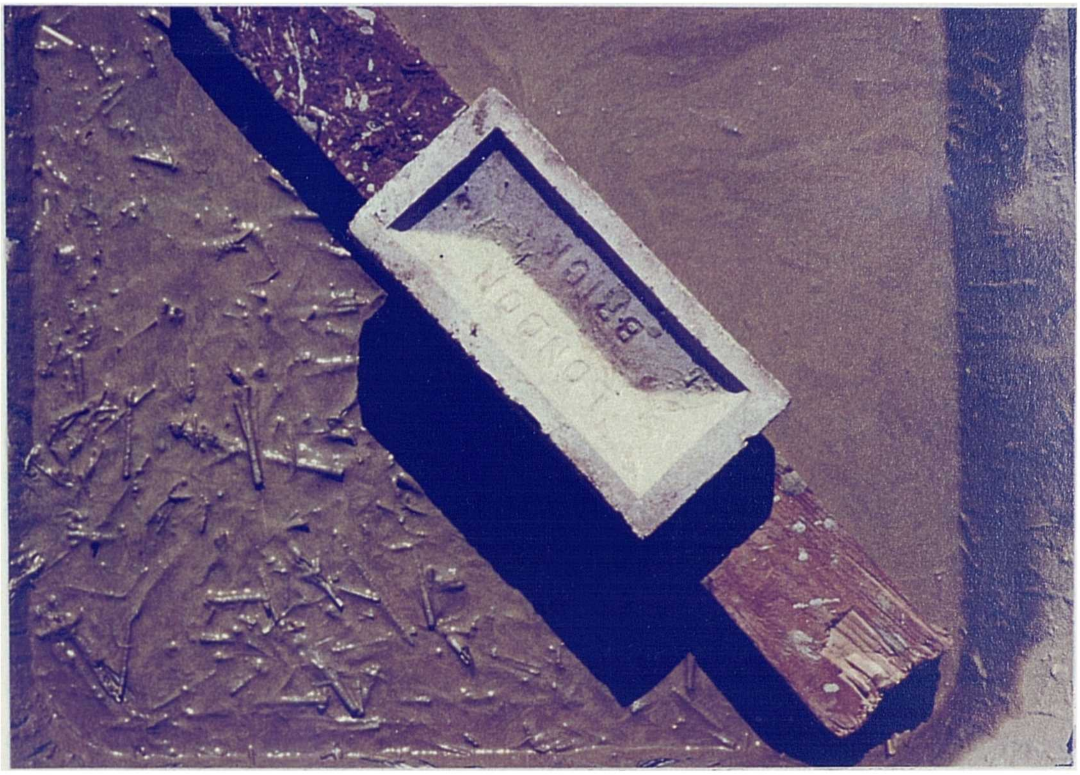


plate 3.2

A wet, clay rich earth mix has been separated into two regions.

One region has fibre mixed into it.

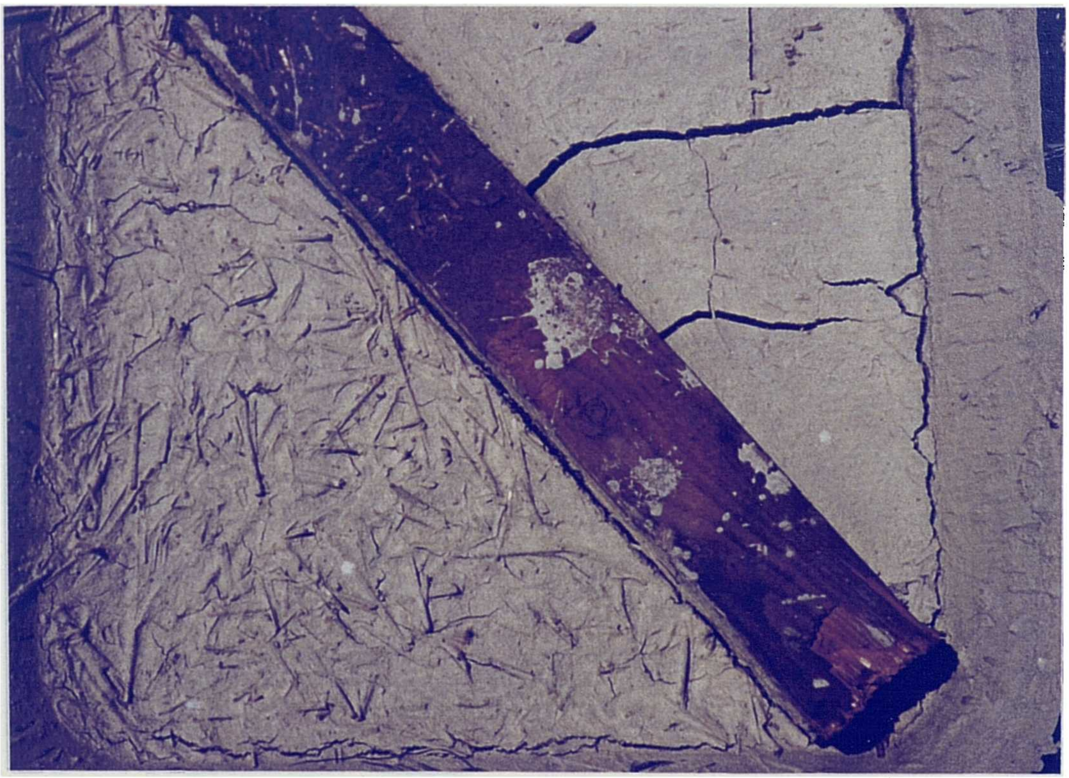


plate 3.3

When the earth mix has dried, the effect of the inclusion of the fibre

is apparent...

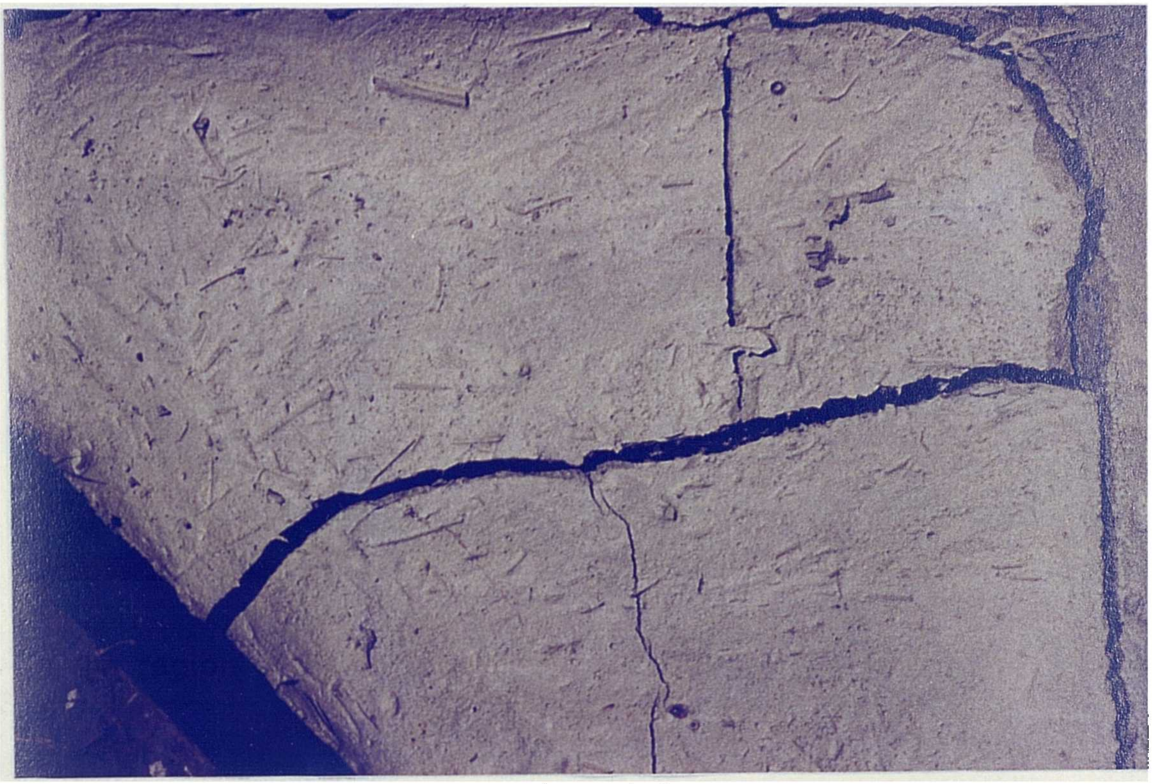


plate 3.4

in the region without fibre, movement due to shrinkage has resulted in a small number of large cracks...

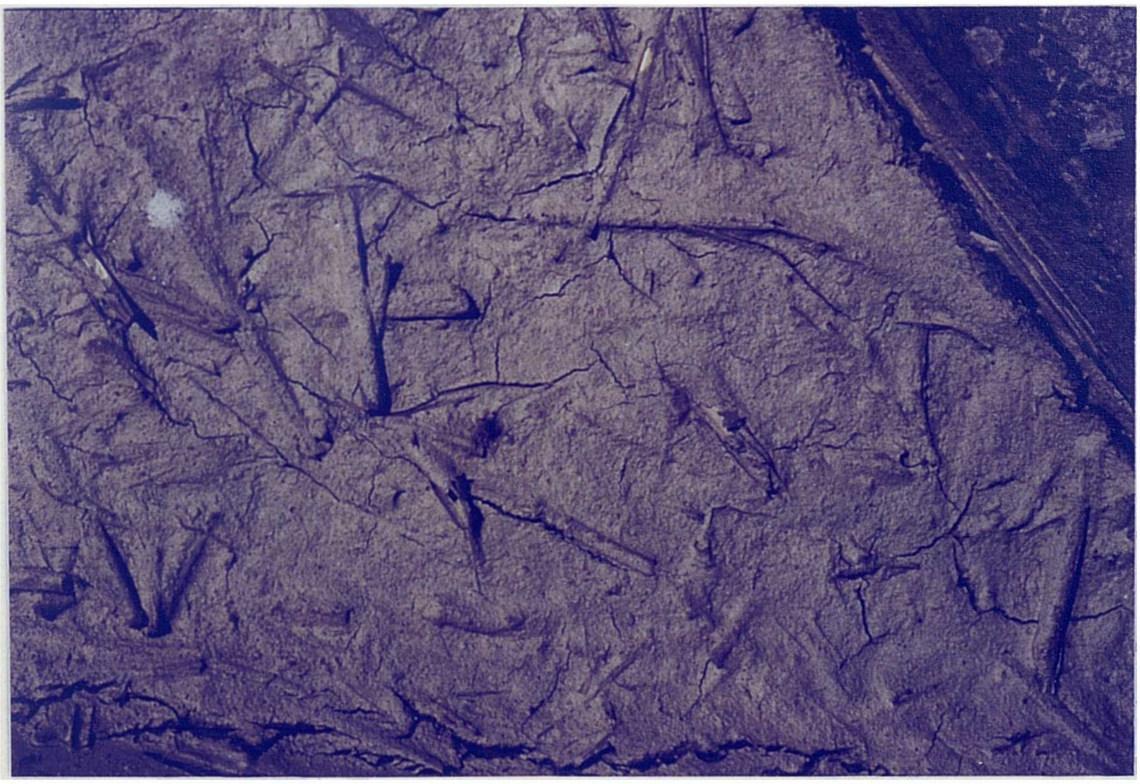


plate 3.5

... the inclusion of fibre, however, allows movement due to shrinkage to be accommodated as a large number of small cracks.

The author has also observed cob production and construction techniques:

- of Alfie Howard, Devon cob builder with over 50 years experience of cob production and construction;
- of Kevin McCabe, Devon cob builder (mechanised cob production technique using a tractor for mixing the cob); and
- during a one day course on cob building in Devon organised by the Society for the Protection of Ancient Buildings.

The non mechanised production and construction of cob is described below with brief reference to some mechanised techniques.

i) Preparation of the soil

In order for the soil to be effectively mixed with the other ingredients of cob, fibre and water, it must first be broken down. This is readily achieved by using a pick axe or spade. The degree to which the soil is broken down is dependent upon the method of mixing to be employed. If the cob is to be mixed manually the soil should be reduced until the maximum size of agglomerates of the soil is approximately 50 mm in diameter. The maximum size of aggregate in the soil will also have an effect upon the production process and structural properties of the material. Therefore, during the reduction of the soil, aggregate particles of approximately 60 mm diameter and greater are removed by hand.

ii) The addition of water and fibre to the soil

Once the soil is prepared it is ready to be mixed with the fibre such that the constituents form as homogeneous a material as is possible. This can only be achieved, using traditional manufacturing methods, if water is added to the mix. The quantity of water that is added to the mix is defined by the properties required of the material both during and after production. During production, the material must be moist enough for the binder fraction to be 'mobilised', enabling it to be evenly worked into the mix. After production, the mix should be sufficiently firm so that it does not deform under its own weight once it has been placed on the wall under construction and so that it can withstand the weight of additional material placed upon it. Furthermore, the amount of water in the material at the time of construction will have a marked effect upon the degree of shrinkage as it dries, and upon the efficacy of the compaction of cob placed on the wall. The influence of moisture on the properties of the cob: consistency, resistance to deformation, and shrinkage, are influenced by the properties of the binder fraction. Traditionally the fibre included in Devon cob was barley or long wheat straw (Harrison, 1980). It appears to have been common practice to chop or break the fibre to reduce its length before it was mixed with the subsoil; this is likely to have been to avoid weak regions in the material due to a concentration of fibre (Harrison, 1980).

iii) Mixing

The cob is mixed in batches. First, a layer of the prepared soil is spread upon a wetted surface largely impervious to water, such as concrete or a wooden board. Next, fibre is scattered over the soil and then water is sprayed on to the soil and fibre. These materials are then mixed together by the builders compressing the mix with their feet as they walk over the material. The material is then turned over, additional water added if required, and the material is mixed further. Mixing is judged to be complete when, during turning, the material adheres together in large clods, and the underside of the mix, exposed when it is turned, is no longer dry. The compression process during mixing is hindered by any large aggregate in the material, this is one reason why such aggregate is removed before mixing begins.

The author has experience of the mechanical mixing of cob using either a cement mixer or a tractor. In order for these mixing methods to be satisfactory it is necessary for the earth mix to have a greater moisture content than that desirable for construction. After mixing, therefore, the moisture content of the material is reduced by allowing it to dry naturally before it is used in construction. The mixing of cob by tractor is illustrated in plate 3.6, the consistency of cob mixed in a cement mixer is illustrated in plate 3.7. The manual mixing of cob is illustrated in plates 3.8 to 3.10.

plate 3.6

Cob production using a tractor. The cob is turned using the tractor bucket, and mixed by driving the tractor over it.

plate 3.7

The consistency of cob necessary for production using a cement mixer. The material must be allowed to dry before construction.

iv) Forming

Cob walling is built in layers which are known in the Southwest as 'lifts'. The height to which lifts are built before being left to dry is determined by the resistance of the cob to deformation when it is at the production moisture content. Theoretically lifts may be built either 'horizontally' or 'vertically'. Horizontal lift building would entail clods of the material being placed over the entire length of the lift until it was made up to the required height. Lifts built vertically would be formed of adjacent sections of material, each reaching the full lift height before the next section was formed. From the author's observation of modern cob construction practice lifts are built in a combination of horizontal and vertical techniques, the exact process being a result of the properties of the cob, the size of the construction, and the preferences of the builder. When the cob is placed on the wall it is compressed, enabling adhesion of the individual clod of material to the rest of the wall. This vertical compression process inevitably causes some horizontal expansion of the wet earth mix. Any material which overhangs the plinth (a low wall, traditionally of random rubble masonry, on which the cob is laid) as a result of this horizontal expansion, is paired back in line with the plinth before it is fully dry.

plate 3.8

The fibre and sub soil of cob ready for manual mixing.

plate 3.9

Manual mixing: the builders compresses the material

as they walk over it.

plate 3.10

Turning manually produced cob prior to further mixing.

Chapter 4: Tests

This chapter will consider:
4.1) the methodology of compression tests
4.2) the determination of the compression properties of cob and cob matrix material
    4.2.1) test series one
    4.2.2) test series two
    4.2.3) test series four
    4.2.4) test series five
4.3) the determination of the drying behaviour of cob and cob matrix material
    4.3.1) drying data from test series four and five
    4.3.2) drying data from an external experimental cob wall.

4.1 The methodology of compression tests

In chapter 1 it was stated that the aim of the project was, 'to enable the behaviour of a range of earth building materials, produced by the cob technique, to be predicted from knowledge of the properties and arrangement of their constituents'. The initial test methodology was the compression testing of samples of cob material obtained from 'donor' buildings constructed from cob material of varying compositions and the comparison of these results with compositional analysis of the specimens. It was hoped this methodology would establish correlations between various compression properties of the samples and aspects of their material composition. In practice this methodology had to be abandoned for the following reasons.

- Using a saw designed for cutting light weight concrete building blocks, the fabrication of samples of cob of sufficient dimensional accuracy and uniformity required for meaningful compression testing proved impossible. The cutting of cob samples by high pressure water jet was also investigated. This technique was rejected because the equipment was bulky and expensive, and its use was dependent upon the cooperation of a commercial organisation based in Wiltshire, an inconvenient distance from Devon.

- Despite recruiting the assistance of many conservation and building control officers in and immediately adjacent to Devon, the discovery of new possible donor buildings only occurred infrequently. This suggested that sufficient variety of cob material, demanded by the initial methodology, could not be tested within the three year time frame of the project.

- Of the four buildings proposed as possible donors all were derelict. If samples had been tested from such buildings the results might have been affected if the material was in a deteriorated state.

- Because the maintenance history, and production and construction techniques of the donor buildings were unknown, the effect of these factors on any measured compression properties would be unknown.

For these reasons an alternative test methodology was adopted, that of manufacturing of samples of material specifically for compression testing. This methodology ensured samples of sufficient dimensional accuracy and uniformity for compression testing and that the manufacturing history of the sample was known.

The first series ('test series 1') of exploratory tests were conducted on a series of cob blocks made by English Heritage craftsmen. These cob blocks were made for renovation and repair work of the Exeter manor house, Bow Hill by English Heritage.

Test series 2 consisted of nine cob blocks manufactured at the University using a mould copied from that used at Bow Hill to manufacture the blocks of test series 1. The blocks were manufactured from soil of the Breccia measures obtained from Shaldon Bridge, Devon. This particular soil was selected under the guidance of Larry Keefe, formerly Conservation Officer at Teignbridge District Council, Devon, on the basis that it was representative of the type of material used for the construction of a large number of cob buildings in Teignbridge.

The results of test series 3 describe the behaviour,during compression testing, of cob tiles manufactured by cob builder Kevin McCabe and employed by the structural engineer Paul Carpenter in the reconstruction of a fire damaged historic cob building in Stokeinteignhead, Devon. This reconstruction is described by Richold (1995). The results of these tests were used to obtain Building Regulations Approval from Teignbridge District Council, Devon. The results of test series 3 are not discussed in this thesis.

The composition of the final two test series, 4 and 5, was designed to investigate the affects of the proportion of aggregate and binder fractions, and moisture content upon selected compression properties of the material. Test series 4 and 5 samples were manufactured from different proportions of material from the Breccia soil used for test series 2.

These test series are discussed below.

4.2) The determination of the compression properties of cob and cob matrix material.

The compression properties of cob and cob matrix material were measured by uniaxial, unconfined compression testing. Test series 1 and 2 involved non standard compression tests, in geotechnical engineering terms, because the samples were 'block shaped'. However, because the samples of test series 4 and 5 were cylindrical, and had a height to width ratio of 2:1, these tests are examples of a standard geotechnical test procedure.

During uniaxial compression test a specimen of the material under investigation is compressed by a test machine at a known uniform rate. This rate is known as the 'strain rate'. The load which the test machine has to apply in order to maintain the fixed strain rate is recorded during the compression test. With knowledge of the strain rate and the force applied to the specimen during the test a load displacement graph may be drawn for the test. An example graph is shown in figure 4.1.

From figure 4.1 it is seen that as the compression displacement of the specimen increases the load applied by the test machine necessary to maintain the constant strain rate changes. The nature of the relationship between load and displacement is influenced by the shape of the test specimen. In order to compare the behaviour during compression testing of specimens of different shapes, the concepts of 'stress' and 'strain' are employed to 'standardise' the compression test results of similar test specimens. For each test specimen the stress and strain imposed on it by the compression test is calculated from:

$$\text{stress} = \frac{\text{force applied by the test machine}}{\text{initial sample cross section area}}$$

$$\text{strain} = \frac{\text{initial sample length - final sample length}}{\text{initial sample length}}$$

Graphs of stress and strain are plotted for each compression test. The stress/ strain graphs allow direct comparison of the material properties of samples whose dimensions vary slightly.

Example stress/ strain graph

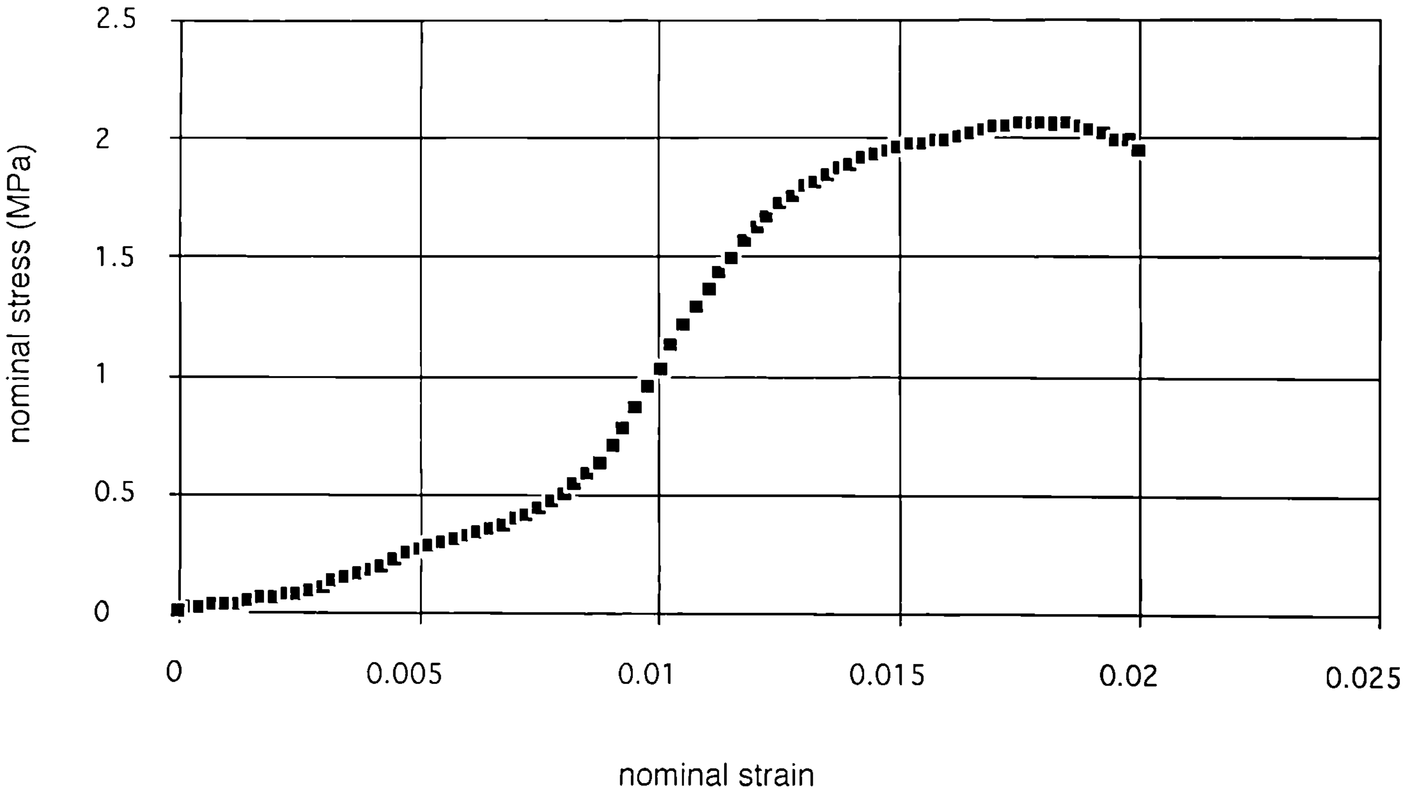


figure 4.1

The compression results of samples whose dimensions vary significantly can not be directly compared. In such cases the difference in dimensions of the samples is taken into account and 'correction factors' are applied in order to make realistic comparisons between the results (Neville 1981, pg. 540). The results of test series 1 and 2 did not produce sufficient data to calculate the effect of the sample dimensions upon the compression results. Therefore the results of test series 1 and 2 are not compared with those of 4 and 5 in this thesis.

From the stress/ strain graphs plotted for each specimen of the different test series, the following data is calculated: compression modulus, the stress and strain at the end of the linear elastic response, failure stress, and failure strain. These properties are defined below.

Compression modulus:
in this project the 'compression modulus' of a test specimen has been described by the steepest gradient of the linear portion of its stress/ strain graph. This is a measure of the maximum resistance to deformation offered by the test specimen. During the discussion of some of the properties of cob and cob matrix material 'compression modulus' will be used to describe resistance to recoverable ('elastic') deformation.

Stress at the end of the linear stress/ strain response (ELR):
the stress at which the gradient of the stress/ strain graph begins to decrease from the maximum gradient.

Strain at the end of the linear stress/ strain response (ELR):
the strain of the sample up to the point where the gradient of the stress/ strain graph begins to decrease from the maximum gradient.

Failure stress:
the maximum stress achieved by the sample during the test.

Failure strain:
the strain of the sample at the point of the failure stress.

These properties are discussed in chapter 7.

4.2.1) Test series one

Eight cob blocks were delivered to the University. All blocks were tested in uniaxial compression at a constant strain rate of 5 mm per minute in an Instron 1175 compression test machine. The test procedure is given below.

i) Each block, measuring approximately 300 x 100 x 150 mm, had a portion removed immediately before testing. The moisture content of this portion was found by oven drying. This moisture content was taken as an approximation of the moisture content of the remainder of the block.

ii) The dimensions of the remaining portion of the block were recorded, approximately 250 x 100 x 150 mm, and it was then tested in uniaxial, unconfined compression. In an attempt to investigate any effect of the sample dimensions upon the results of the compression test, two of the eight blocks were cut in half, and each half tested in compression individually. This produced compression data for blocks measuring approximately 125 x 100 x 150 mm.

iii) After testing the block was broken up and a sample of it analysed to find the particle size distribution, fibre content, and plastic and liquid limits of the material.

Of the ten possible sets of results only eight are presented: two specimens were ‘spent’ finding appropriate test machine settings (strain rate and full scale deflection) for the material.

4.2.2) Test series two

The test procedure for test series 2 evolved from that of test series 1. The differences between the two test series were:

i) the samples for test series 2 were manufactured at the University from soil of the Breccia measures (plate 4.1); and

ii) the moisture content of the samples at the time of testing was determined by a different method.

The procedure for test series 1 estimated the moisture content of the test block from a sample removed before the compression test. In order to eliminate any error resulting from this procedure the moisture content of test series 2 blocks was determined after the compression test by oven drying the entire block. During the oven drying process blocks were periodically removed from the oven and weighed to determine when their weight stopped decreasing: this was the dry weight of the block. Once dry, the blocks were broken up and a sample analysed to find the particle size distribution and fibre content of the material. Because moulds of the same size were used to produce both test series 1 and 2 blocks, this new technique meant that the test 2 samples were larger than those of test series 1: approximately 300 x 100 x 150 mm.

Test series 2 blocks were tested in Instron 1175 at a strain rate of 5 mm per minute.

The Instron 1115 and 1175 test machines used in test series 1 and 2 automatically draw a load/ displacement graph for the test in progress. The compression modulus, the stress and strain at the end of the linear stress/ strain response (ELR), failure stress, and failure strain of the test block was calculated from this graph.

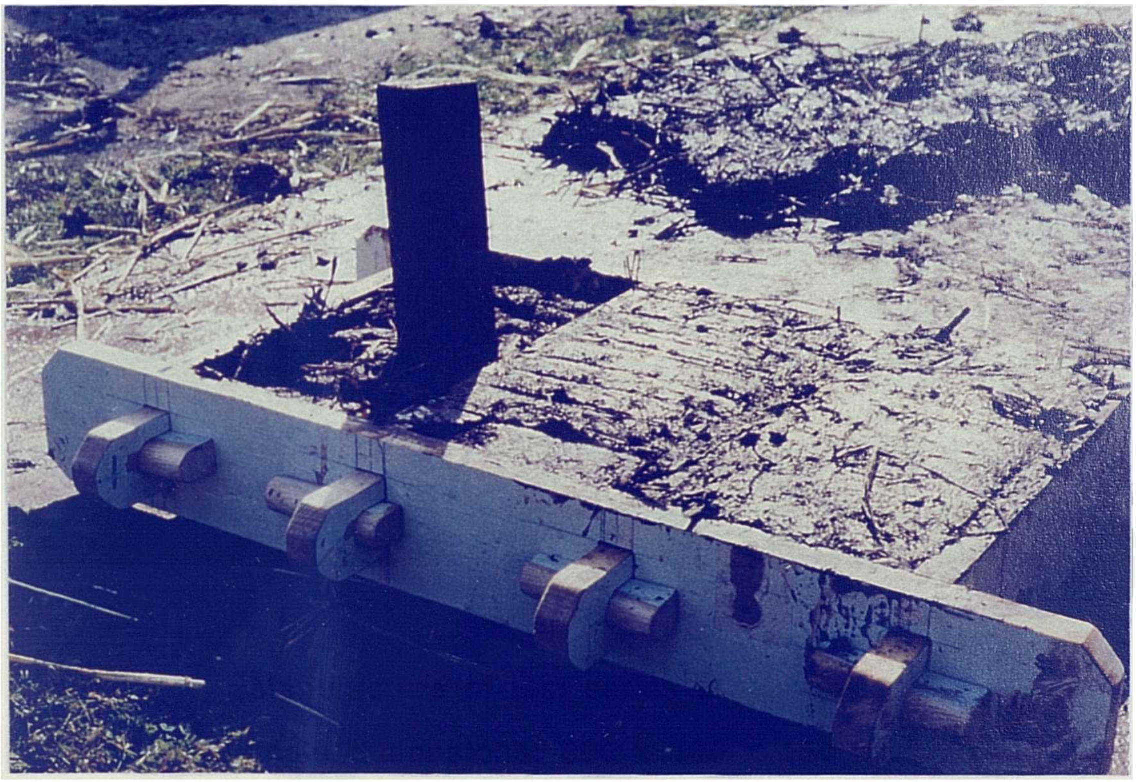


plate 4.1

Manufacture of test series 2 samples.

(Sample dimensions: 300 x 100 x 150 mm).

4.2.3) Test series four

Test series 1 and 2 provided information about the behaviour of two different cob materials in compression. This behaviour will have been determined by the following factors.

i) The internal structure of the samples.
ii) The nature of the sample's constituents, for example the surface roughness and angularity of the particles in the earth mix, and the particular clay type present in the binder fraction.
iii) The proportions of the sample's constituents: fibre content, binder and aggregate fractions and moisture content at the time of testing.

In order to investigate the relationship between some of the constituents of cob and its compression properties, and the mechanisms responsible for these properties, it was necessary to reduce the number of variables, listed above, which may affect the test results. Variables listed in (ii) above were eliminated by manufacturing test samples from earth mixes consisting of five particle size ranges taken from the same soil: the Breccia measures soil used in test series 2. To reduce the number of variables listed in (iii) above, these samples were made without any fibre content: the test samples were of cob matrix material.

So that the effects of varying the proportions of binder and aggregate fractions could be investigated, the samples were manufactured from mixes of three different proportions of particle sizes. The three mixes were labelled 'high', 'medium' and 'low' according to the relative amount of binder fraction they contained. The composition of the three mixes is given numerically below in table 4.1, and graphically in figure 4.2.

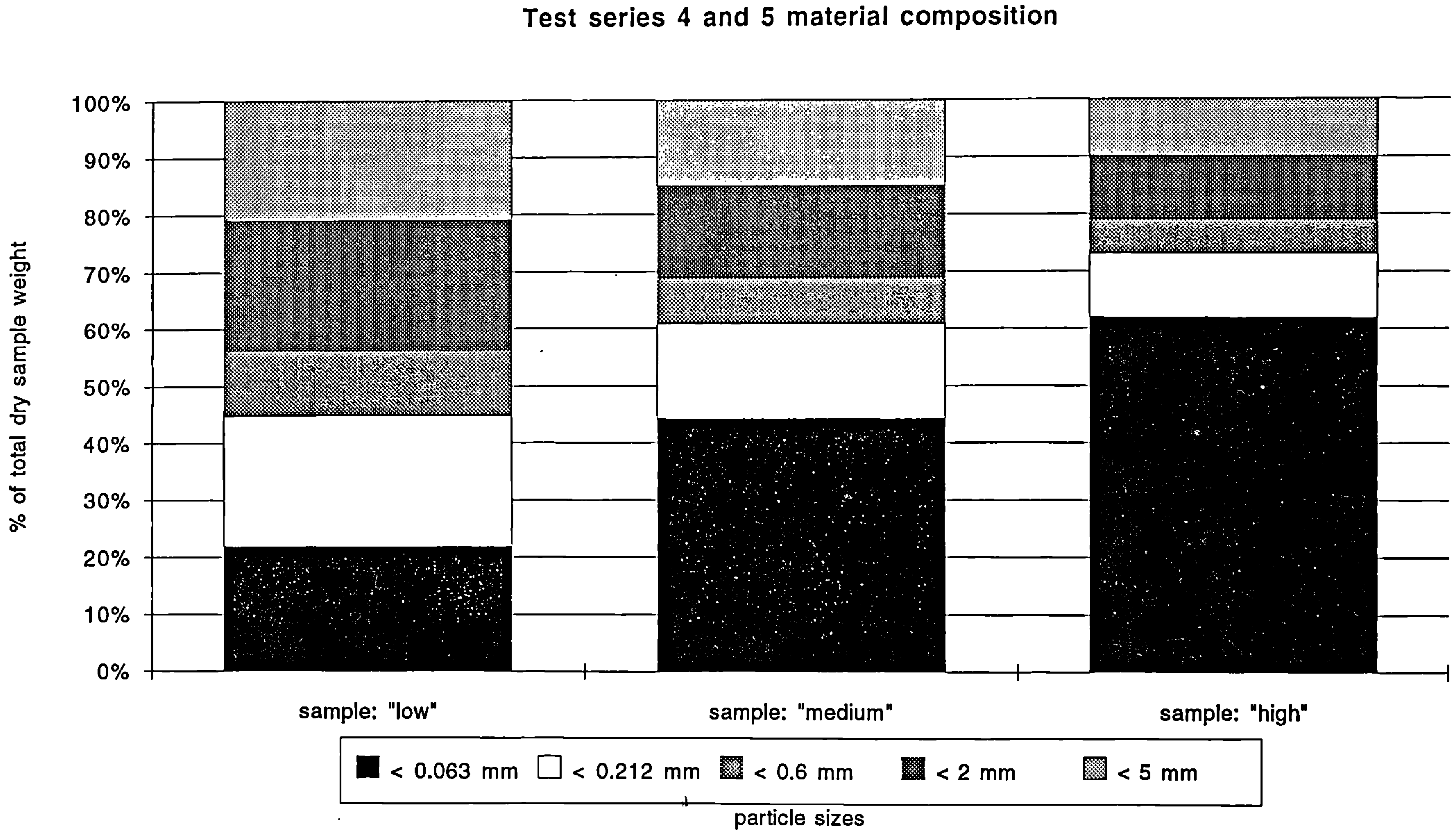

Test series 4 and 5 material composition
% of total dry sample weight
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
sample: "low"
sample: "medium"
sample: "high"
■ < 0.063 mm
□ < 0.212 mm
▨ < 0.6 mm
▩ < 2 mm
▧ < 5 mm
particle sizes

figure 4.2

particle size range	'low' mix	'medium' mix	'high' mix
fine GRAVEL	21 %	15 %	10 %
coarse SAND	23 %	17 %	11 %
medium SAND	11 %	8 %	6 %
fine SAND	23 %	16 %	11 %
CLAY/ SILT	22 %	44 %	62 %

table 4.1

Composition of test series 4 and 5 material.

(figures are percentage weights of the total dry sample weight)

As the mixes contained different amounts of binder fraction each mix type required a different amount of moisture to be added to achieve the required consistency for manufacture of a sample. Target values of 'moisture content at manufacture' were established by manufacturing samples from the different mixes at various moisture contents. The moisture contents producing a consistency of the material which allowed the manufacture from each mix of good quality specimens became the target values.

The consistency of the earth mix during the manufacture of the sample is likely to have a significant effect upon the internal structure of the sample. In order for the affect of the moisture content at manufacture upon the internal structure of each type of sample, 'high', 'medium' or 'low' mix, to be nominally the same, the same target values for moisture content at manufacture were maintained for each sample type throughout test series 4.

The target values for moisture content at manufacture are given in table 4.2 below:

high mix	26 %
medium mix	20 %
low mix	17 %

table 4.2
Target moisture contents of manufacture for test series 4 and 5.
(figures are percentage weights of water of the total dry sample weight)

The material used in test 4 was recycled: that is after testing the remains of a sample were rehydrated to the required moisture content at manufacture and a new sample manufactured. The moisture content at manufacture was determined by the mix type to which the sample belonged. This moisture content was then verified by oven drying a sample of the material from which the sample had just been formed. To avoid any change in the material caused by the oven drying process affecting the test results, the material used to determine the moisture content at manufacture was not reused. In order to account for the reduction in the material due to the removal of moisture content samples, more material was mixed than was required for just one sample .

Once manufactured the samples from test series 4 were weighed and then dried in an humidity oven at a nominal temperature of 26 °C and a relative humidity of 22%.

As the purpose of the test series was to determine the properties of the samples at particular moisture contents it was necessary to monitor their drying progress. This was achieved by periodically weighing the samples. The moisture content of a sample could then be calculated as follows:

$$\text{estimated dry sample weight} = \frac{W}{100 + mcm} \times 100$$

and:

$$\text{moisture content of sample} = \frac{w - dw}{dw} \times 100$$

where W- initial sample weight
mcm- moisture content at manufacture
w- current weight of sample
dw- estimated dry sample weight

Samples in test series 4 were tested at different moisture contents in the range of 2- 9%. In order to avoid samples reaching the required moisture content for testing when access to the test laboratory was restricted, it was necessary to suspend the drying process of some samples by removing them from the humidity oven and sealing them in a close fitting, impermeable plastic bag. The drying progress of these samples was then continued at a later time so that they could be tested when they reached the required moisture content.

It was discovered that the most suitable machine in the University to compress test series 4 samples was one designed for the testing of cylindrical samples of earth of a particular size. In order to utilise this machine the thirteen samples of test series 4 were cylindrical, manufactured in preexisting purpose made moulds, and measured approximately 36 mm in diameter and 77 mm long. The cylinders were tested in compression (plate 4.2) in a 5 000 kg Wykeham Farrance compression test machine (plate 4.3) at a strain rate of 0.1 mm per minute. This strain rate is one fiftieth that of test series 1 and 2. This much slower strain rate was chosen because the Wykeham Farrance compression test machine, unlike the Instron machines used for test series 1 and 2, does not automatically draw a load/ displacement graph for the test in progress. Instead, the strain of the test sample, and the load applied to it by the test machine must be read from dial gauges mounted on the machine. The chosen strain rate for test series 4 gave enough time to record many readings of strain and applied load for each test.

The readings recorded from the dial gauges were converted into measurements of stress and strain, and a stress/ strain graph plotted for each test. The compression modulus, the stress and strain at the end of the linear stress/ strain response, failure stress, and failure strain of the test sample were derived from this graph.

4.2.4) Test series five

Test series 5 used the same experimental procedure and test machine as test series 4. However fresh high, medium and low material was used, and the samples were tested over a wider range of moisture contents.

The full results of test series 1, 2, 4 and 5 detailed above are given in:

'Appendix J: test series 1 and 2 compression and composition data';
'Appendix L: test series 4 and 5 compression data'; and
'Appendix M: test series 4 and 5 stress/ strain graphs'.

4.3) The determination of the drying behaviour of cob and cob matrix material.

The drying behaviour of cob was described by data from the following two experimental procedures.

4.3.1) Drying data from test series four and five.

This is data acquired during the monitoring of the drying progress of test series four and five cylinders. The results of this monitoring process are given in chapter 6.

plate 4.2

Sample of test series 5 under compression test.

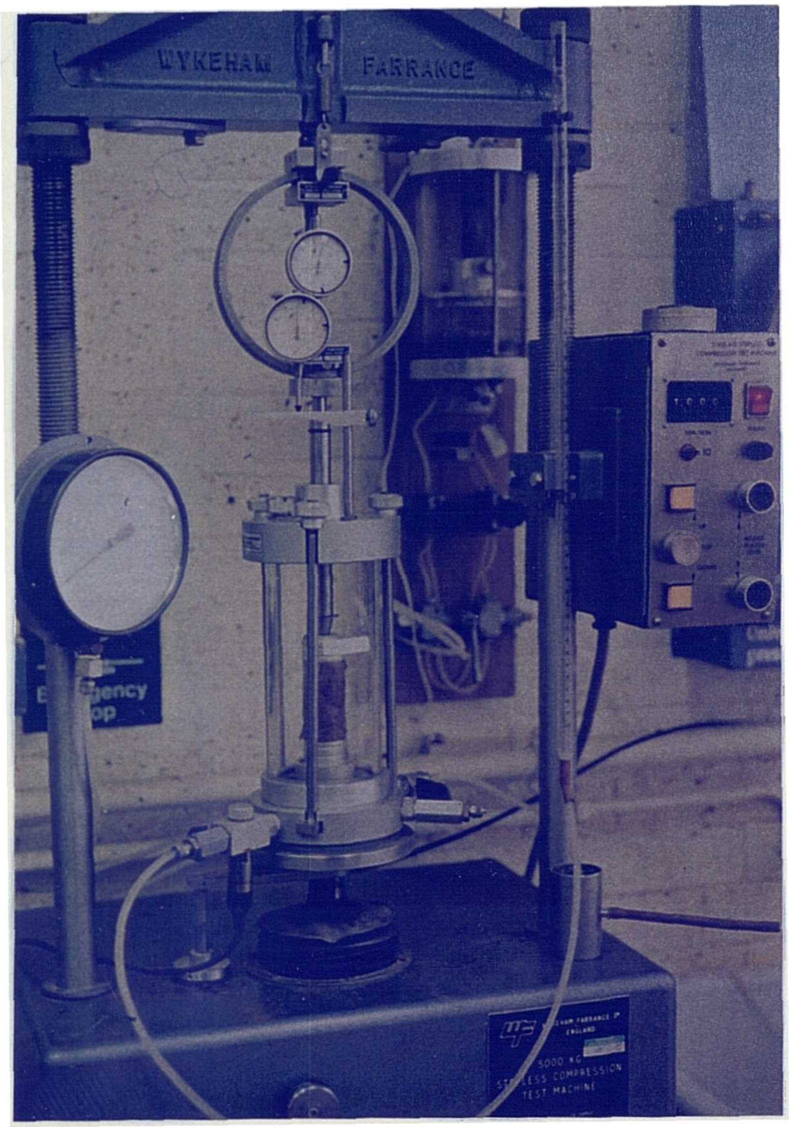


plate 4.3

Wykenam Farrance 5 000 kg compression test machine used for test series 4 and 5.

4.3.2) Drying data from an external experimental cob wall

This data was collected from a total of forty five probes, fifteen being included in each of the three lifts of the experimental wall. The distribution of the probes in each lift is shown in figure 4.3. The installation of a set of probes is illustrated in plate 4.4. Details of the experimental wall are shown in figure 4.4 (a) and (b).

In order to achieve a moisture measurement the probes are connected to a Time Domain Reflectometer (TDR). "The determination of soil water content using the time domain reflectometer technique is based on the relationship that exists between the relative complex dielectric constant of the soil and its water content. Studies done previously (Davis and Annan, 1977; Topp et al., 1980) show that the relative complex dielectric constant of a dry soil doesn't vary significantly with density, texture, salt content, or temperature between frequencies of 1 MHz and 1 GHz [This the band of frequencies of the test signal transmitted by the TDR.]. Because the relative complex dielectric constant of liquid water is about twenty times higher than either soil or ice (Von Hipple, 1961), the relative complex dielectric constant of the total soil will vary primarily due to changes in the liquid water content." (Stein and Kane 1983). The following extract from the thesis of TJ Heimovaara (1993) outlines the theory of this method of moisture measurement.

"Time domain reflectometry is based on the measurement of voltage changes occurring when a fast rise step voltage is sent along a transmission line. The voltage pulse travels as an electromagnetic (EM) wave guided by the conductors of the transmission line (Von Hipple, 1954, Davidson, 1978). The propagation of the EM wave is related to the impedance of the transmission line. TDR cable testers were originally developed to locate discontinuities in cables with an impedance Zc. If the discontinuity has an impedance Zd, part of the travelling wave will be reflected towards the cable tester. Cable testers display voltage as a function of time. Discontinuities with an impedance different than the cable, cause a change in the trace level. The magnitude of the reflection is defined by the voltage reflection coefficient (rho), which is the ratio of amplitudes of the voltage wave reflected, vr, and the incident voltage wave, va. The voltage reflection coefficient is related to the impedance at the discontinuity (Ramo and Whinnery, 1952; Davidson, 1978):

$$rho = vr/ va = (Zd - Zc)/(Zd + Zc)$$

The impedance of an ideal coaxial transmission line depends on the geometry of the conductors and on the relative dielectric permittivity (e) of the material between the conductors (Davidson, 1978). The velocity, and as a result the travel time, of the voltage wave in the transmission line also depends on the dielectric permittivity of the material between the conductors (von Hipple, 1954). Topp et al. (1980) applied TDR to measure this travel time in soils (Δts) in order to determine volumetric water content. The apparent dielectric permittivity (Ka) of the material between the probes can be calculated because the length of the TDR probe embedded in the soil (L) is known:

$$Ka = (c\Delta ts/ 2L)^{2}$$

in which c is the velocity of light in free space (3×10^{8} m/s).

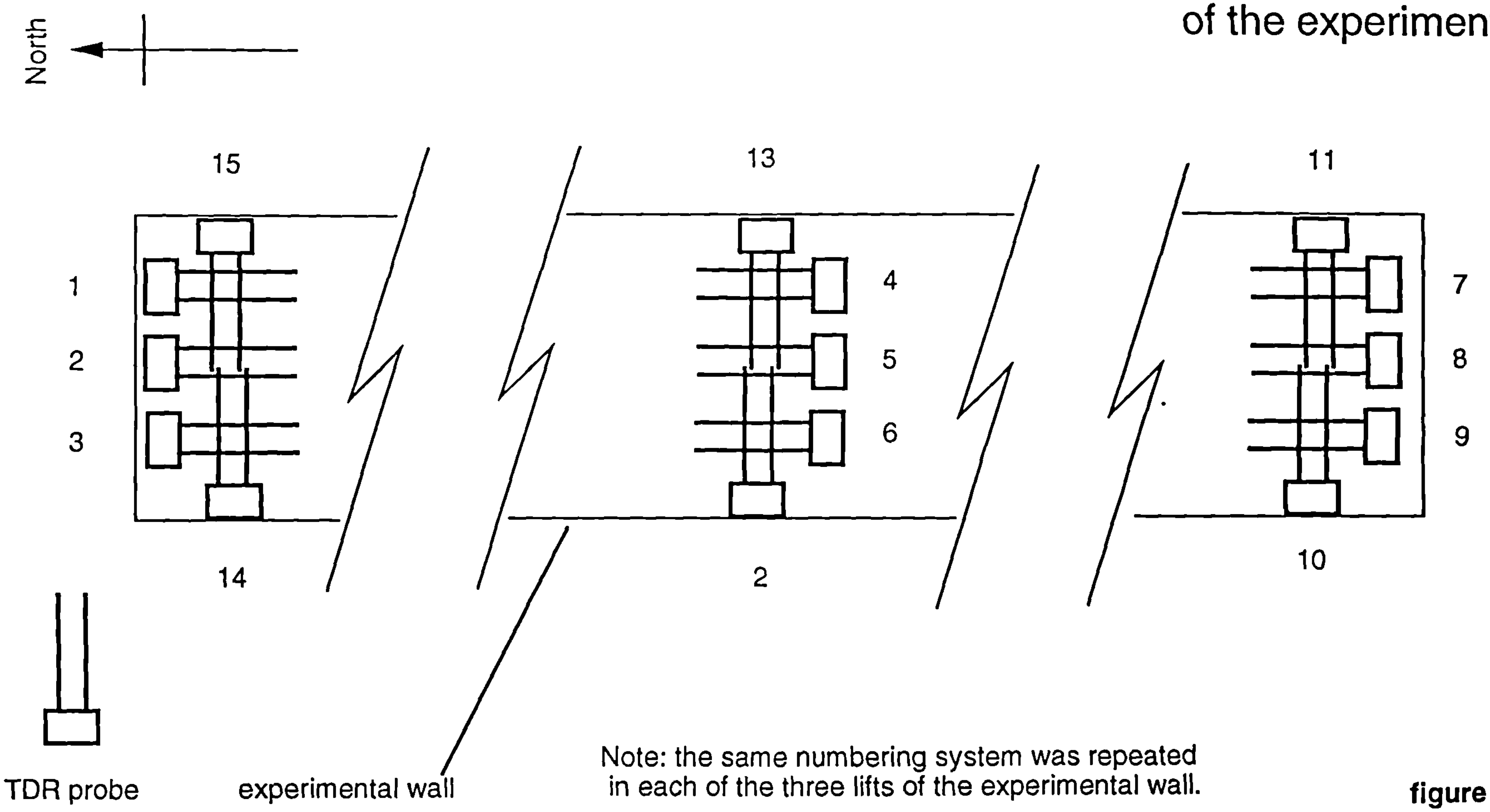
Topp et al. (1980) presented an empirical third order relationship relating soil water contents (theta) to the measured apparent dielectric permittivity:

$$theta = (-530 + 292\ Ka - 5.5\ Ka^{2} + 0.043\ Ka^{3}) / 10^{4}$$ "

In soil science based disciplines moisture contents are usually expressed in volumetric terms. Volumetric moisture content is calculated as:

$$\text{theta (volumetric moisture content)} = \frac{\text{volume of water}}{\text{volume of soil}}$$

Probe numbers in a lift of the experimental wall

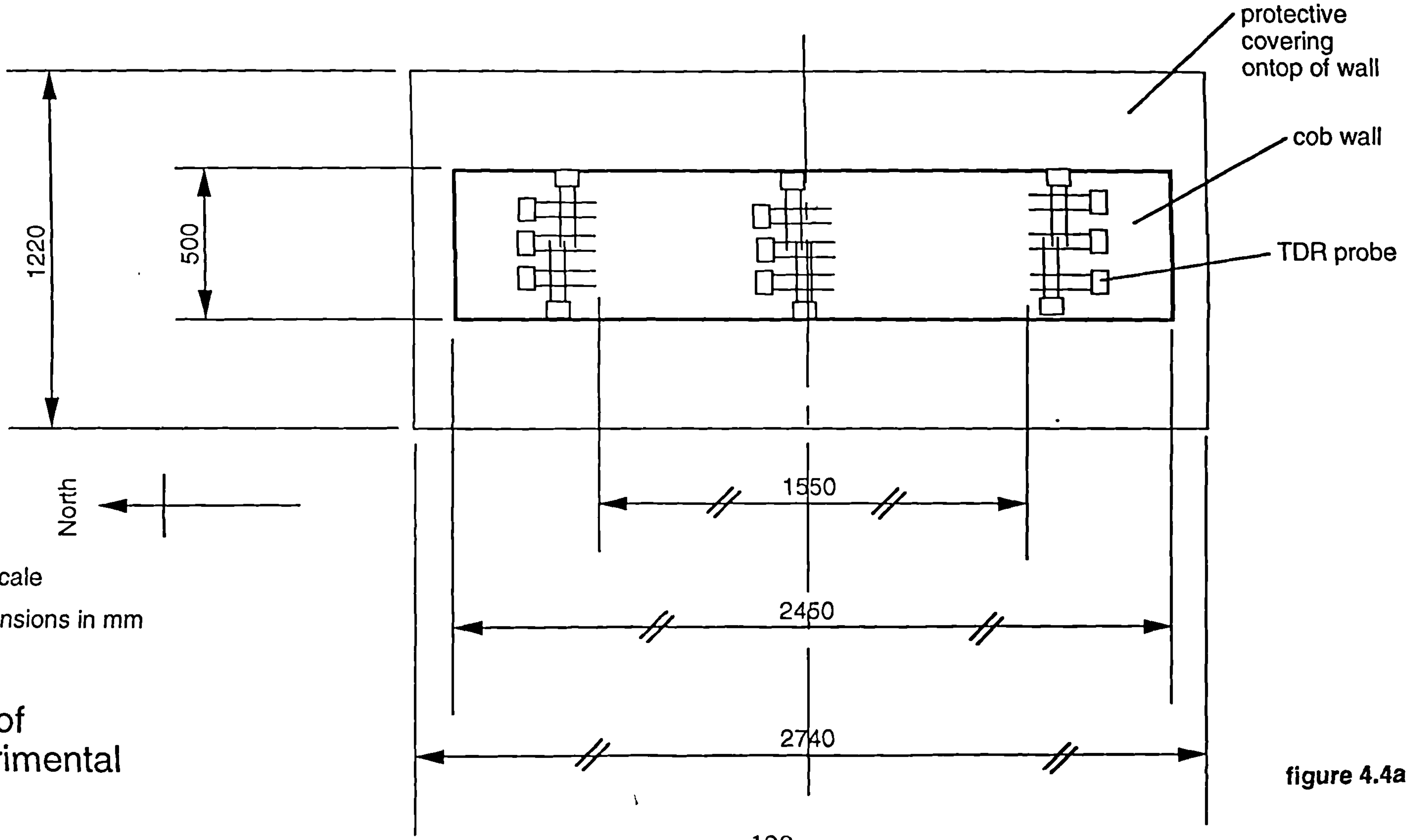


Note: the same numbering system was repeated in each of the three lifts of the experimental wall.

figure 4.3

plate 4.4

Installation of a set of TDR probes into the experimental wall

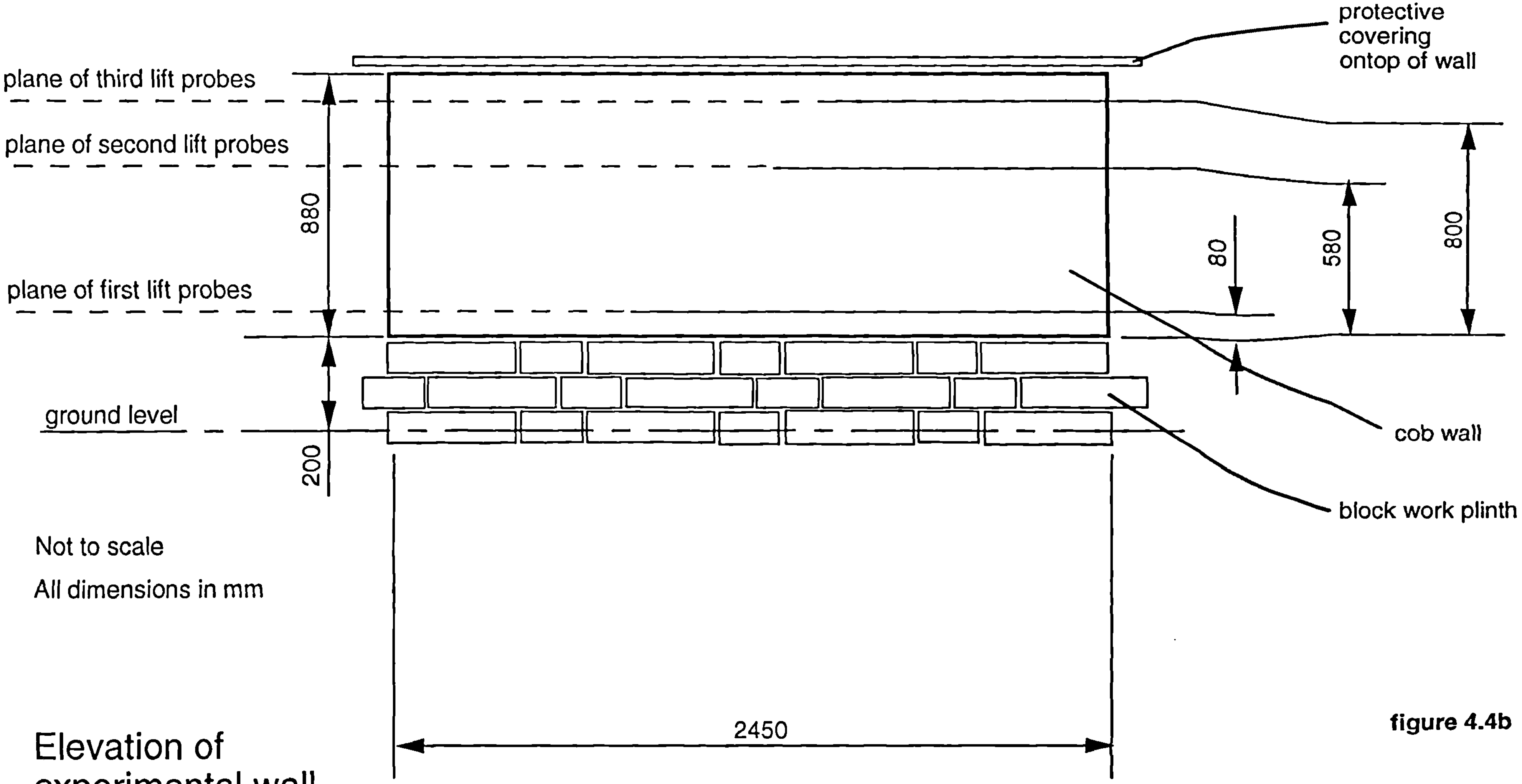


Not to scale

All dimensions in mm

Plan of experimental wall

figure 4.4a



Not to scale

All dimensions in mm

Elevation of experimental wall

figure 4.4b

Topp's equation relates volumetric moisture content to the TDR measurement of the apparent dielectric permittivity of the test soil. Other moisture contents in this project are all measured in gravimetric terms: the weight of water in a sample is presented as a percentage of the dry sample weight. In order enable comparisons to be made between the moisture content of the experimental wall and those of the mechanical test specimens the TDR moisture content readings were calibrated to gravimetric moisture content readings. This was achieved by manufacturing a block of cob from the Teignmouth soil, inserting a TDR probe into it and measuring the moisture content of the block as it dried in air. The moisture content at which the block was manufactured was established by oven drying a sample of the cob material at manufacture. With each TDR moisture measurement the weight of the block was also recorded. With knowledge of the moisture content at manufacture of the block the gravimetric moisture content at each TDR reading could be calculated. The resulting calibration graph is shown in figure 4.5.

It was found that this calibration curve was very well described by the equation:

$$\text{gravimetric moisture content} = 2.4318 \times (\text{TDR reading})^2 - 0.8463$$

$$r = 0.91 \quad t = 13.00 > t_{crit}(30, 0.025) = 2.04$$ [1]

Gravimetric moisture contents of the experimental wall were calculated from the TDR readings using this equation.

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[1] the significance of this value will be explained in chapter 6

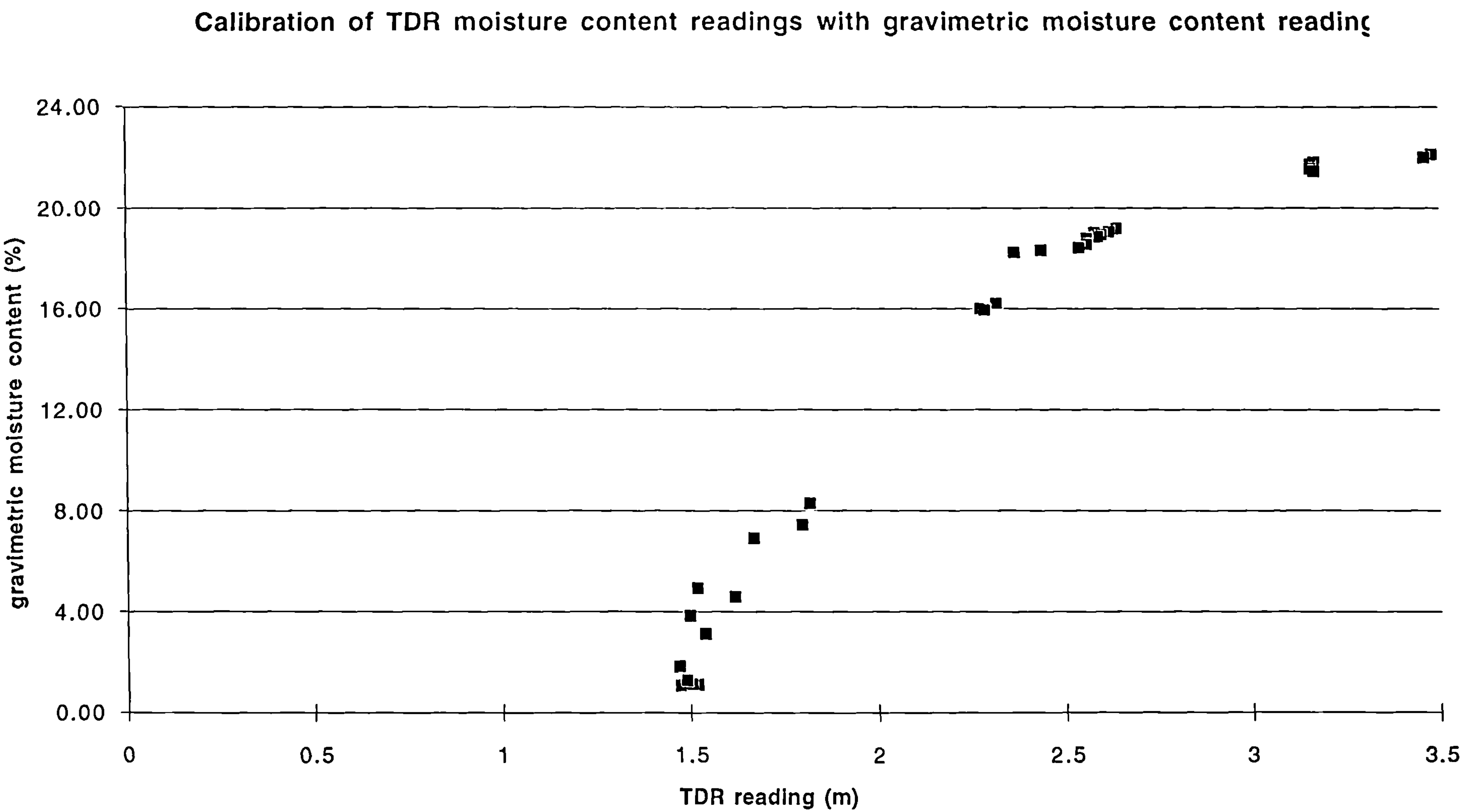
Calibration of TDR moisture content readings with gravimetric moisture content readinç
gravimetric moisture content (%)
24.00
20.00
16.00
12.00
8.00
4.00
0.00
0
0.5
1
1.5
2
2.5
3
3.5
TDR reading (m)

figure 4.5

When connected to a conductor with an impedance change in it (for example a cable-probe assembly with the probe buried in soil) the screen of the TDR displays a trace. The trace shows the variation of the voltage reflection coefficient with distance along the conductor attached to the TDR. The TDR calculates the distance element of this trace from the equation:

$$L = \Delta t \times Vp$$

where L is a distance along the conductor under test, Δt is the time taken for the transmission signal to be reflected back to the instrument from this distance and Vp is the velocity of propagation of the test signal and test signal reflection in the conductor.

When used for the detection of discontinuities in conductors, the velocity of propagation is set on the TDR controls to the correct value for the material of the conductor. The discontinuity will result in a change in impedance of the conductor. This will be evident as a change in the level of the trace of the voltage reflection coefficient displayed by the TDR. A vertical cursor is moved along the trace by the operator to this change in level, and then the distance along the conductor to the discontinuity is read off from the TDR.

Probes made according to two different designs were used in the monitoring of the drying progress of the wall (plate 4.5). Once installed in the wall, it was found that a large proportion of the probes did not provide a reliable reading. The probes of the first design were made by welding the cable conductors of the probe into slots cut in the stainless steel probe rods. Initially it was thought that the exposed conductor and weld had been vulnerable to damage during the construction of the wall. In order to reduce this perceived vulnerability, the probes were redesigned so that electrical continuity was achieved between the cable conductors and the probe rods via a strip of metal electrical connectors set in plastic. The connection between the probe rods and cable conductors, including the strip of electrical connectors, were then encased in an epoxy resin. This second design had three important benefits, it:

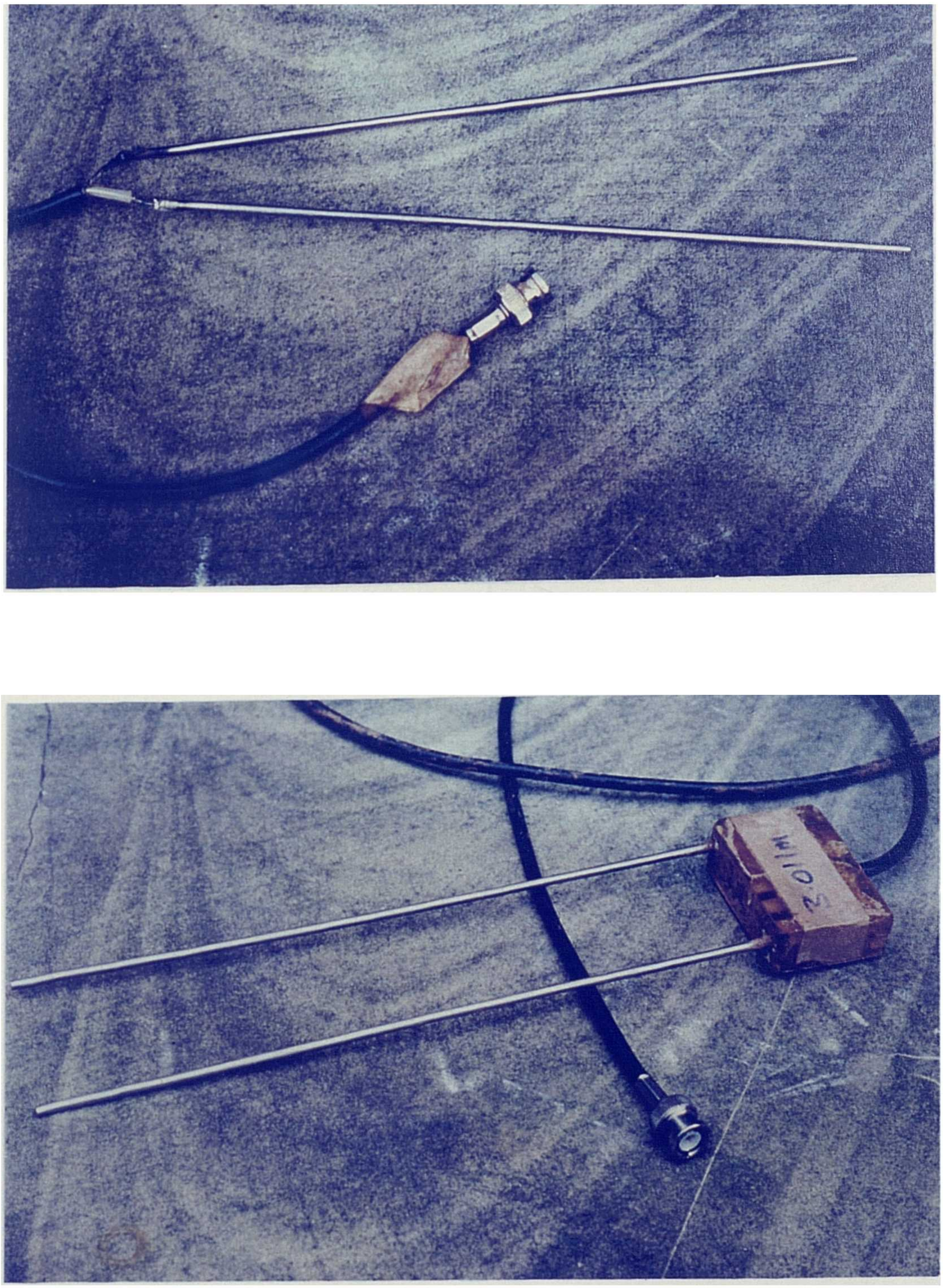

plate 4.5

The first and second designs, respectively, of TDR probes.

The metal probe rods are 250 mm long.

i) improved ease of manufacture by eliminating the welding process of the first design;
ii) ensured that the probe members were held parallel (this is important for the accuracy of the probe readings); and
iii) provided protection for the probe whilst being placed in the wall as the wall was constructed.

After the probes had been redesigned and a batch manufactured ready for installation in the second lift of the wall, it was discovered that the malfunction of the majority of faulty probes in the first lift was caused by a loose connection between the probe lead and the BNC connector which attaches the probe to the TDR. Despite this discovery the second design of probes was used in the second and third lifts of the wall as it appeared that the benefits of the second design would out weigh any problems caused by using two different designs to monitor the drying progress of the wall.

When used to determine the moisture content of a soil, distances measured by the TDR are relative to the beginning of the probe rods. In order to achieve this a previously established zero point for the particular probe design is entered into the TDR at the beginning of each measurement session. A different zero point was used for each of the two probe designs. The zero point of a probe is found by 'shorting' the end of the probe rods nearest the cable with a spare probe rod and measuring the point on the TDR display about which the trace appeared to pivot.

An example trace of a cable and probe assembly attached to the TDR is shown in figure 4.6 and illustrated in plate 4.6. In order to measure the moisture content of the soil between the probe members the vertical cursor is moved along the trace to the point of inflection shown: the TDR reading, in meters, can then be determined.

Example TDR trace

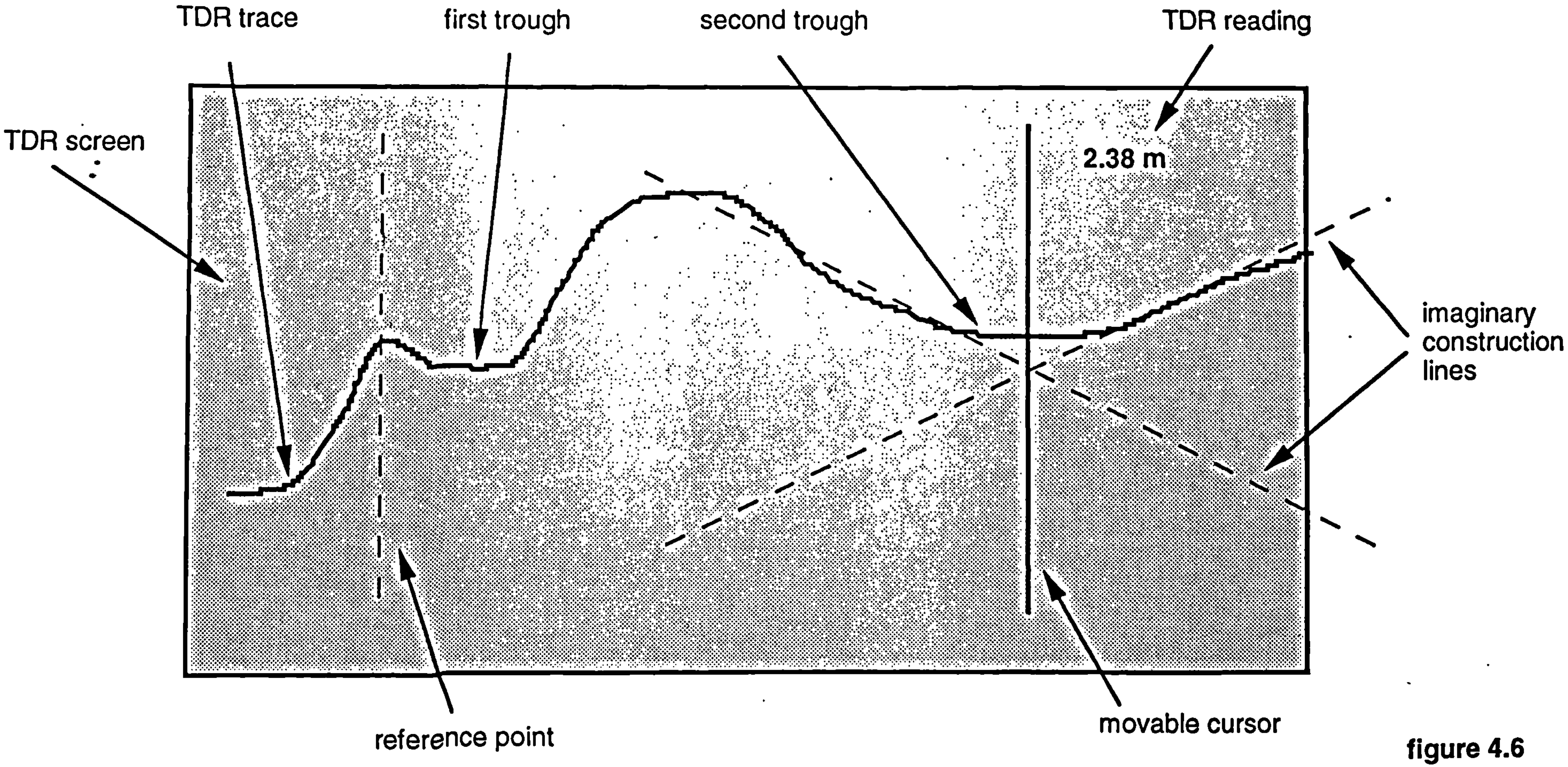

figure 4.6

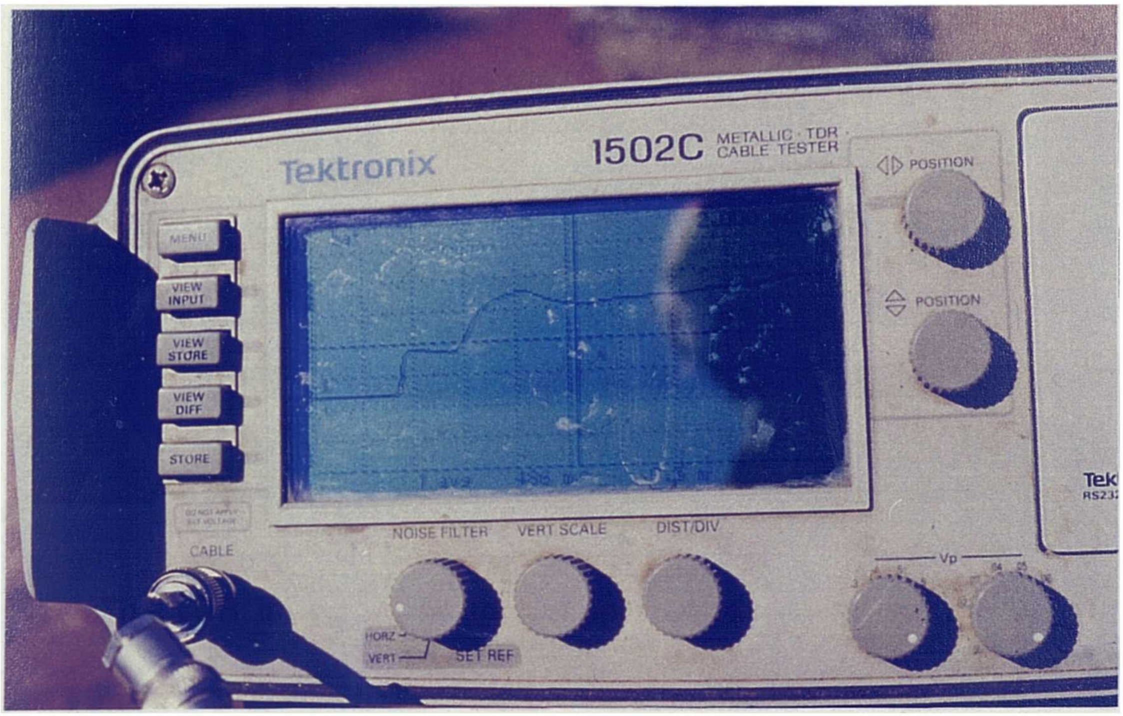

plate 4.6

The TDR instrument and example trace of a probe in the experimental wall.

During the analysis of the data collected from the experimental wall it became apparent that there was a large increase in the TDR readings between the first and second measurement blocks. Further more, the highest TDR readings obtained in the first measurement time period were less then the lowest TDR readings of the calibration experiment. This discrepancy has been attributed to incorrect interpretation of the TDR traces of the first measurement time period. It is believed that the TDR readings of the first measurement time period were taken at the point of inflection of the first 'trough' of the trace (figure 4.6). This error would account for the fact that all of the measurements of the first time period are lower then the values in later measurement blocks. During the experiment which calibrated the TDR readings with gravimetric measurement of moisture content, a limited number of readings were taken based on the point of inflection of the first trough of the TDR trace. These readings do not cover the range of values recorded in measurement time period one and so can not be used to establish an equation to convert the incorrect TDR readings into gravimetric values of moisture content. However, over the range of measurements taken of these TDR readings they are proportional to the gravimetric moisture content of cob.

The measurement by eye of the TDR traces has two major disadvantages: it is liable to error due to the difficulty in determining the point of inflection of some traces, and the form of the trace is lost. As the form of the trace can give information about the magnitude and direction of the moisture gradient along a probe, the inability to record the trace means that not all of the information which is captured by the TDR is available for analysis. Computer systems now exist which are capable of capturing the traces from many TDR probes (Holden et al. 1995; Heimovaara & de Water 1991 & 1993).

The drying progress of the second and third lifts was monitored from the time they were manufactured. However, monitoring of the first lift only began 15 days after it was completed because the TDR was unavailable for use. The unavailability of the TDR affected the continuity of monitoring of the experimental throughout the project. The wall was further monitored in 1995, for two seven day time periods in February and March. Monitoring of all three lifts stopped on 8/8/95.

During 1993, the relative humidity and temperature of the air around the wall was recorded at each reading of the TDR probes in the experimental wall. Analysis of this data did not establish any correlation between relative humidity and temperature, and the moisture content, or change in moisture content, of the experimental wall. This is because one instantaneous measurement of relative humidity and temperature can not be taken as an average value for the time period between that measurement and the previous measurement[2] : the values of relative humidity and temperature varied greatly between successive measurements. Therefore, monitoring of the experimental wall during 1995 did not include measurement of the relative humidity and temperature of the air around the wall.

The experimental wall was built in three lifts, each lift taking two days to construct. The construction dates for the 3 lifts were: for the first lift the 7th and 8th of June 1993; for the second lift the 22nd and 23rd July 1993; and for the third lift the 17th and 18th of August 1993. The cob used in construction was mixed manually using barley straw for the fibre content. This process is described and illustrated in chapter 3. The Breccia measures soil used to construct the experimental wall was the same material used for the manufacture of the samples in test series 2, 4 and 5.

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[2] It was presumed that the moisture content of the experimental wall would not change rapidly. Therefore, for this quantity, one instantaneous measurement has been taken as an average value for the time period between successive measurements. During monitoring this time period was typically twenty four hours.

Protective coverings of the experimental wall

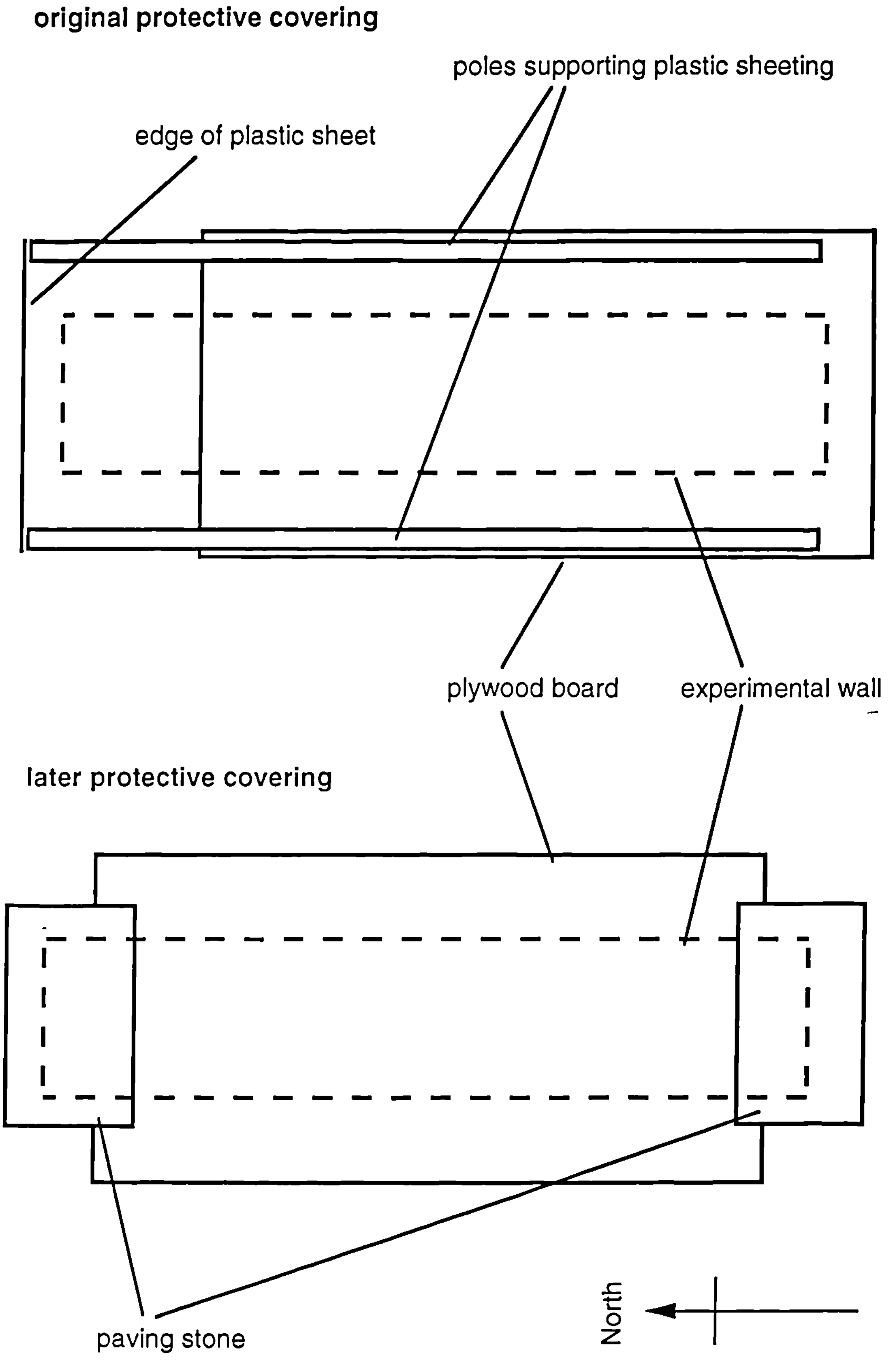


figure 4.7

During the construction and subsequent monitoring of the experimental wall a covering was used to protect the top of the wall from water ingress. This covering was wider than the wall to provide some shelter to the vertical faces of the wall. The protective covering consisted of an exterior grade plywood board resting on top of a plastic sheet. Initially, as the board was smaller then the top of the wall, the plastic sheet protruded from beneath the board at the north end of the wall. The sheet was supported in this region at each side by a pole which rested on the plywood board. This plastic sheet was later replaced by a thicker, larger sheet. The later sheet was arranged so that it protruded at each end of the board. In order for the protective covering to protrude from the wall a paving stone was placed overhanging the wall at each end. The plastic sheet was wrapped around the paving stone at each end. As the paving slabs projected out from the wall they were counterbalanced to prevent them falling to the ground. The two different protective coverings are shown in figure 4.7.

The foundations of the experimental wall were three courses of light weight concrete block work built on a bed of sand spread over the ground. Mortar was not used between the blocks, but they were separated from each other by dry sand. Because the foundations of traditional cob walls are of random rubble masonry, the foundations of the experimental wall are not representative of those of traditional cob walls.

Chapter 5: The Characterisation of Cob

This thesis considers that the properties of cob are determined by particular properties of the constituents and their dispersal. The role of the constituents of cob are investigated by comparing the properties of different mixes of cob materials. To achieve this it is necessary to describe cob in terms of the constituents from which it is made.

This chapter considers the four processes that have been used to describe the cob materials tested during this project. These processes measure:
5.1) moisture content;
5.2) particle size distribution and fibre content;
5.3) plastic and liquid limits; and
5.4) particle densities.

5.1) The measurement of moisture content

Two methods of measuring the moisture content of cob have been used in this project. The moisture content of compression test specimens was established by the technique of oven drying. The moisture content of an experimental wall built at the University of Plymouth for this project was monitored using the method of Time Domain Reflectometry. This method is described in chapter 4.

The moisture content of test series 1, 4 and 5 was measured by oven drying a sample of the test specimen. The moisture content of test series 2 was established by oven drying the entire specimen after the compressive test procedure. The gravimetric moisture content (mc (%)) of a sample or a complete test specimen is expressed as the ratio of the initial weight of material with the oven dry weight of the same material, that is:

$$\text{mc}\ (\%) = \frac{\text{material wet weight - material dry weight}}{\text{material dry weight}} \times 100$$

In this project all moisture content measurements are gravimetric unless otherwise stated. Care should be taken when comparing moisture contents from the literature as moisture contents are also expressed as a percentage of the wet material weight, or in volumetric terms.

5.2) The measurement of particle size distribution and fibre content

5.2.1) The measurement of particle size distribution

The particle size distribution of material in this project was measured by the technique described in British Standard (BS) 1377: Part 2. This technique is widely used in the geotechnical industry. Particle size distribution describes the composition of the cob matrix material in terms of the weight of particles within several particular size ranges. The size ranges used in this project and the labels applied to them are given in table 3.2.

This 'distribution of particle sizes' is established by sieving a sample of the material. The sieving process can be either 'dry' if the clay content of the material is very low, or 'wet' if the clay content is high. All of the particle size distributions measured in this project were found by wet sieving. These processes differ in that the wet sieving method includes the removal of the smallest particles of the material by a washing process. This is done to prevent misleading particle size distributions being measured due to these small particles binding other larger particles together.

The analysis of particle size distribution is divided into three sub processes A, B and C. Each sub process describes a portion of the overall particle size distribution. The data from each sub process may then be combined to describe the overall particle size distribution. The analysis of particle size distribution is described in table 5.1 below.

Process A

take an oven dried sample of the material and divide it for analysis by process B and C

Process B- size distribution of particles with a diameter d > 425 μm

i) break up the material taking care not to break individual particles

ii) wash the material through a 425 μm sieve

iii) dry and weigh the remaining material

iv) sieve through the following series of sieves: 37.5, 20, 10, 5, 2.36, 1.18 mm; and 600 and 425 μm

Process C- size distribution of particles with a diameter 63 μm < d > 425 μm

i) break up the material taking care not to break individual particles

ii) dry sieve the material to achieve a workable sample of fines (< 63 μm) material for particle size analysis in process B

iii) weigh and then wash the material through a 63 μm sieve

v) dry and weigh the material now held on the 63 μm sieve

vi) sieve through 300, 150, and 63 μm sieves

Process D- size distribution of particles with a diameter d < 63 μm

using material obtained in C (ii), the size distribution of these particles was measured using an optical method (described below)

table 5.1

Analysis of particle size distribution.

The sieving processes in table 5.1 (B) and (C) give weights of material held by each sieve size. These weights are then expressed as a percentage of the initial sample for each sieving process and combined to give the distribution of the size of particles with a diameter > 63 μm in the material. This is achieved by scaling the distribution found in C(v) to fit the amount of material washed away in B(ii). The size distribution of particles with a diameter < 63 μm was measured optically using a Malvern Master Sizer X. This instrument uses the technique of Low Angle Laser Light Scattering to measure particle size distribution (Allen 1993, pg. 715; Malvern Master Sizer X manual).

When a spherical particle is illuminated by a parallel beam of monochromatic coherent light, a diffraction pattern is generated. The form of the diffraction pattern is related to the size of the particle. A range of particle sizes can be divided into a series of size intervals, each size interval generating a different diffraction pattern according to its average particle size. The intensity of the diffraction pattern generated by each size interval is dependent upon the number of particles in that size range. This phenomena is used by the Malvern Master Sizer X to determine particle size distribution. A suspension of the material to be examined is illuminated by a low- power laser. The resulting diffraction patterns are focused onto a multi element solid state detector. This is achieved using either 'conventional Fourier optics' or 'reverse Fourier optics' depending upon the particle size range of the sample. The electrical output of each element of the detector is proportional to the amount of light falling upon it, and therefore related to the average particle size of each of the 32 size intervals imposed on the sample by the instrument. During the determination of particle size distribution, the suspension of the sample is continually forced between the laser and the detector: the instrument calculates an average particle size distribution from many measurements of the detector output. This process takes approximately five seconds. The data gathered by the instrument is processed and presented by computer.

The particle size distributions are presented in chapter 6. The range of particle sizes found in the Breccia soil by the wet sieving process is illustrated in plate 5.1.

5.2.2) The measurement of fibre content

If the material whose particle size distribution is being measured contains fibre then this content is found in sub process B of table 5.1. This is achieved by immersing the material to be washed in process B and allowing the fibre content to float to the surface of the water. This fibre is then removed by a net, washed further, and then dried in an oven. The fibre content is expressed as a percentage of the dry weight of the original sample in table 5.1 A. This non standard test was developed during the project.

5.3) The measurement of plastic and liquid limits

Determination of three material 'limits' is common in the geotechnical engineering industry: these are the liquid, plastic and shrinkage limits. The tests to determine the plastic and liquid limits of a soil are normally seen as part of the system used by the geotechnical industry to classify soils. The limit tests give the moisture content of a sample of the 'fines' material of a particular soil when it possesses certain physical properties. The plasticity index is defined as the difference between the moisture content at the liquid limit and the moisture content at the plastic limit. The shrinkage, plastic and liquid limits; and the plasticity index are illustrated in figure 5.1. These limits are discussed in chapter 7.

The procedure for determining the liquid limit and plastic limits is described briefly below.

plate 5.1

Range of particle sizes in Breccia soil found by wet sieving process (50 mm - 425 μm).

The liquid limit of samples of the fines content of soils used in this project has been found using a 'drop cone penetrometer' (plate 5.2). A sample of fines material of the soil under investigation is thoroughly mixed with distilled water (plate 5.3) and placed in the small pot that is part of the test apparatus. The rest of the apparatus is designed such that a cone of standard mass and dimensions can be held just touching the surface of the sample and then allowed to fall into the sample. The depth of the penetration of the cone into the fines material can be measured with the apparatus. The moisture content of the fines material is determined by oven drying a sample of it. The test is repeated at successively higher moisture contents, the results of the series of tests being plotted on a graph of moisture content and penetration. The liquid limit is arbitrarily defined as the moisture content of the fines material necessary for the cone to penetrate 20 mm into the sample.

"For the determination of the plastic limit the test soil [fines material] is mixed with distilled water until it becomes sufficiently plastic to be moulded into a ball. Part of the soil sample is formed into a thread, approximately 6 mm in diameter between the first finger and thumb of each hand. The thread is then placed on a glass plate and rolled with the tips of the fingers of one hand until its diameter is reduced to approximately 3 mm: the rolling pressure must be uniform throughout the test. The thread is then remoulded between the fingers (the water content being reduced by the heat of the fingers) and the procedure is repeated until the thread of soil shears both longitudinally and transversely when it has been rolled to a diameter of 3 mm. The procedure is repeated using three more parts of the sample and the percentage water content of all the crumbled soil is determined as a whole. This water content is defined as the plastic limit of the soil." (Craig 1983, pg. 10).

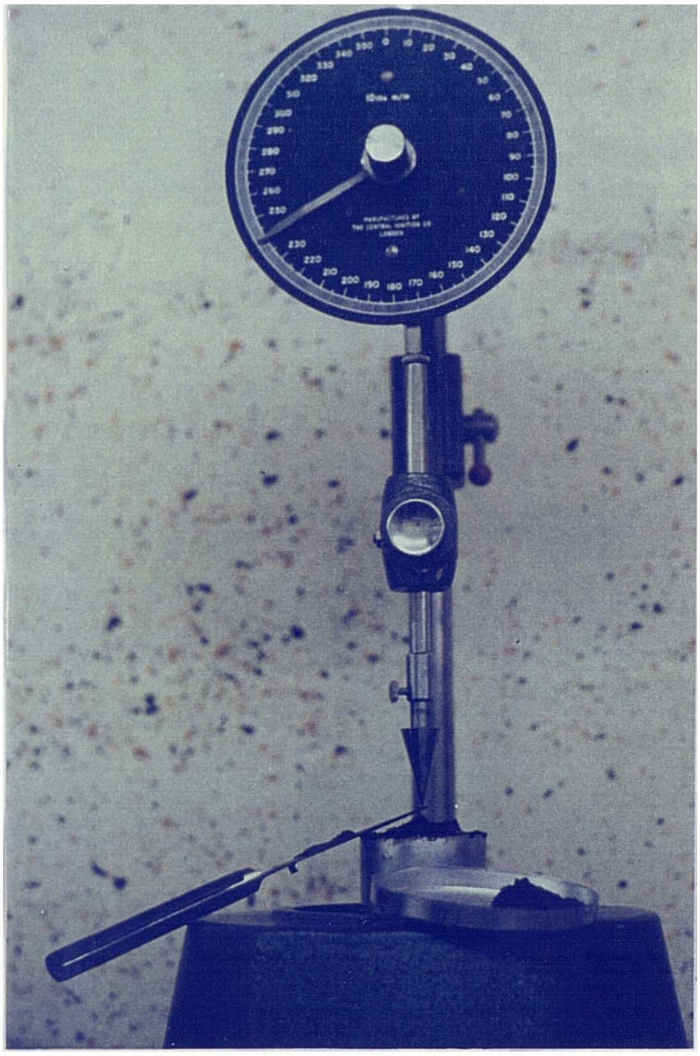


plate 5.2

Drop cone penetrometer used to determine the liquid limit of fines material.

The initial intention was to measure the plastic and liquid limits of the material of each sample tested in compression. This was done for the majority of the blocks in test series 1. However, it was realised that the distribution of the values of these limits did not appear to have a variance greater than that which may reasonably be attributed to experimental error. Therefore, the plastic and liquid limit results quoted for the remaining test series are for samples of the material from which samples were manufactured, rather than individual samples. The liquid and plastic limits measured in this project are given in section 6.3 of chapter 6.

The relationship between moisture content of soil and material limits

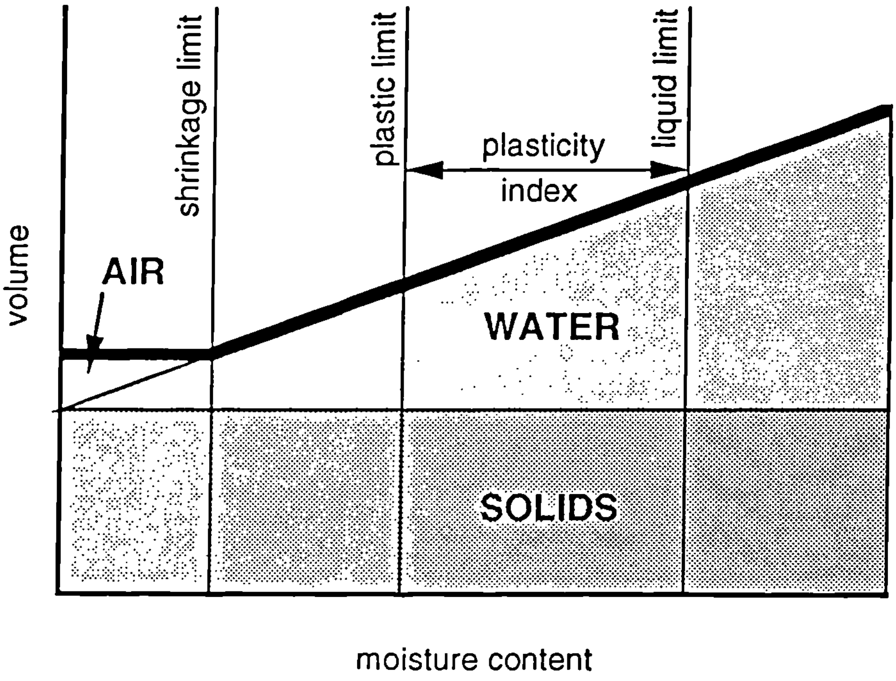


figure 5.1

plate 5.3

Sample of fines material for the liquid limit test.

5.4) The measurement of particle densities

The density of particles in nine size ranges of the Breccia soil was measured. These size ranges were: 5 - 2 mm, 2 - 1.18 mm, 1.18 - 0.6 mm, 600- 425 µm, 425- 300 µm , 300 - 212 µm, 212- 150 µm, 150 - 63 µm.

Particle density was measured in accordance with BS 1377: Part 2. This process uses an air free liquid to measure different volumes of sample material within a density bottle. The density of both the sample and the air free liquid will change with temperature. Because of this steps are taken to ensure that the measurements are of materials at constant temperature. The air free liquid used in the process was deaerated distilled water.

Chapter 6: Results

This chapter presents the results of the compression tests and characterisation procedures described in chapters 4 and 5, and a description of the analysis of these results. The results are discussed in the following order:

6.1) particle size distributions
6.2) particle densities
6.3) plastic and liquid limits
6.4) compression test data from test series 1,2, 4 and 5
    6.4.1) test series 1 and 2
    6.4.2) test series 4 and 5
6.5) drying data from test series 4 and 5
6.6) drying data from an external experimental cob wall
    6.6.1) analysis of the initial drying progress of the wall
    6.6.2) analysis of the environmental progress of the wall.

Some of the results presented in this chapter have been derived from statistical analysis of the experimental data. The principal statistical techniques used are:

i) analysis of variance used primarily in the analysis of the drying data from the external experimental cob wall;
ii) the Pearson product moment correlation coefficient used to describe the degree of correlation between sets of data; and
iii) the coefficient of determination used to describe the degree to which a regression equation 'fits' the experimental data. Fisher's transformation has also been used to compare the coefficients of determination of different regression equations.

All of these techniques are described by Howell (1992).

The techniques described in (i) and (ii) are used in the analysis of the data of test series 1, 2, 4 and 5.

Statistical techniques are used to determine the probability that any differences or correlations in the data have occurred due to chance. In this project probabilities less than 5% (two tailed) that any apparent differences or correlations between data are due to chance is taken as significant.

This chapter will not derive or describe most of these techniques, but it will include the significance of the statistical analysis of the data.

6.1) Particle size distribution

The technique used to measure the particle size distribution is described in chapter 5. Measurements of particle size distribution were made on all of test series 1 blocks (figure 6.1) and test series 2 blocks 1, 2, 3, 5, 6, 7 and 9 (figure 6.2).

Using the concept of 'confidence intervals' it is possible to estimate the variation in the measurement of particle size distribution due to 'experimental error'. Figure 6.3 shows the average particle size distribution of all the samples in test 2. These average sample values are bracketed by values of 'percentage of material passing' calculated from (Allen 1990, pg. 7):

average of samples +/ - confidence interval
'percentage of material passing'

Where:
confidence interval = t x sample standard deviation/ √(number in sample)

The value 't' is found from statistical tables and depends upon the amount of information available from the samples for the estimation of the population average.

Assuming that the population of values of 'percentage of material passing' are only approximately normally distributed about the population average, there is a finite probability that the population average lies within +/ - one confidence interval from the sample average. In figure 6.3 this finite probability, due to the 't' value selected, is 95%. All confidence intervals presented in this thesis are at this level of probability. In fact, the size of this interval over estimates the experimental error: some of the 'scatter' of the data shown in figure 6.2 is very likely due to actual variation in the particle size distribution of the material measured. The narrow 95% confidence interval shown in figure 6.3, and the fact that this over estimates the experimental error, illustrates that the experimental error of the measurement of the particle size distribution is small.

The particle size distribution of individual cylinders of test series 4 and 5 was not measured. However, the cylinders of high, medium, and low mixes of these test series were manufactured to a predetermined composition ('design' particle size distribution). In addition, the 'actual' particle size distribution of the test series 5 mixes was measured after the test series was complete. The actual and design particle size distributions of the aggregate fractions of test series 4 and 5 materials are shown in figure 6.4.

The particle size distribution of five different samples of the binder fraction used in test series 4 and 5 were measured optically (figure 6.5). The average particle size distribution of these measurements and their confidence intervals are shown in figure 6.6.

6.2) Particle densities

The densities of particles of the Breccia soil was measured in nine size ranges as described in chapter 3, table 3.1. The measured density of the particles, relative to that of water (1000 kg/ m ^{3}), are given in table 6.1 below. In accordance with BS 1377: Part 2, the relative densities are given to two decimal places.

particle size range	relative density
5 - 2 mm	2.67
2 - 1.18 mm	2.71
1.18 - 600 µm	2.71
600 - 425 µm	2.69
425 - 300 µm	2.68
300 - 212 µm	2.69
212 - 150 µm	2.67
150 - 63 µm	2.67
< 63 µm	2.66

table 6.1
Particle densities.

In addition to these measurements the density of the aggregate fraction of the high, low and medium mixes of test series 4 and 5 were also measured. These densities are given below.

aggregate fraction of...	relative density
...high mix	2.70
...medium mix	2.70
...low mix	2.69

table 6.2
Densities of the aggregate fractions of test series 4 and 5.

6.3) Plastic and liquid limits

Measurements of plastic and liquid limits were made on all of test series 1 blocks. For test series 2 one measurement was made from the material from which the blocks were manufactured. This technique was also used for test series 4, that is: one measurement was made from each of the three materials from which the cylinders were manufactured. Each measurement of a plastic or liquid limit is the average of four separate measurements of each property. The results of the measurements of the plastic and liquid limits are shown below in table 6.3, the figures are percentage moisture contents of total dry weight.

6.4) Compression test data from test series one, two, four and five

A full glossary of the variables used in the analysis of test series 1, 2, 4 and 5 is given in 'Appendix C: variable glossary'. The experimental compression data of test series 1 and 2 is given in 'Appendix J: test series 1 and 2 compression and composition data'. The experimental compression data of test series 4 and 5 is given in 'Appendix L: test series 4 and 5 compression data'.

	plastic limit	liquid limit	plasticity index
test series 1			
block number			
2	20	36	17
3	21	38	17
4	19	35	15
6	20	35	15
7	18	31	13
8	/	32	/
averages for test series 1	20	35	15
test series 2 material			
	20	37	17
test series 4 and 5 material			
high mix	20	38	18
medium mix	18	32	14
low mix	16	26	10

table 6.3
Plastic limit, liquid limit, and plasticity index for all test series materials.

6.4.1) Test series one and two

Variables in the test series 1 and 2 are divided into three groups. These groups are listed together with the variable names below.

i) Variables describing sample and sample history:
test series (ts), identifying code (id).

ii) Variables describing the physical nature of the sample:
final weight (final.wht), moisture content at test (mct), content of particles of a particular size (<425 and <75), straw content (straw).

iii) Variables describing the compression test of the sample:
failure stress (fs), strain to failure (strfail), stress at ELR (ELRstress), compression modulus (compmod).

The analysis is concentrated on the effect that the variables in groups (i) and (ii) have upon the variables in group (iii); and the prediction of one or more of the variables in group (iii) from knowledge of the variables in group (ii).

The relationship between variables can be investigated by examining the degree of correlation between them. Below are listed Pearson product-moment correlation coefficients (r) for test series 1 and 2 which are 'statistically significant'. For a perfect correlation between variables the Pearson product-moment correlation coefficient would have a value of $r= -1$ or $r= +1$: the 1 indicating a perfect correlation and the sign the direction of the relationship. For example, the correlation between failure stress and moisture content at test given below is $r= -0.76$: this indicates that failure stress decreases with an increase in moisture content. The phrase 'statistically significant' in this report this will mean that the probability that the apparent observed correlation is due to chance is less than 5% unless stated otherwise.

The probability that a particular correlation is due to chance is found by calculating the t statistic for that correlation of variables. The calculated t statistic is compared to a critical value of t which is related to the number of variables in the correlation and the 'level of significance'. The level of significance is the maximum probability that the observed correlation is due to chance. In this case the level of significance is 5%, this is denoted as $p<0.05$. If the calculated t statistic is greater than the critical t value, which is found from statistical tables, then the probability that the correlation has occurred by chance is less than 5%. For a level of significance of 5% and for the number of pairs of variables in the correlations of test series 1 and 2 the critical value of t is 2.26 (t_{crit} (9, 0.025)= 2.26). By comparing the calculated t values with the critical value of t, it can be seen whether the following correlations are statistically significant:

between the variables of group (ii) and group (iii);

failure stress (figure 6.7)	and	moisture content at test	r= -0.76, t= 3.47
stress at ELR (figure 6.8)	and	moisture content at test	r= -0.66, t= 2.61
compression modulus (figure 6.9)	and	moisture content at test	r= -0.49, t= 1.70
strain to failure (figure 6.10)	and	moisture content at test	r= 0.44, t= 1.48

and within the variables of group 3;

compressive modulus (figure 6.11)	and	failure stress	r= 0.72, t= 3.10
stress at ELR (figure 6.12)		failure stress	r= 0.81, t= 4.21
strain to failure (figure 6.13)		failure stress	r= -0.59, t= 2.19
strain to failure (figure 6.14)		compressive modulus	r= -0.81, t= 4.13

Graphs of these pairs of variables are shown in the figures indicated above.

The variable indicating to which test series, 1 or 2, samples belong is significantly correlated with moisture content at test (r= 0.79, t= 3.89).

There are no significant correlations between the variables in group 1 and any of the variables in groups 2 or 3. There are no significant correlations between straw content and any other variables in the groups above.

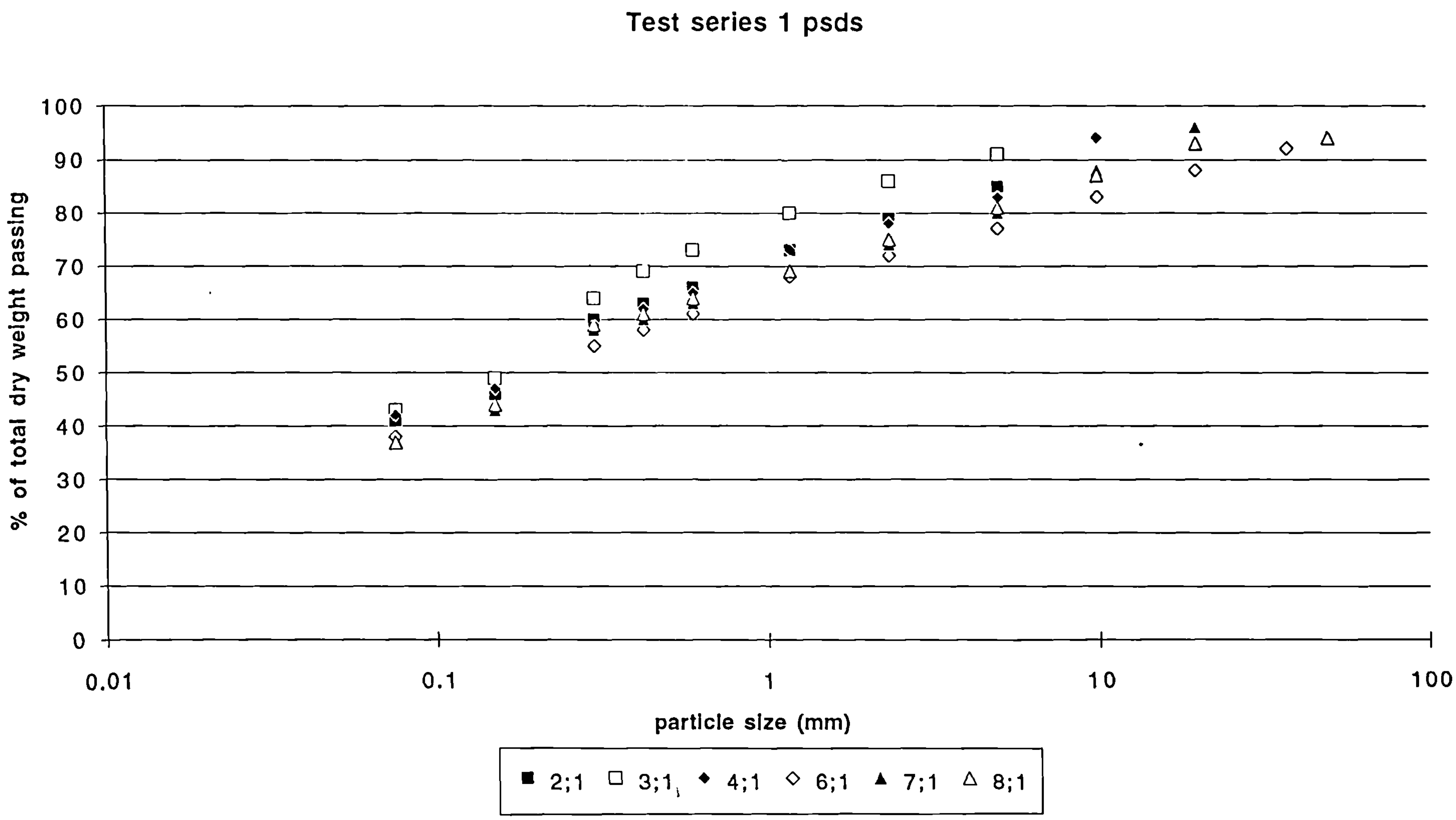

Test series 1 psds
100
90
80
70
60
50
40
30
20
10
0
% of total dry weight passing
0.01
0.1
1
10
100
particle size (mm)
■ 2;1
□ 3;1
◆ 4;1
◇ 6;1
▲ 7;1
△ 8;1

figure 6.1

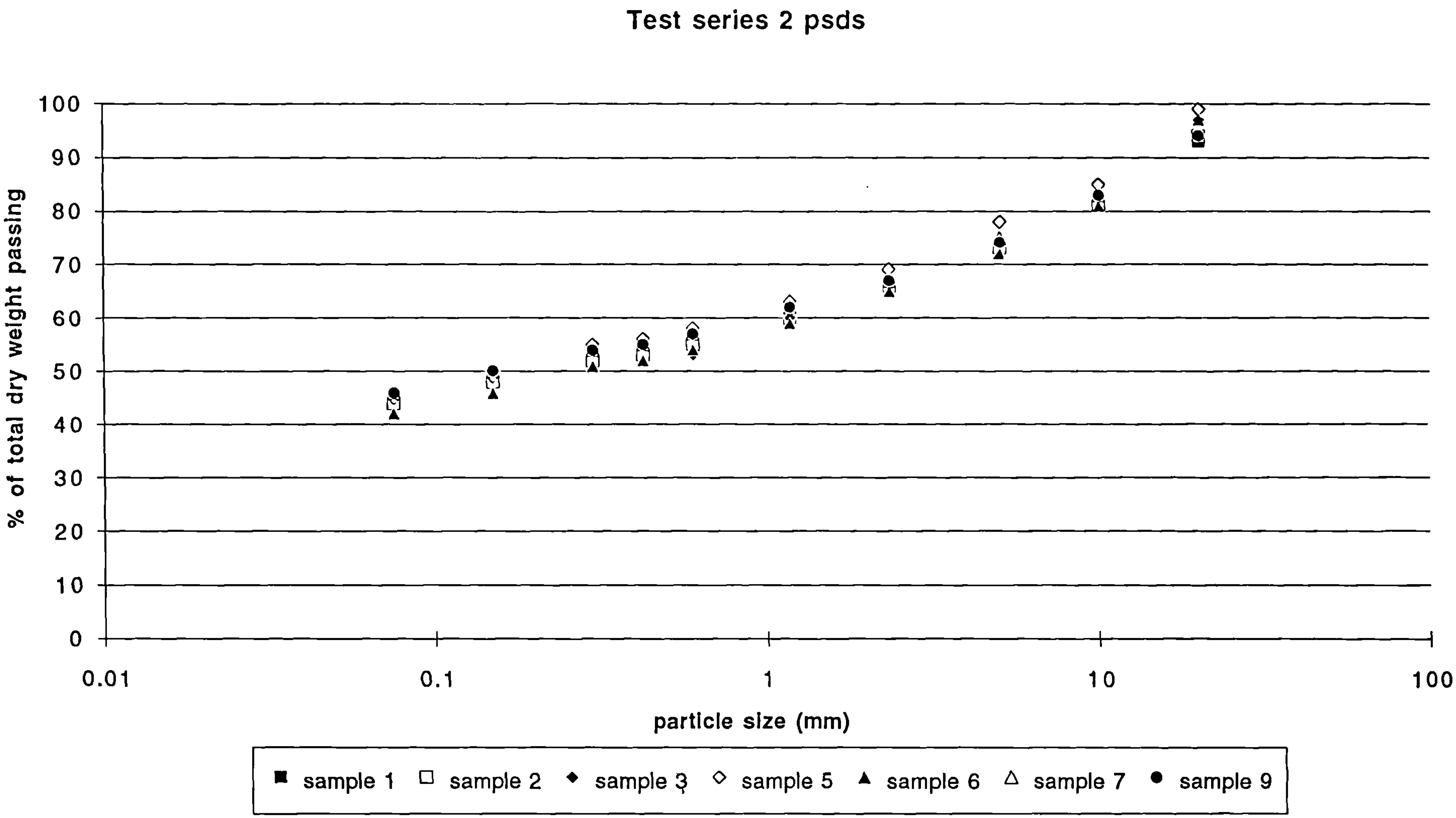

Test series 2 psds
% of total dry weight passing
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
100
particle size (mm)
■ sample 1
□ sample 2
◆ sample 3
◇ sample 5
▲ sample 6
△ sample 7
● sample 9

figure 6.2

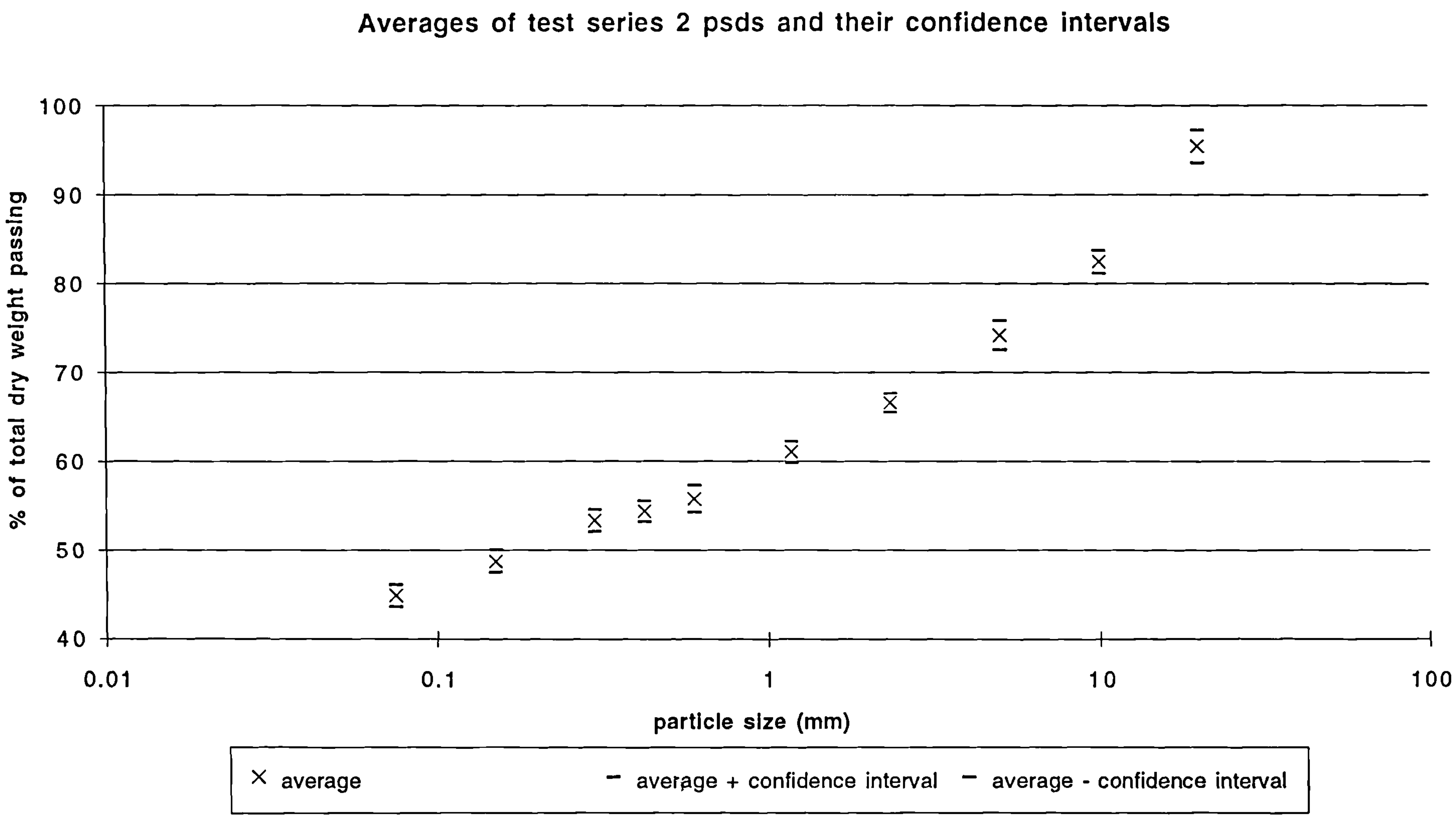
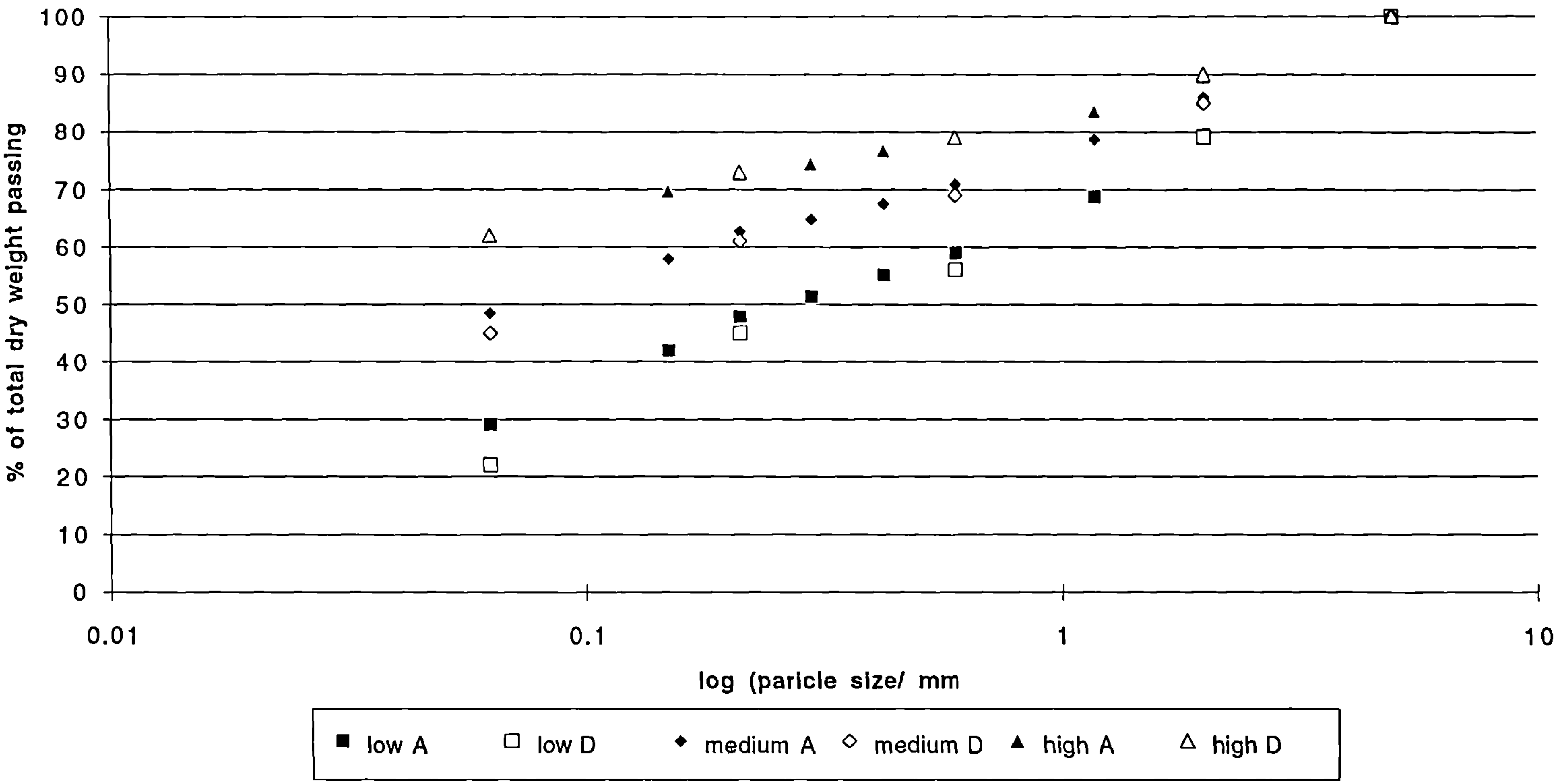

Averages of test series 2 psds and their confidence intervals
% of total dry weight passing
100
90
80
70
60
50
40
0.01
0.1
1
10
100
particle size (mm)
× average
average + confidence interval
average - confidence interval

figure 6.3



Test series 4 and 5 actual (A) and design (D) particle size distribution

figure 6.4

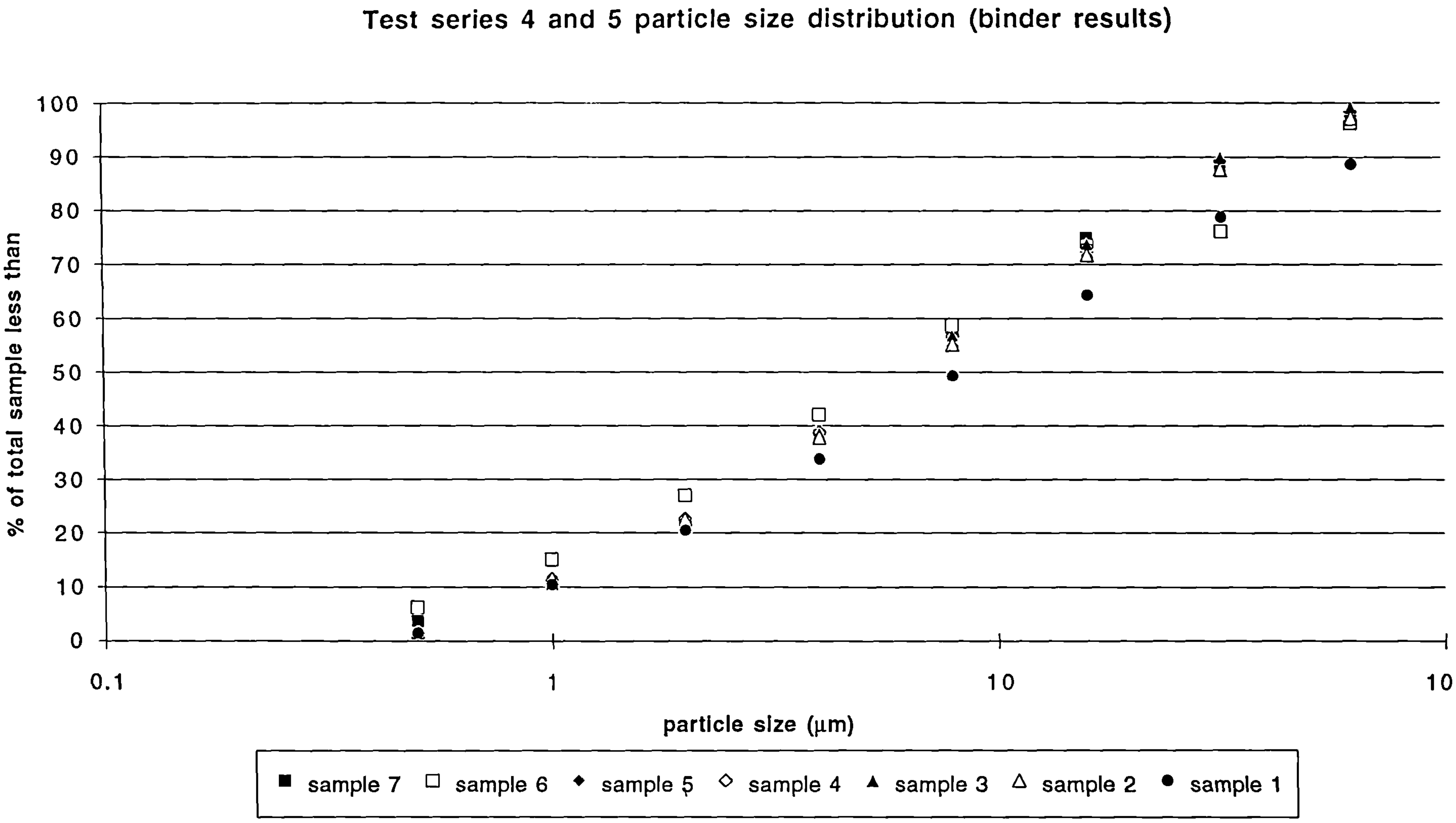
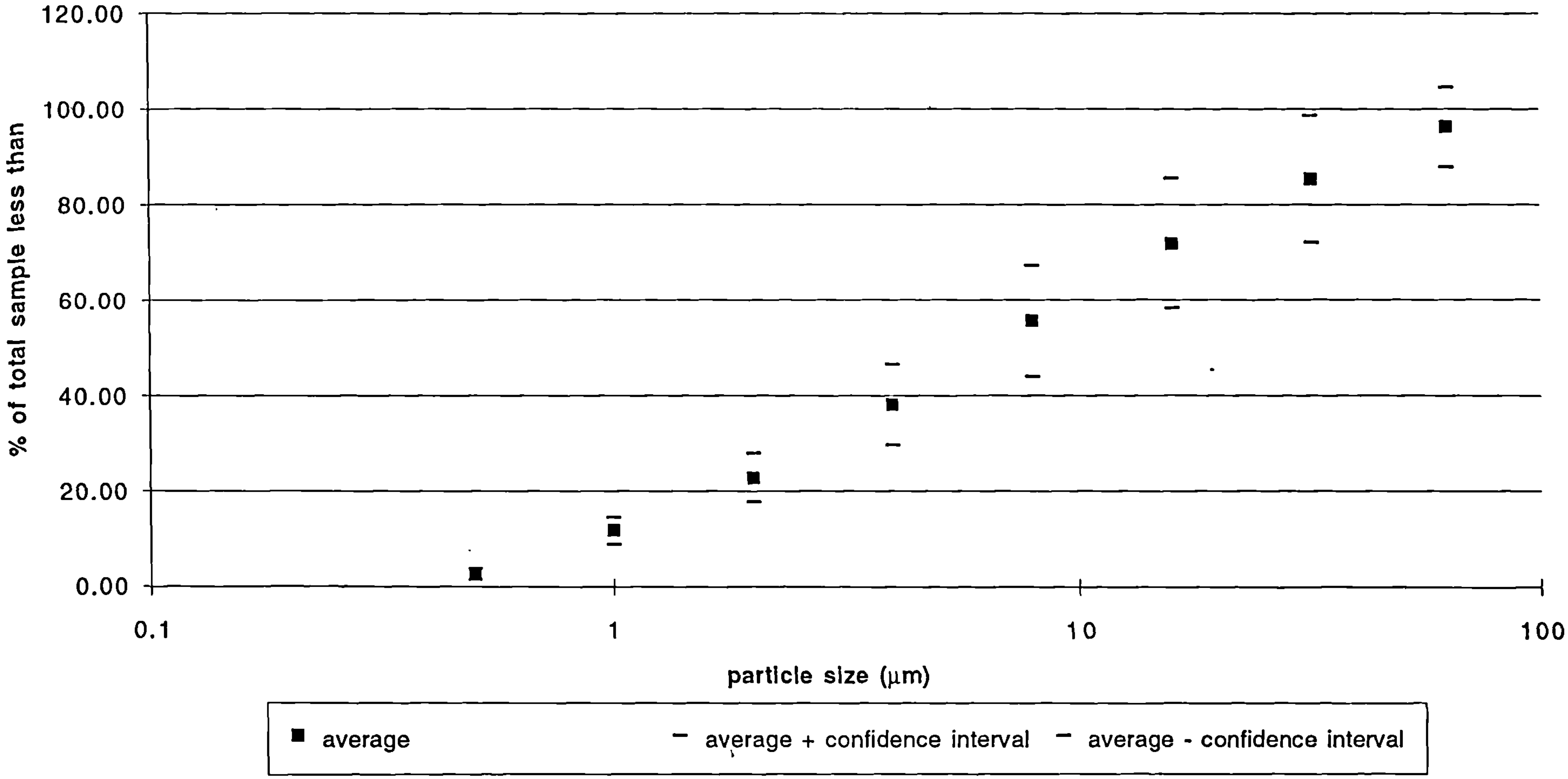
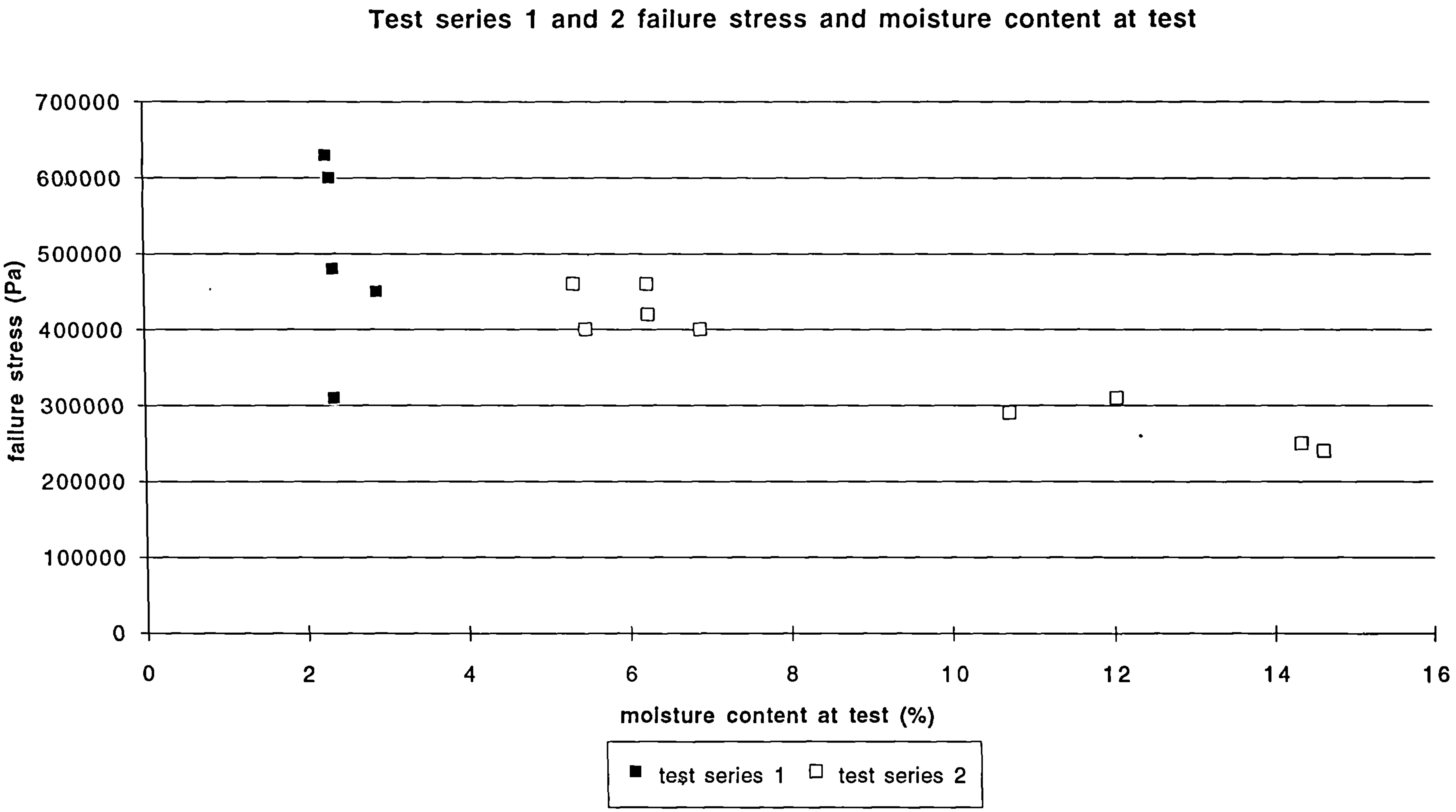

Test series 4 and 5 particle size distribution (binder results)
% of total sample less than
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10
100
particle size (µm)
■ sample 7
□ sample 6
◆ sample 5
◇ sample 4
▲ sample 3
△ sample 2
● sample 1

figure 6.5



Averages of test series 4 and 5 binder psds and their confidence intervals

figure 6.6



Test series 1 and 2 failure stress and moisture content at test
failure stress (Pa)
700000
600000
500000
400000
300000
200000
100000
0
0
2
4
6
8
10
12
14
16
moisture content at test (%)
■ test series 1
□ test series 2

figure 6.7

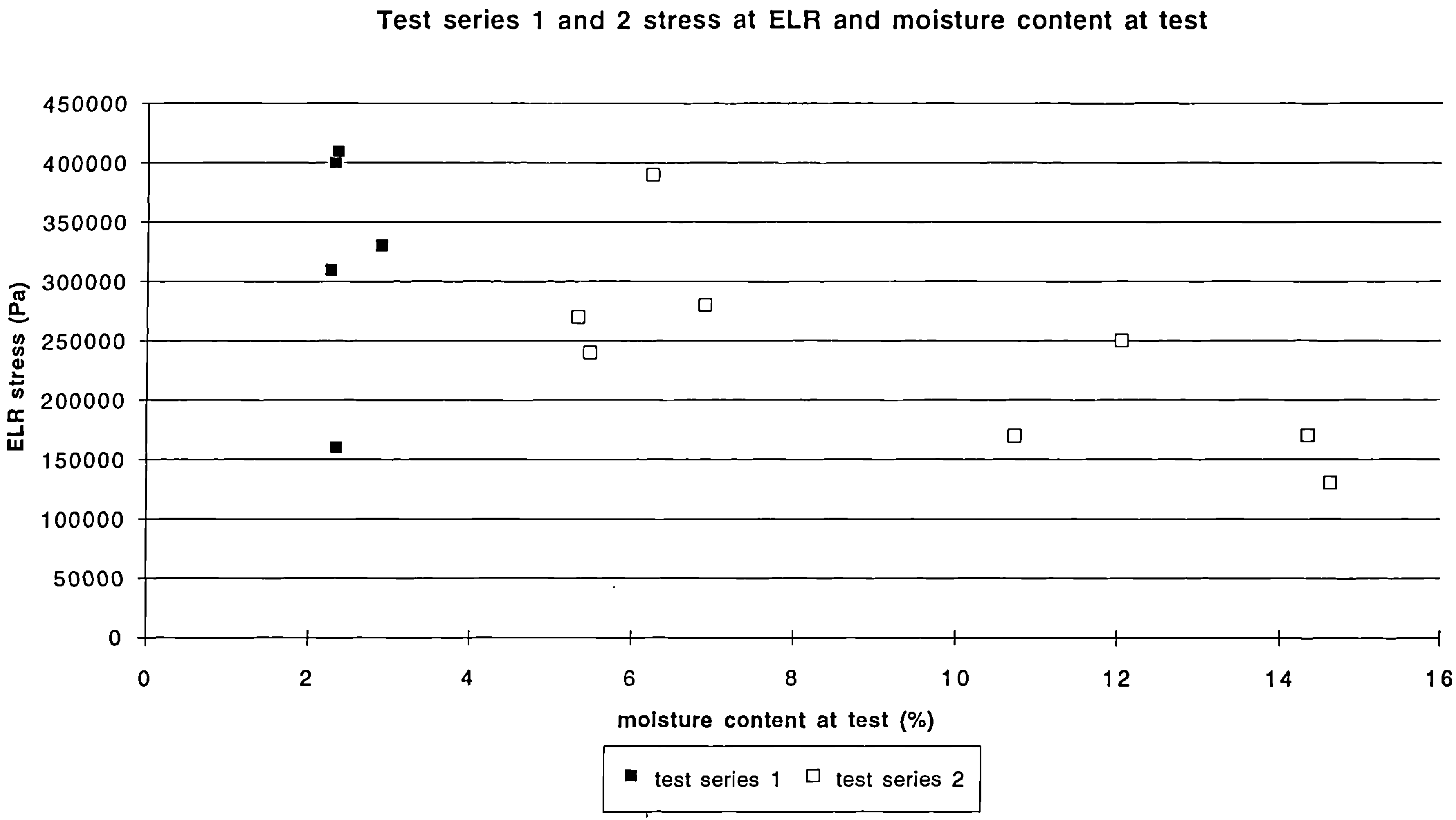

Test series 1 and 2 stress at ELR and moisture content at test
ELR stress (Pa)
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0
2
4
6
8
10
12
14
16
moisture content at test (%)
■ test series 1
□ test series 2

figure 6.8

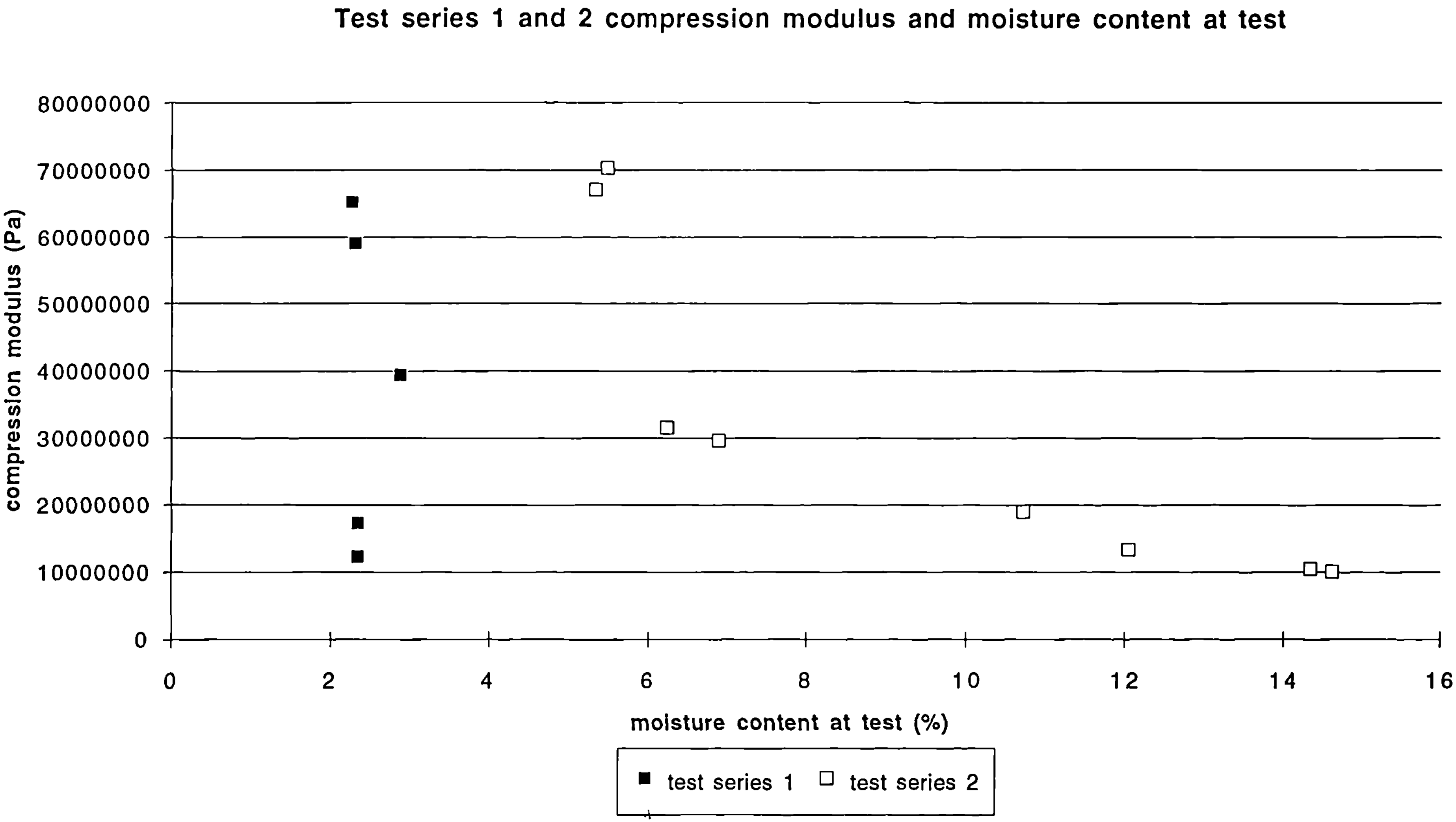

Test series 1 and 2 compression modulus and moisture content at test
compression modulus (Pa)
80000000
70000000
60000000
50000000
40000000
30000000
20000000
10000000
0
0
2
4
6
8
10
12
14
16
moisture content at test (%)
■ test series 1
□ test series 2

figure 6.9a

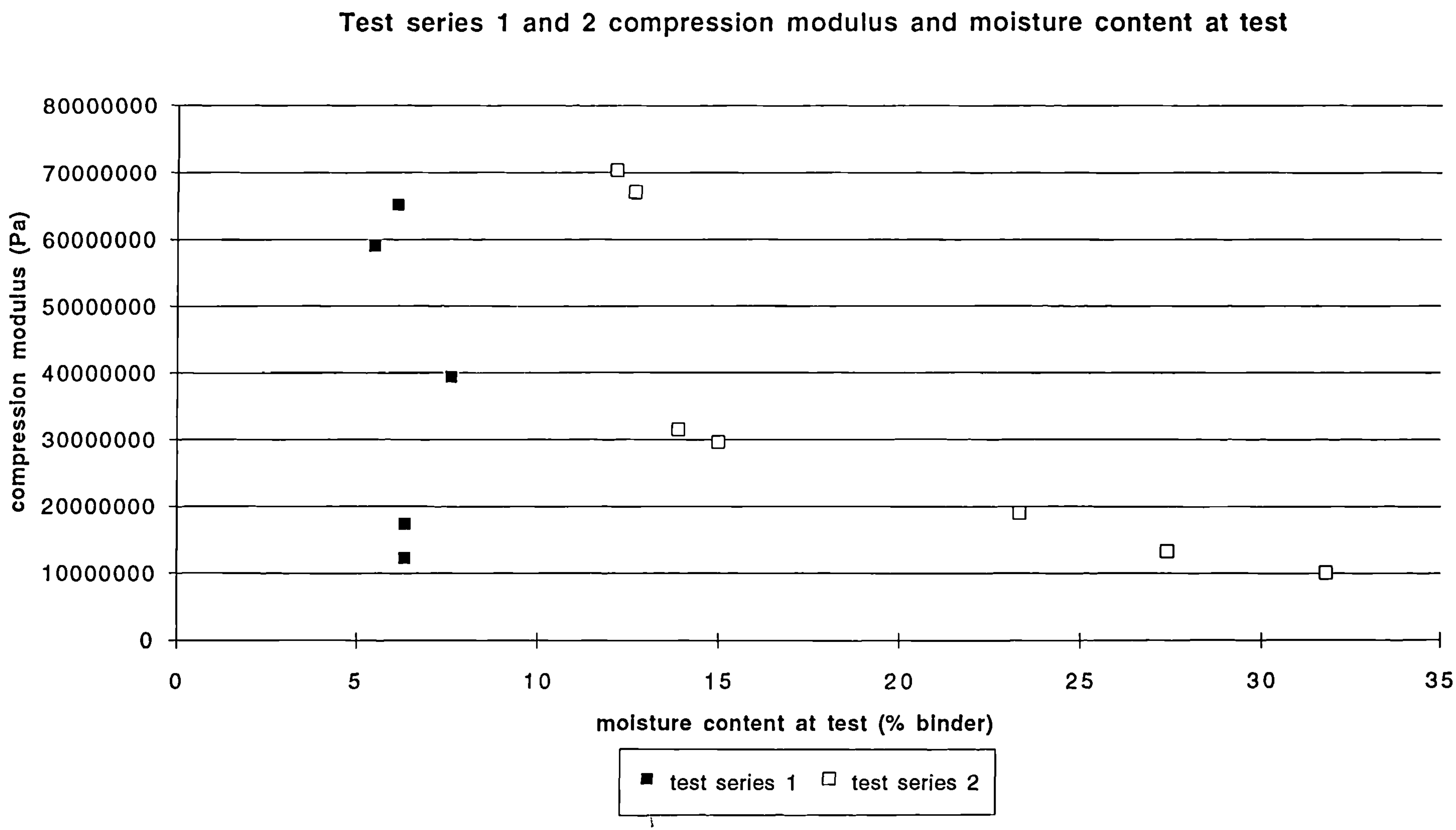

Test series 1 and 2 compression modulus and moisture content at test
compression modulus (Pa)
80000000
70000000
60000000
50000000
40000000
30000000
20000000
10000000
0
0
5
10
15
20
25
30
35
moisture content at test (% binder)
■ test series 1
□ test series 2

figure 6.9b

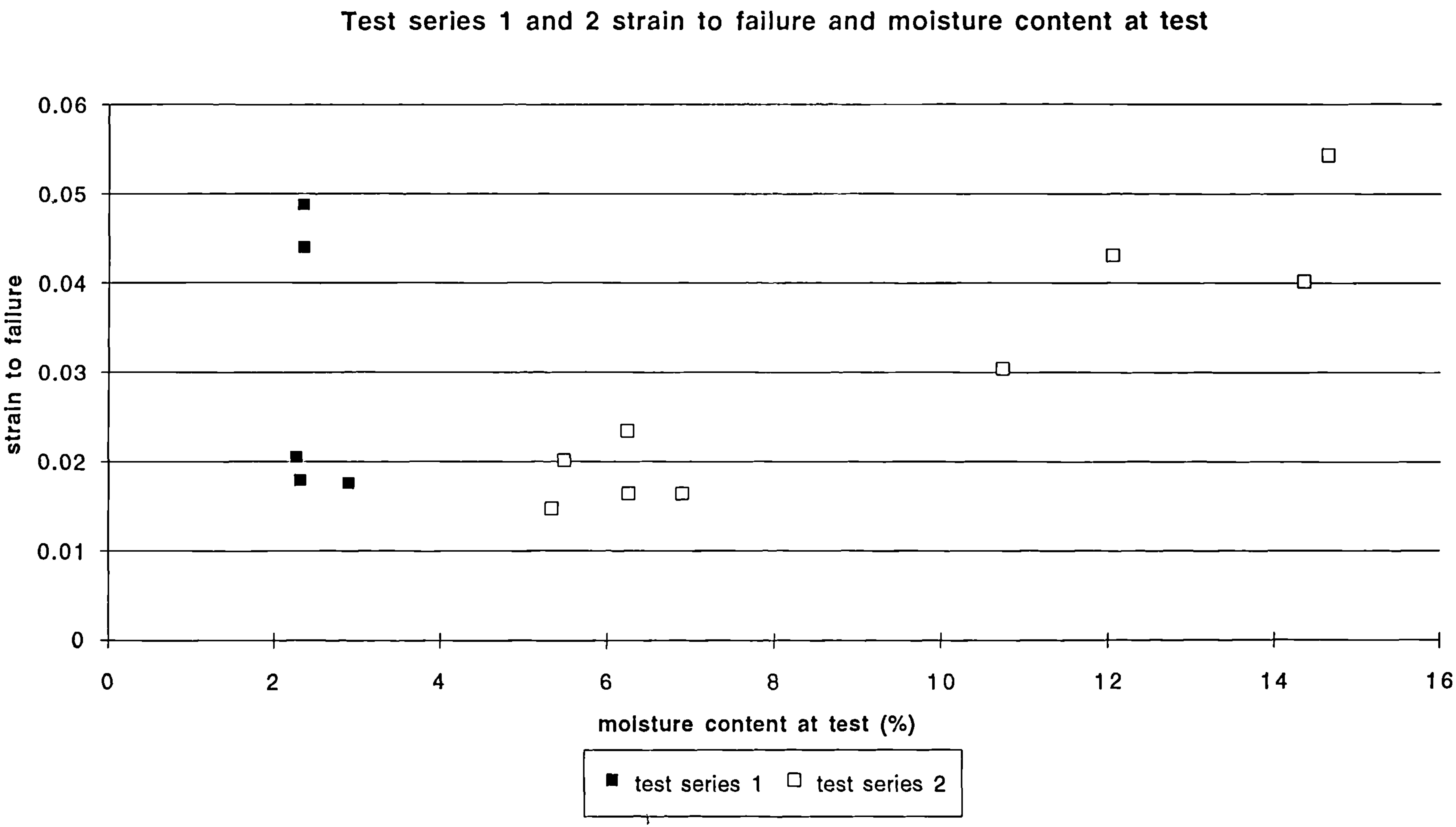

Test series 1 and 2 strain to failure and moisture content at test
strain to failure
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
12
14
16
moisture content at test (%)
■ test series 1
□ test series 2

figure 6.10a

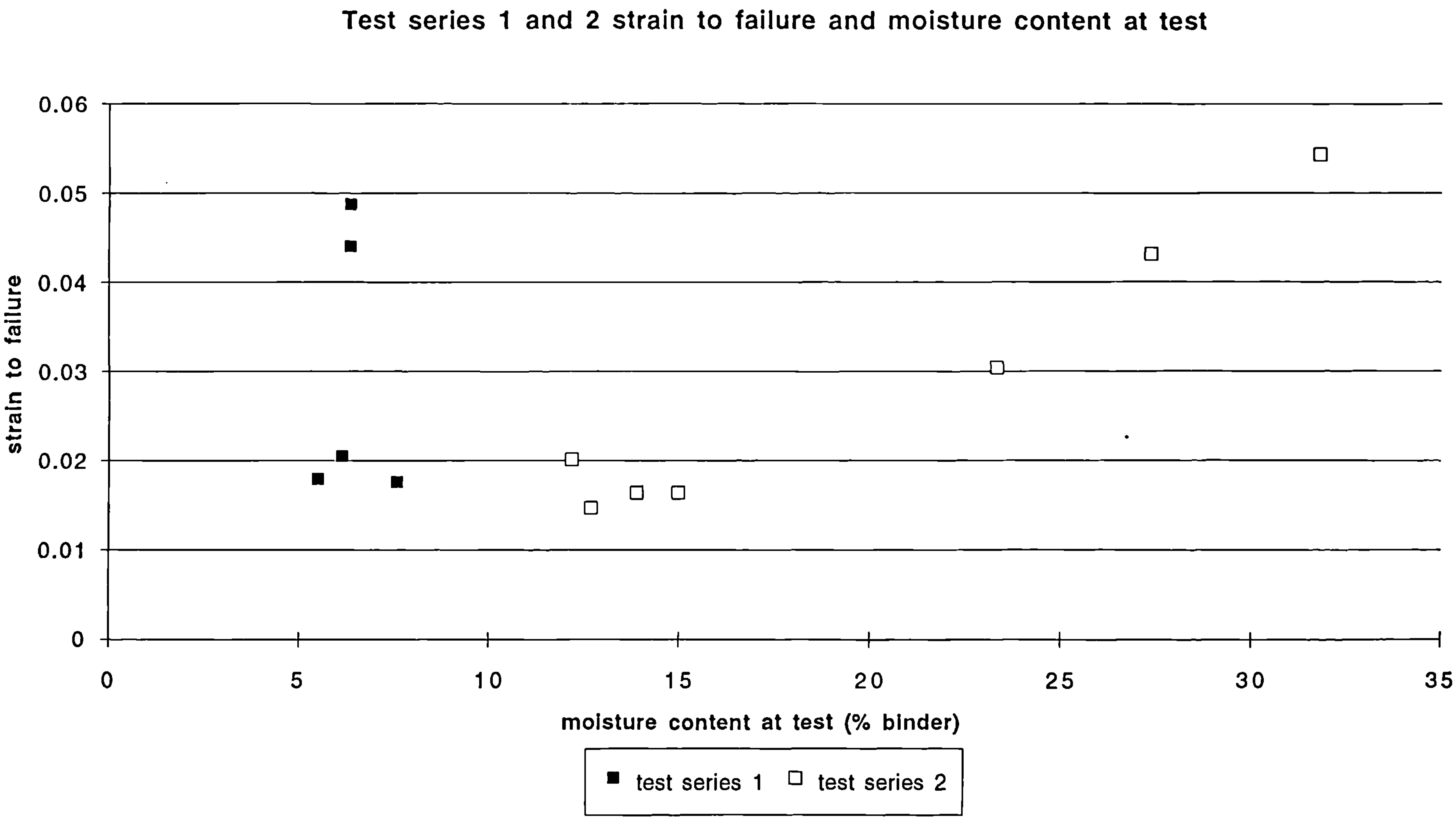

Test series 1 and 2 strain to failure and moisture content at test
strain to failure
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20
25
30
35
moisture content at test (% binder)
■ test series 1
□ test series 2

figure 6.10b

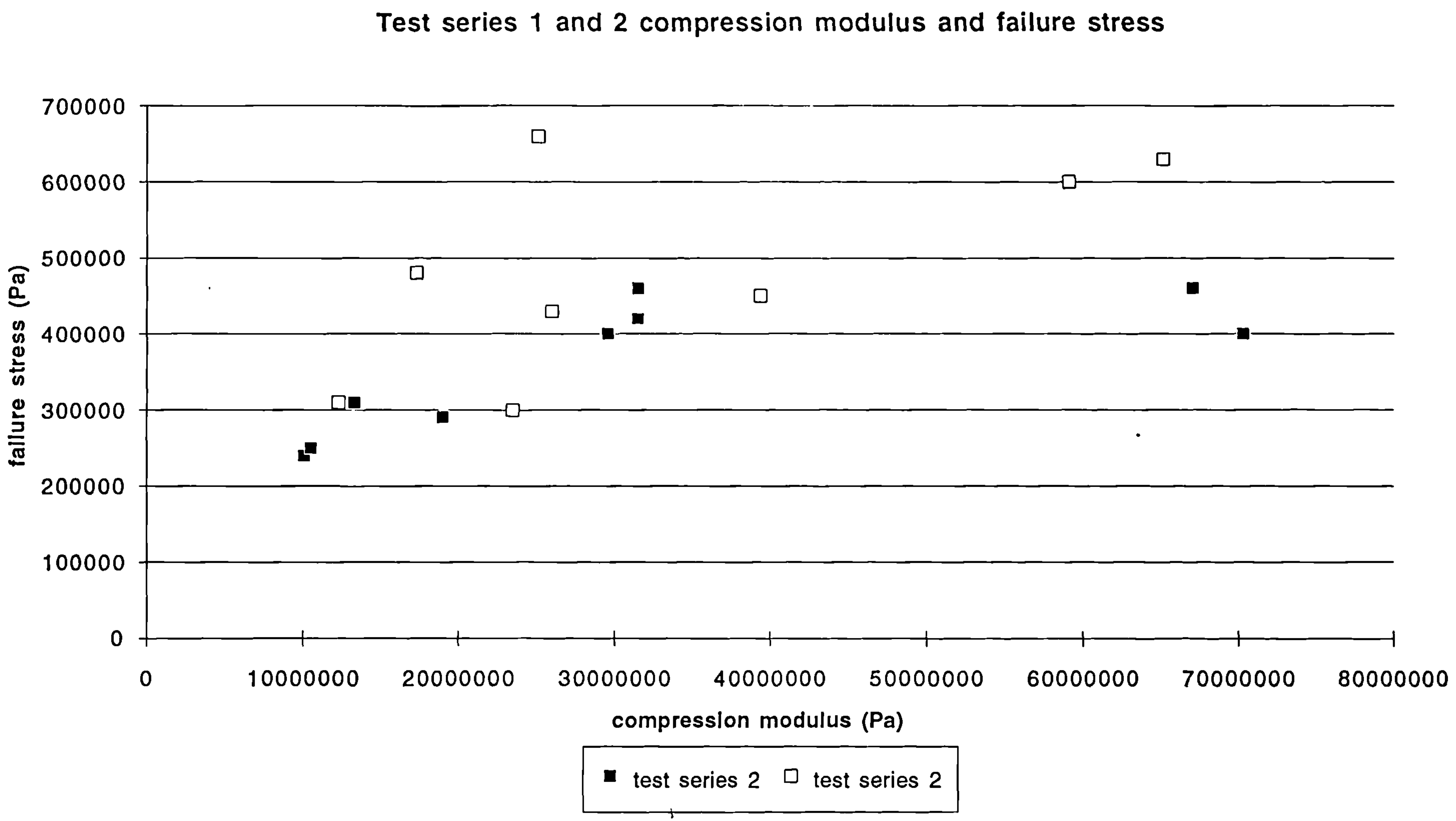

Test series 1 and 2 compression modulus and failure stress

figure 6.11

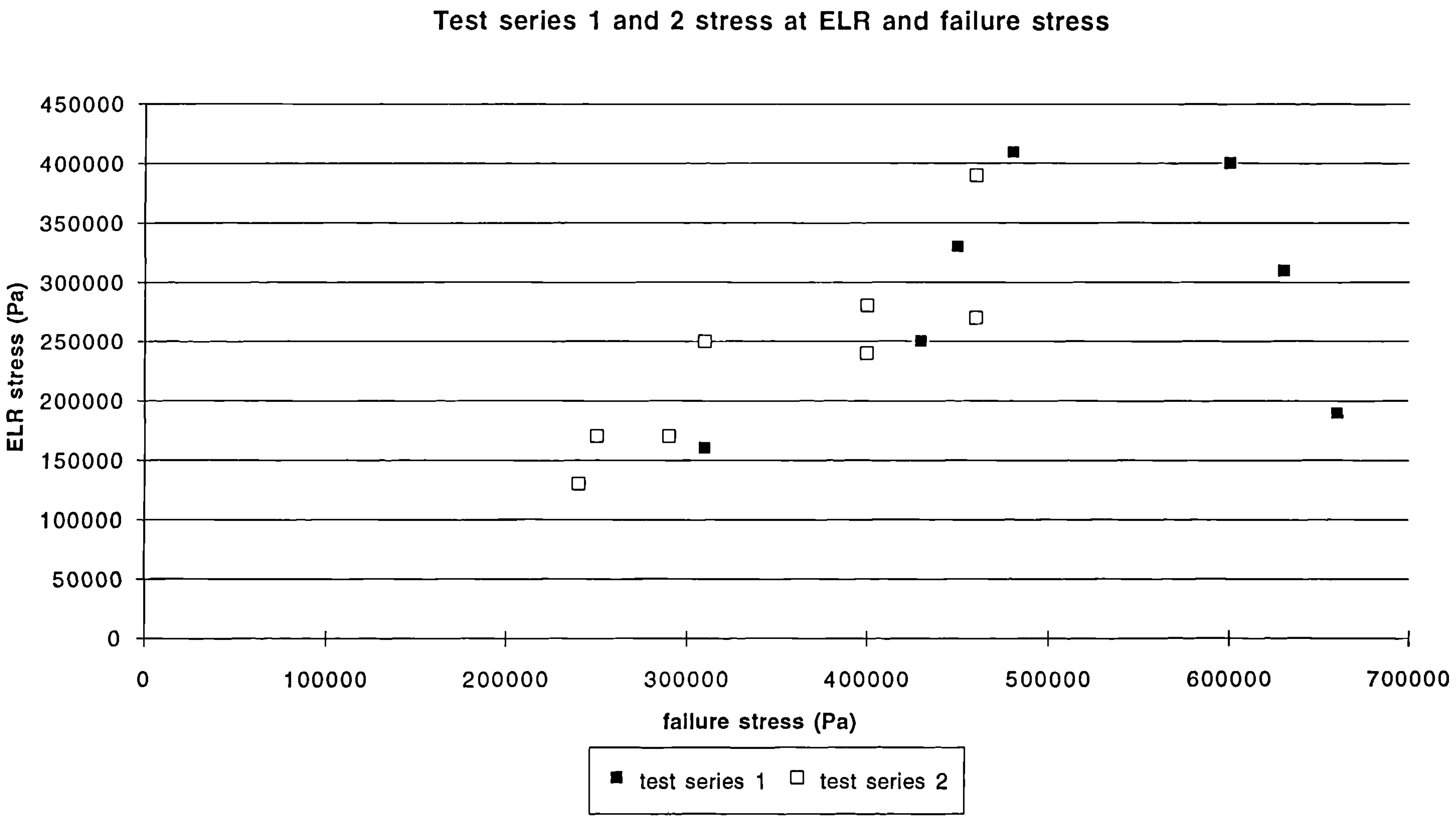

Test series 1 and 2 stress at ELR and failure stress
ELR stress (Pa)
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
0
100000
200000
300000
400000
500000
600000
700000
failure stress (Pa)
■ test series 1
□ test series 2

figure 6.12

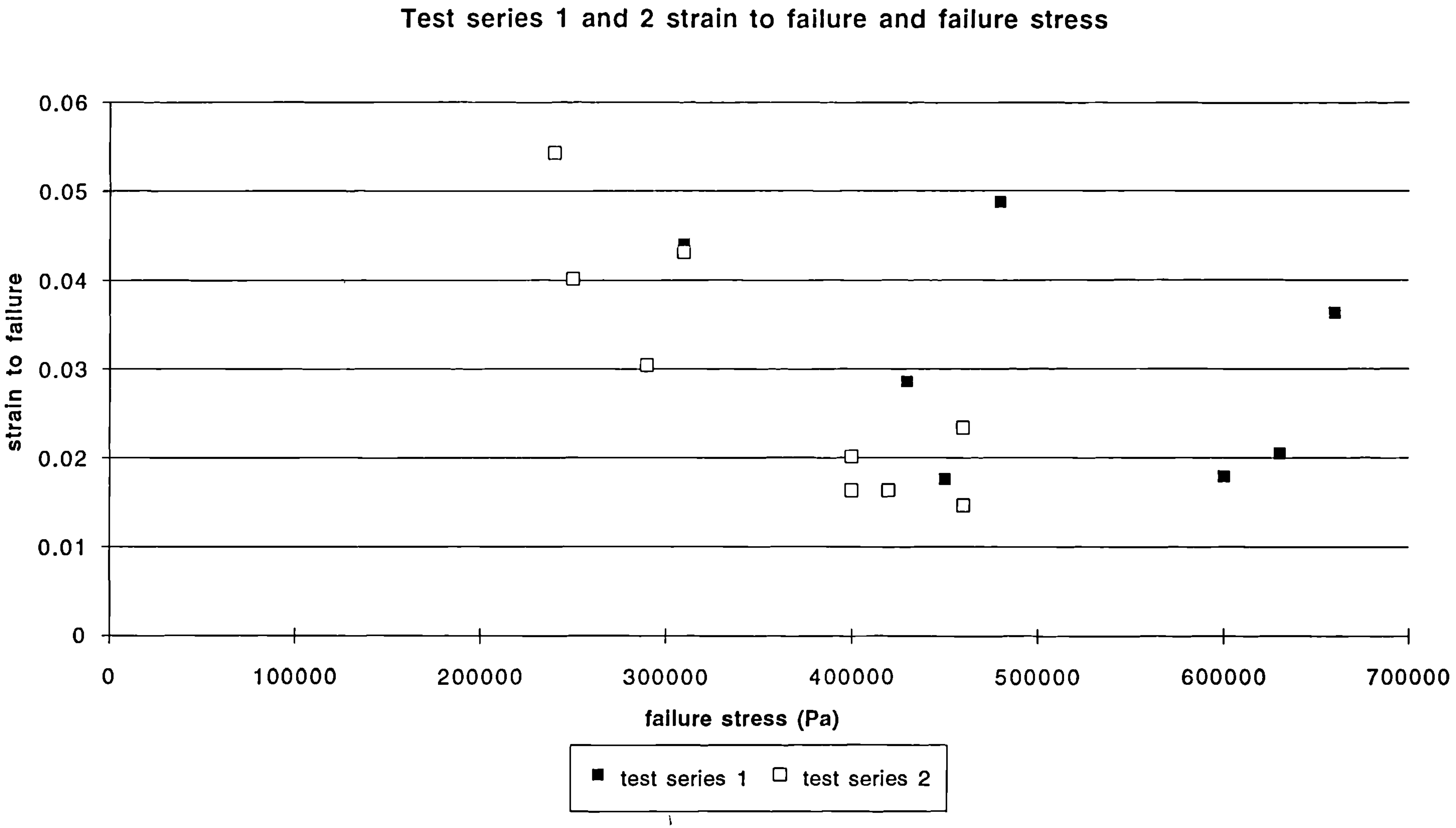

Test series 1 and 2 strain to failure and failure stress
strain to failure
0.06
0.05
0.04
0.03
0.02
0.01
0
0
100000
200000
300000
400000
500000
600000
700000
failure stress (Pa)
■ test series 1
□ test series 2

figure 6.13

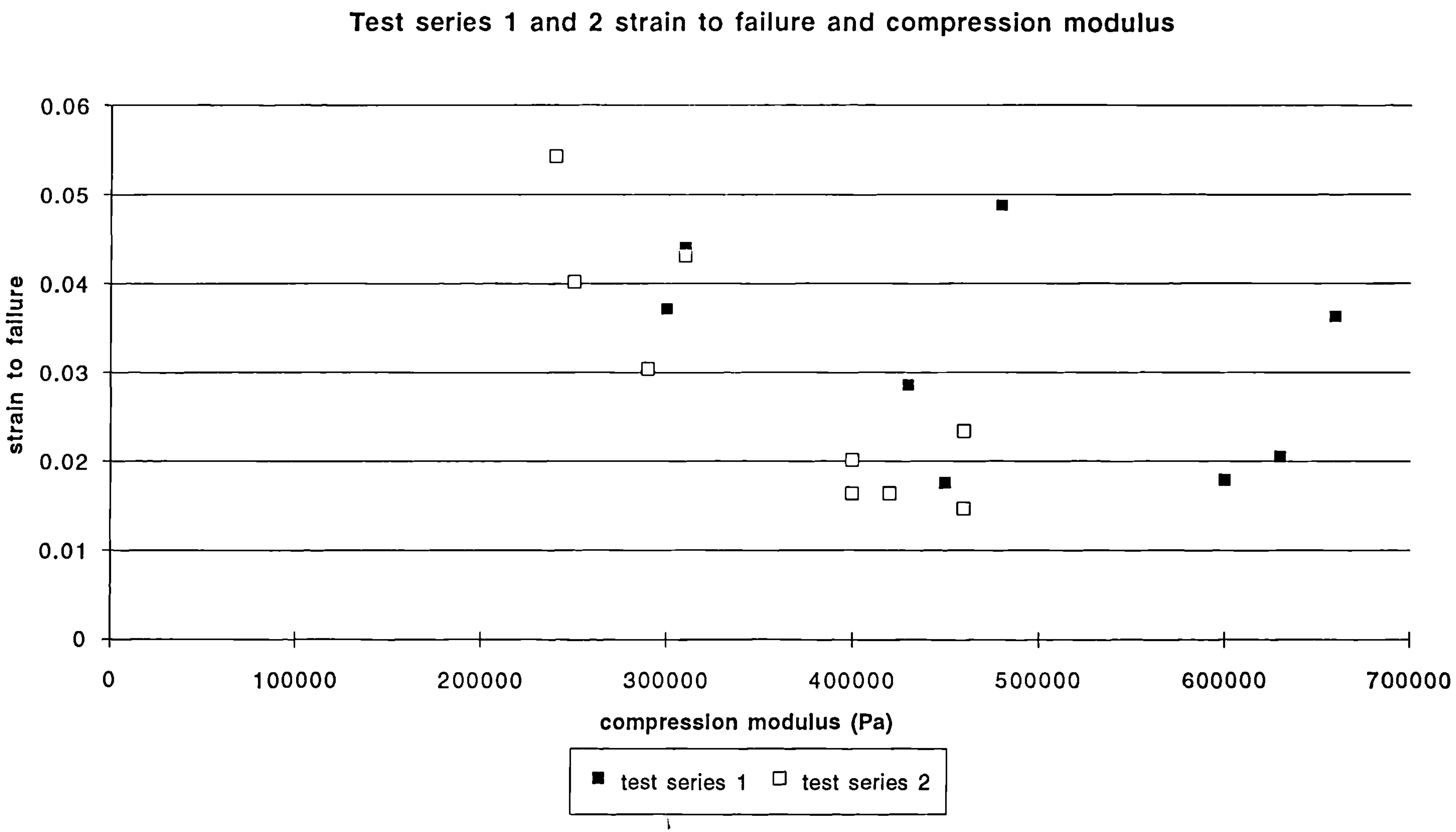

Test series 1 and 2 strain to failure and compression modulus
strain to failure
0.06
0.05
0.04
0.03
0.02
0.01
0
0
100000
200000
300000
400000
500000
600000
700000
compression modulus (Pa)
■ test series 1
□ test series 2

figure 6.14

6.4.2) Test series four and five

As with test series 1 and 2 there are three groups of variables in the test series 4 and 5. These groups and the variable names are listed below.

i) Variables identifying the sample and describing the sample history:
test series (ts), identifying code (id), what samples dried together (ovencode), whether the drying process was deliberately interrupted (O/I).

ii) Variables describing the physical nature of the sample:
dry weight (dry.wht), final weight (final.wht), bulk density (bulk.den), moisture content at test (mct), volume (volume), mix type (mixhigh?, mixlow?).

iii) Variables describing the compression test of the sample:
failure stress (fs), strain to failure (strfail), stress at ELR (ELRstress), strain at ELR (ELRstrain), compressive modulus (compmod), form of stress/ strain curve (drop, 2drymod, both, none).

The analysis is concentrated on: the effect that the variables in groups (i) and (ii) have upon the variables in group (iii); and the prediction of one or more of the variables in group (iii) from knowledge of the variables in group (ii).

Below Pearson product-moment correlations for test series 4 and 5 are presented for pairs of variables with high correlations in test series 1 and 2. Because test series 4 and 5 produced a greater volume of data than test series 1 and 2, a different computer analysis was used for test series 4 and 5. Instead of the t statistic shown with the correlation coefficients above, this analysis presents correlations with a level of significance, 'p'. For example, in the first correlation the probability that the correlation between failure stress and moisture content at test is due to chance is less than 0.3%.

Pearson product-moment correlations for test series 4 and 5:
between the variables of group 2 and group 3;
failure stress and moisture content at test $r = -0.44$, $p < 0.003$
(figure 6.15)

stress at ELR and moisture content at test $r= -0.49, p< 0.001$
(figure 6.16)
compressive modulus and moisture content at test $r= -0.52, p< 0.000$
(figure 6.17)
strain to failure and moisture content at test $r= 0.48, p< 0.001$
(figure 6.18)

and within the variables of group (iii);

compressive modulus and failure stress $r= 0.75, p< 0.000$
(figure 6.19)
stress at ELR failure stress $r= 0.97, p< 0.000$
(figure 6.20)

strain to failure failure stress $r= -0.07, p< 0.639$
(figure 6.21)
strain to failure compressive modulus $r= -0.32, p< 0.390$
(figure 6.22)

Additional important relationships are discussed below.

In order to predict the effect of variables in group (i) and (ii) on those in group (iii) regression equations have been fitted to the data using the method of least squares. The coefficient of determination (r^2) is a statistic describing the degree to which the regression line 'fits' the data: it is calculated from the deviation of values predicted by a regression equation from those measured by experimentation. The coefficient of determination of a regression equation which perfectly described the relationship between variables would be either -1 or +1: the 1 indicating a perfect correlation between the variables of the data set and the sign indicating the direction of the relationship. For example: -1 would indicate that the decrease in one variable was perfectly correlated with an increase in the other variable(s).

It will be necessary to establish whether the inclusion of a variable or variables in a regression equation affects the correlation in a statistically significant manner. This is done by comparing the correlation coefficients of the two data sets, one including the additional variable and the other excluding it, and then calculating if there is a significant difference between the correlation coefficients. The correlation coefficients are calculated by taking the square root of the coefficients of determination. The comparison between correlations is made using Fisher's transformation. The detailed results of of these calculations is given in 'Appendix D: Fisher's transformations'.

There are some correlations between variables in group (i) and variables in other groups. For example, in chapter 4 it was stated that, "As the mixes contained different amounts of binder fraction, each mix type required a different amount of moisture to be added at manufacture." This has resulted in a high correlation ($r= 0.93$, $p<0.000$) between the mix type of the sample, and the moisture content at manufacture of the sample. This correlation is to be expected due to the design of the test series. There are also high correlations between:

i) particular oven 'batches', groups of samples that were in the humidity oven together, and variables in groups (ii) and (iii); and
ii) samples whose drying progress was intentionally interrupted and variables in groups (ii) and (iii). The variable describing an interruption in the drying progress of a sample is O/I. If O/I for a sample is equal to 1 then the drying progress of that sample was intentionally interrupted.

It is important to establish whether these unexpected correlations have a significant affect on the prediction of some of the variables in group (iii). This can be done by comparing the correlations of regression equations for the following variables for a significant difference:

[failure stress] and [moisture content at test, ovencode, O/I]

r= 0.71 t= 6.32 > tcrit (40, 0.025)= 2.021

and;

failure stress and moisture content at test

r= 0.44 t= 3.12 > tcrit (40, 0.025)= 2.021

Using Fisher's transformation to compare these correlations shows that, although there is a decrease in correlation, the decrease is not statistically significant. Similar tests on the effect of the variables oven batch and O/I on the prediction of stress at ELR, compressive modulus and strain to failure showed no significant difference in resulting correlations.

As was described in chapter 5, stress/ strain graphs were drawn for each sample tested. The form of these graphs illustrated four distinct types of behaviour. These were:

i) samples showing a 'drop' in the rate of increase of stress with strain before the failure stress was achieved (figure 6.23);

ii) samples showing a marked change in compressive modulus during the test, (figure 6.24);

iii) samples displaying the behaviour in both (i) and (ii), (figure 6.25); and

iv) samples displaying none of the behaviour in (i) to (iii), (figure 6.26).

Examples of these classifications are shown in figures indicated above.

In order to establish whether the behaviour described by these classifications had a significant effect upon the test variables, the correlation coefficients of the following two sets of variables was compared using Fisher's transformation.

[failure stress] and [moisture content at test; mixhigh?; mixlow?; none]

r= 0.82 t= 6.32 > tcrit (40, 0.025)= 2.021

[failure stress] and [moisture content at test; mixhigh?; mixlow?]

r= 0.79 t= 8.22 > tcrit (40, 0.025)= 2.021;

The variable ‘none’ labels samples whose behaviour is described by (iv) above and the variables ‘mixhigh?’ and ‘mixlow?’ describe the mix type of the sample. Comparing these two correlation coefficients using Fisher’s transformation shows that there is no significant difference between them. Similar tests on the affect of the ‘none’ variable on the prediction of compressive modulus, stress at ELR and strain to failure showed no significant difference in the resulting correlations.

Using a ‘Chi square test’ it has been established that the frequency of samples exhibiting the behaviour listed, (i- iv) above, was randomly distributed across the three different mix types. The calculations for this test are shown in ‘Appendix E: probability of form abnormalities in stress/ strain graphs of test series 4 and 5.’

Using the method of least squares regression equations have been calculated to predict the variables failure stress, stress at ELR and compressive modulus given knowledge of mix type and moisture content at test. These regression equations are of the form:

$$\text{variable} = a \times (\text{moisture content at test})^{n}$$

where ‘variable’ represents failure stress, stress at ELR or compressive modulus. If this form of equation perfectly described the data then a plot of log (variable) and log (moisture content at test) would be a straight line with a gradient of n and a constant equal to log (a). Below are the regression equations predicting failure stress, stress at ELR and compressive modulus from the moisture content at test and mix indicator variables. The coefficients of the variables have been rounded for ease of comparison:

compressive = $180 \times 10^{6} \times (\text{mcttw})^{(-0.55 + 0.16\ \text{mixhigh?} - 0.12\ \text{mixlow?})}$
modulus

$r = 0.74$ $t = 6.32 > \text{tcrit}\ (40, 0.025) = 2.021$

stress at = $1.55\ 10^{6} \times (\text{mcttw})^{(-0.43 + 0.16\ \text{mixhigh?} - 0.23\ \text{mixlow?})}$
ELR

$r = 0.84$ $t = 6.32 > \text{tcrit}\ (40, 0.025) = 2.021$

failure= $1.78 \times 10^{6} \times (\text{mcttw})^{(-0.32 + 0.15\ \text{mixhigh?} - 0.16\ \text{mixlow?})}$
stress

$r = 0.82$ $t = 6.32 > \text{tcrit}\ (40, 0.025) = 2.021$

Until this point in this chapter the ‘moisture content at test’ has been the weight of water in the sample at the time of testing expressed as a percentage of the estimated dry weight of the sample (mcttw). During this project an alternative method of measuring the moisture content at test has been used: the weight of water in the sample at the time of testing expressed as a percentage of the estimated dry weight of binder fraction of the sample (mctbin). Using this measure of moisture content at the time of test of the samples, regression equations were calculated which give significant coefficients of determination between mctbin and failure stress, stress at ELR and compressive modulus. These equations allow the prediction of these properties regardless of mix type. This is shown by a comparison, using Fisher’s transformation, of the correlation coefficients of the following regression equations:

variable = function [moisture content at test and mix indicators]; and
variable = function [moisture content at test only]

where ‘variable’ is used to represent either stress at ELR or failure stress.

When moisture content at test is measured as a percentage of the total dry sample weight (mcttw), the correlation coefficient of the first equation is significantly greater than that of the second equation. However, there is no significant difference between the correlation coefficients of these equations when moisture content at test is measured as a percentage of the binder weight of the sample.

Regression equations of the following form have been calculated to predict the compressive modulus of the test specimens:

compressive= function [moisture content at test and mix indicators];
modulus
and
compressive modulus = function [moisture content at test only].

The degree of correlation of these equations is independent of the method of moisture content measurement.

The equations predicting failure stress and stress at ELR regardless of mix type are:

failure stress = $315\text{x}10^6$ x $(\text{mctbin})^{-0.55}$

$r= 0.74 \qquad t= 6.62 > \text{tcrit } (40, 0.025)= 2.021$

stress at ELR = $2.69\text{x}10^6$ x $(\text{mctbin})^{-0.51}$

$r= 0.77 \qquad t= 7.73 > \text{tcrit } (40, 0.025)= 2.021$

The strain to failure of the cylinders in test series 4 and 5 can be predicted from the equation:

strain to failure =

$990\text{x}10^{-6}$ x (mcttw) $-4.92\text{x}10^{-3}$ mixhigh? $-759\text{x}10^{-6}$ mixlow? + $18.9\text{x}10^{-3}$

$r= 0.59 \qquad t= 6.33 > \text{tcrit } (40, 0.025)= 2.021$

Excluding the mix indicator variables the regression equation becomes:

strain to failure = 0.11×10^{-3} x (mcttw) + 16×10^{-3}

$r= 0.48$ $t= 3.47 > t_{crit}(40, 0.025)= 2.021$

Comparison of the two correlation coefficients above using Fisher's transformation shows that the decrease is not statistically significant. Therefore the inclusion of the mix indicator variables does not significantly affect the correlation between strain to failure and mcttw.

Using moisture content relative to the estimated dry weight of the binder fraction of the materials to predict the strain to failure from moisture content at test gives the following equations:

strain to failure =

352×10^{-6} x(mctbin) -8.29×10^{-3} mixhigh? $+545\times10^{-6}$ mixlow? $+19.8\times10^{-3}$

$r=0.59$ $t= 6.33 > t_{crit}(40, 0.025)= 2.021$

Excluding the mix indicator variables the regression equation becomes:

strain to failure = 151×10^{-6} x (mctbin) + 19.8×10^{-3}

$r= 0.22$ $t= 1.40 < t_{crit}(40, 0.025)= 2.021$

Comparison of the two correlation coefficients above using Fisher's transformation shows that the decrease is statistically significant.

The numerical difference between the failure strain and the strain at ELR can be predicted from the equation:

failure strain - strain at ELR = 970×10^{6} (mcttw) + 3.54×10^{-3}

$r= 0.67$ $t= 5.65 > t_{crit}(40, 0.025)= 2.021$

or

failure strain - strain at ELR = 232×10^{6} (mctbin) + 5.16×10^{-3}

$r= 0.51$ $t= 3.71 > t_{crit}(40, 0.025)= 2.021$

There is no statistical significance in the difference of the correlations of these equations.

The above discussion has identified either mcttw or mctbin as the best single predictor of each of the properties compressive modulus, stress at ELR, failure stress, strain to failure and (strain to failure - strain at ELR). This is summarised in table 6.4 below.

Until this point this chapter has focused upon the correlation of variables 'within' each mix type; for example, the effect of the moisture content at test of samples of each mix type upon their failure stress. The experimental data can also be manipulated to provide correlation of variables between the different mix types; this may provide information about the effect of the proportions of the aggregate and binder fractions upon the compression test results.

property	single predictor	significance (t crit (40, 0.025)= 2.021)	
log (failure stress)	log (mctbin)	r= 0.74	t= 6.90
log (stress at ELR)	log (mctbin)	r= 0.77	t= 7.73
log (compressive modulus)	log (mctbin/ tw)	r= 0.72 or 0.60	t= 6.62 or 4.70
strain to failure	mcttw	r= 0.48	t=3.47
(strain to failure - strain at ELR)	mctbin or mcttw	r= 0.67 or 0.51	t= 5.65 or 3.71

table 6.4
'Best single predictors' for various properties
of test 4 and 5 cylinders.

It has already been established that changes in the moisture content at test are highly correlated with changes in the behaviour of the test series 4 and 5 samples in compression. Before making comparisons between the different mix types, it is necessary to establish that the moisture content at which the samples of each mix type were tested will not bias the comparison. Figure 6.27 shows the moisture content at test (mctbin) of all the samples in test series 4 and 5. From observation it is apparent that the distribution of these values between the different mix types is not uniform. This observation is verified by the result of a statistical technique the 'analysis of variance' which indicates a significant difference between the variance of the distributions: ($F(2, 39)= 39.5$; $p< 0.0078$).

Further observation of figure 6.27 appears to show that the cause of this difference in variance is the different number of samples of each mix type with a moisture content at test greater than 18% (mctbin). This second observation is also verified by the results of an analysis of variance: ($F(2, 39)= 39.5$; $p> 0.2936$) this indicates that there is no significant difference between the variance of the distributions of moisture content once the above samples are eliminated from the analysis. Therefore, comparison of behaviour between mix types is valid for samples with mctbin < 18%. The results of analysis of variance are shown in 'Appendix F: ANOVA tables'.

Figures 6.28, 6.29 and 6.30 respectively show the distributions of aggregate volume fractions and compressive modulus, failure stress and dry density of the three mix types. In order to establish the statistical significance of any correlation between these variables, 'best fit' lines have been fitted to each data set using the method of least squares. The results of this process are shown below in table 6.5.

correlation between aggregate volume fraction and...	significance (t crit (30, 0.025)= 2.04)	
...compressive modulus	r= 0.08	t= 0.46
...failure stress	r= 0.50	t= 3.16
...dry density	r= 0.76	t= 6.39

table 6.5
Correlation between mix types and compressive modulus, failure stress and dry density

These correlations are discussed in chapter 7.

6.5) Drying data from test series four and five

The change in moisture content of the cylinders in test series 4 and 5 with time was recorded by repeatedly weighing samples at different times (elapsed times) during their drying history. This data was analysed in two sets, one consisting of moisture content, elapsed time and mix indicator variables; the second set, excluding the mix indicator variables, consisting only of moisture content and elapsed time. This data is presented in 'Appendix I: test series 4 and 5 drying data'.

Using the method of least squares, 'best fit' lines were fitted to each data set to describe the relationship between the elapsed time and cylinder moisture content. Using the regression equation fitted, the moisture content of a cylinder can be estimated from knowledge of the time that it has spent in the humidity oven. The regression equation fitted in this case is of the form:

$$\text{moisture content (\% total weight)} = a \times (\text{elapsed time (hours)})^{n}$$

If this equation described the relationship between moisture content and time exactly then a graph of the log (elapsed time) against log (moisture content) would be a straight line with a gradient of n and a constant equal to log (a). By comparing the correlation coefficient (r) of the best fit line for each of the two data sets described above (one including, one excluding mix indicator variables) it is possible to calculate whether including the mix indicator variables affects the correlation significantly.

The best fit line for the data set including mix indicator variables is:
moisture content % total weight =

$$30.19 \times (\text{time/ hours})^{-0.6809} + 1.26\ \text{highmix?} - 1.34\ \text{lowmix?}$$

$r = 0.9029 \quad t = 30.75 > t_{crit}(100, 0.025) = 1.98$

The best fit line for the data set excluding mix indicator variables is:
moisture content % total weight = $28.84 \times (\text{time/ hours})^{-0.6655}$

$r = 0.8586 \quad t = 24.50 > t_{crit}(100, 0.025) = 1.98$

Comparing these two correlation coefficients using Fisher's transformation indicates that there is no significant difference between them. This result is interpreted as showing that mix type has no significant affect upon drying behaviour of the test 4 & 5 samples.

Figure 6.31 shows a graph of elapsed time and moisture content for all the cylinders in test series 4 and 5.

Figure 6.32 shows a graph of log (elapsed time) and log (moisture content).

Figure 6.33 shows a graph of the rate of drying (change in moisture content/ time) and moisture content. This graph will be discussed in chapter 7.

6.6) Drying data from an external experimental cob wall

An experimental cob wall was constructed at the University of Plymouth in order to investigate the following phenomena.

i) The 'initial drying progress' of the wall from the moisture content at manufacture. The initial drying period was taken as being until a time where there was a marked decrease in the rate of change of moisture content of the wall. From this time the moisture content of the wall varied with the moisture content of the environment around it.
ii) Changes in moisture content of the wall after the initial drying period ('environmental progress of the wall').

The moisture content of the wall was measured at various points in time. Although the measuring process takes approximately twenty minutes it is considered that the moisture content of the wall will not change significantly during this period. Therefore, for the purposes of analysis, all moisture contents in each measurement session are considered to have been recorded simultaneously.

Data was collected from a total of forty five probes, fifteen being included in each of the three lifts of the experimental wall. The data was collected in five time periods given below in table 6.6:

time period	date interval	number of measurements
1	29/7- 14/9/93	36
2	11/2- 15/2/95	5
3	17/3- 22/3/95	6
4	26/7- 4/8/95	10
5	7/8- 8/8/95	2

table 6.6
Periods of data collection from the experimental wall.

The TDR was not available to measure the initial drying process of the first lift. Therefore, measurements were only taken of the initial drying process of the second and third lifts.

During the monitoring of the moisture content of the wall after the initial drying period the cables of some of the probes were accidentally severed by a lawn mower. This rendered these probes inoperative. So that these inoperative probes did not unfairly bias the comparison of average moisture contents analyses of variance only included probe positions for which there was an operational probe in each lift. In order to meet this criteria, probe positions 6,10, 12, 13, 14 and 15 were excluded from the analyses of variance of time periods 2, 3, 4 and 5.

Further exclusions from the analyses of variance were necessary to account for occasional situations when the reading on the TDR for a particular probe was indecipherable. One indecipherable probe reading in a measurement session required that all of the readings in that session be excluded from the analyses. Sessions excluded for this reason were those on the following dates: 11/2/95,17/3/95, 26/7/95 and 27/7/95.

The moisture content of the experimental wall has been measured thirty times since it was constructed. Those measurements considered to be valid, under the criteria above, have been analysed using analysis of variance. This analysis uses three different averages to describe the distribution of moisture content in the experimental wall. These averages are:

i) average wall moisture content calculated from the readings of all probes in the wall;
ii) average lift moisture content calculated from the readings of all probes in a particular lift; and
iii) average probe position moisture content calculated from the readings of vertically aligned probes in the lifts.

The data used in the analysis of the experimental wall is presented in 'Appendix G: experimental wall data, time period 1' and 'Appendix H: experimental wall data, time periods 2 to 5'.

6.6.1 Analysis of the initial drying progress of the wall.

This analysis is made using data from period 1. For the reasons explained in section 4.2.2 of chapter 4 the readings of measurement period 1 have not been converted into gravimetric moisture contents. The moisture content of the second and third lifts of the wall is compared when the lifts are of a similar age: that is at similar elapsed times from the construction of the lift. Analyses of the distribution of moisture content in the lifts are made when the age of the third lift is within + or - 5 % of the age of the second lift.

i) There is a significant change of the average moisture content of both the second and third lifts with time (F(10, 150)= 206.08; $p<0.000$) (figure 6.34).
ii) There is 'interaction' between the second and third lifts (F(10, 280)= 2.19; $p< 0.0183$) (figure 6.35).
iii) There is no significant interaction between probe position, that is: there is no statistically significant difference in the rate at which the average reading of any vertically aligned probes in the wall change in comparison to the rate of change of the total average moisture content of the wall (F(140, 150)= 0.95; $p< 0.6251$) (figure 6.36).
iv) There is no statistically significant difference between probe positions in the wall for similar elapsed times since construction of the second and third lifts (F(14, 15)= 1.21; $p< 0.3560$) (figure 6.37).

From figure 6.38 it can be seen that the rate of change of moisture content of the second lift decreases markedly at an elapsed time of approximately 600 hours (25 days). Beyond this time the rate of change of moisture content of the second lift fluctuates although the overall trend indicated that the lift continued to dry. The rate of change of moisture content of the third lift also appears to decrease markedly at an elapsed time of approximately 600 hours.

6.6.2 Analysis of the environmental progress of the wall

This analysis uses moisture readings from periods 2, 3, 4 and 5.

i) There is a statistically significant effect of time on the total average moisture content of the wall ($F(18, 324)= 47.71$; $p< 0.000$) (figure 6.39).

ii) There is no statistically significant difference in the moisture contents of the second and third lifts. However, there is a statistically significant difference between the moisture content of the first and second lift; and the moisture content of the first and third lift ($F(2, 24)= 11.16$; $p< 0.0004$) (figure 6.40).

iii) There is no statistically significant interaction between lifts and time, that is: the rate of change of average moisture content for each lift does not differ sufficiently to be statistically significant ($F(36, 432)= 1.10$; $p< 0.3156$) (figure 6.41).

iv) There is a statistically significant interaction between the moisture content of probe positions and time, that is: the difference in the rate of change of the average reading of probes vertically aligned in the wall is statistically significant ($F(144, 324)= 2.29$; $p< 0.0000$) (figure 6.42).

v) There is no statistically significant difference in the average reading of vertically aligned probes in the wall for periods 2, 3, 4 and 5 ($F(8, 18)= 1.21$; $p< 0.3460$) (figure 6.43 (a and b)).

In order to find the probe positions which had a statistically significantly different rate of change of moisture content identified in (iv) above the same data was analysed in two parts: time periods 2 and 3; and time periods 4 and 5. For each pair of time periods the average moisture content of each vertically aligned probe position was calculated. The difference between the two averages obtained for each probe position is shown in figure 6.44. The difference between the pairs of averages for probe positions 1 and 3 is statistically significantly higher then that of all other probe positions except positions 2 and 5. Therefore the greatest rate of change of moisture content of probe positions 1 and 3 are over the time from the end of period 3 to the beginning of period 4.

The analysis of variance tables of results are included in
'Appendix F: ANOVA tables.'

Test series 4 and 5 failure stress and moisture content at test

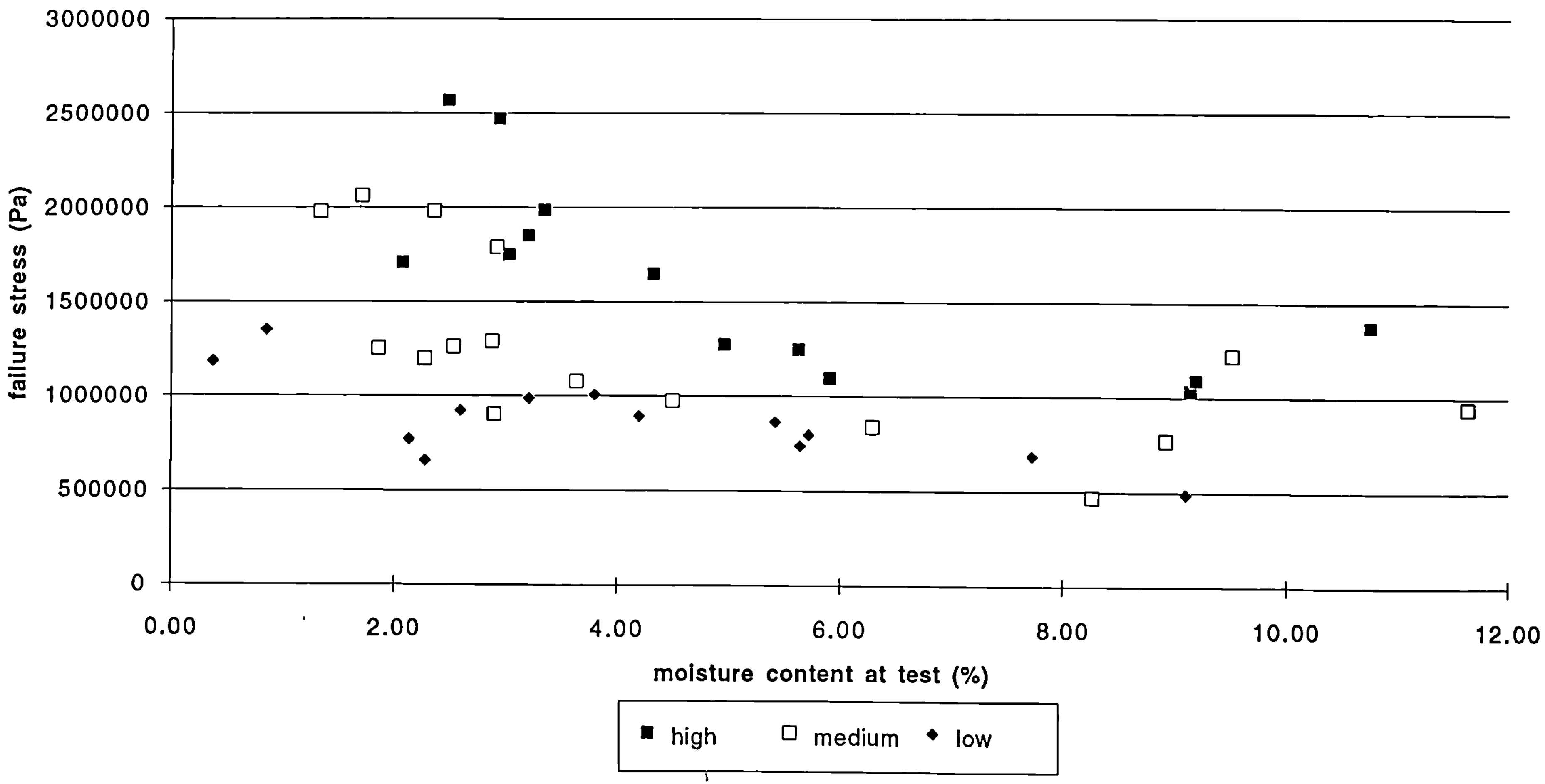


figure 6.15

Test series 4 and 5 stress at ELR and moisture content at test

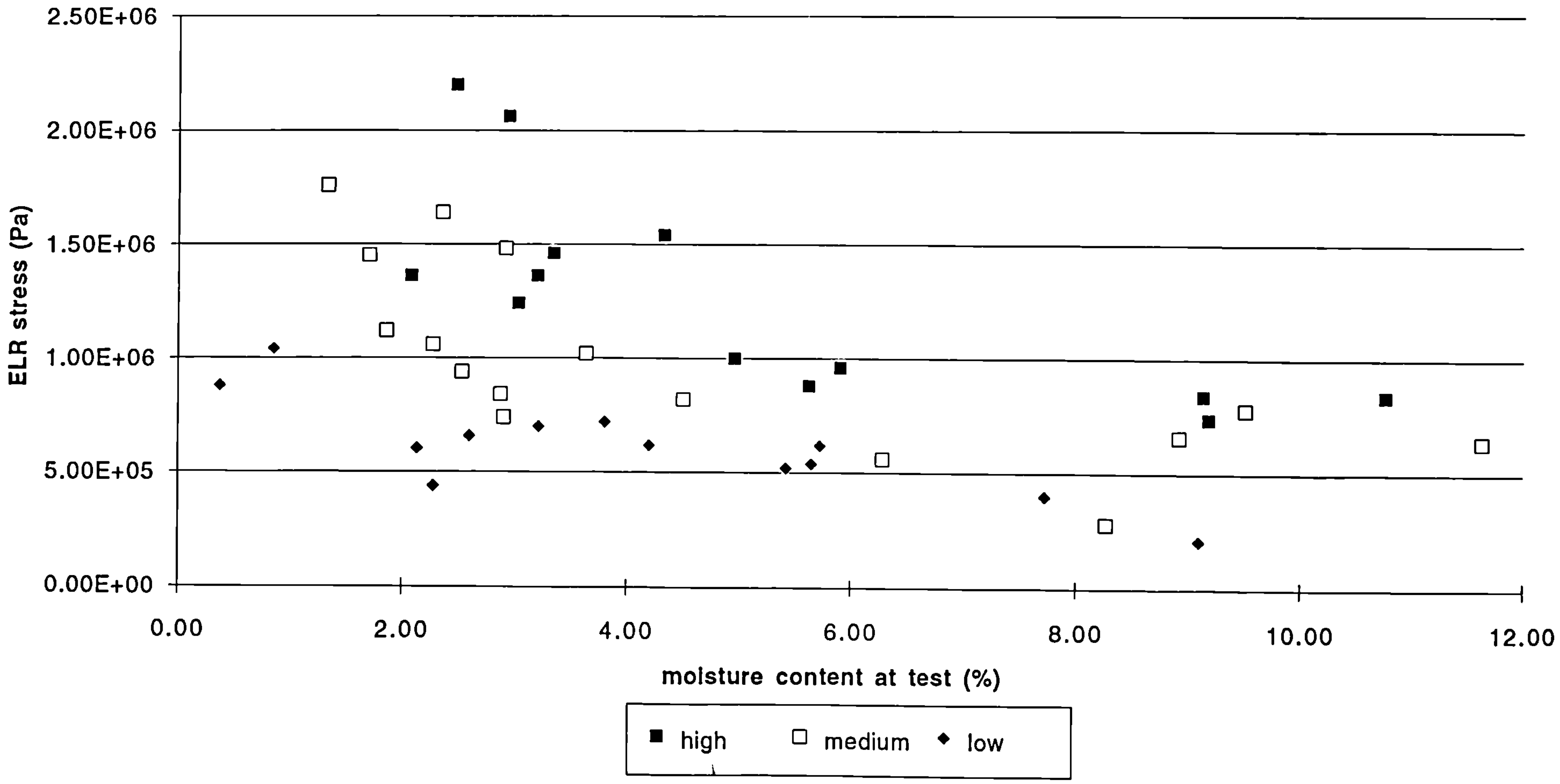


figure 6.16

Test series 4 and 5 compression modulus and moisture content at tes

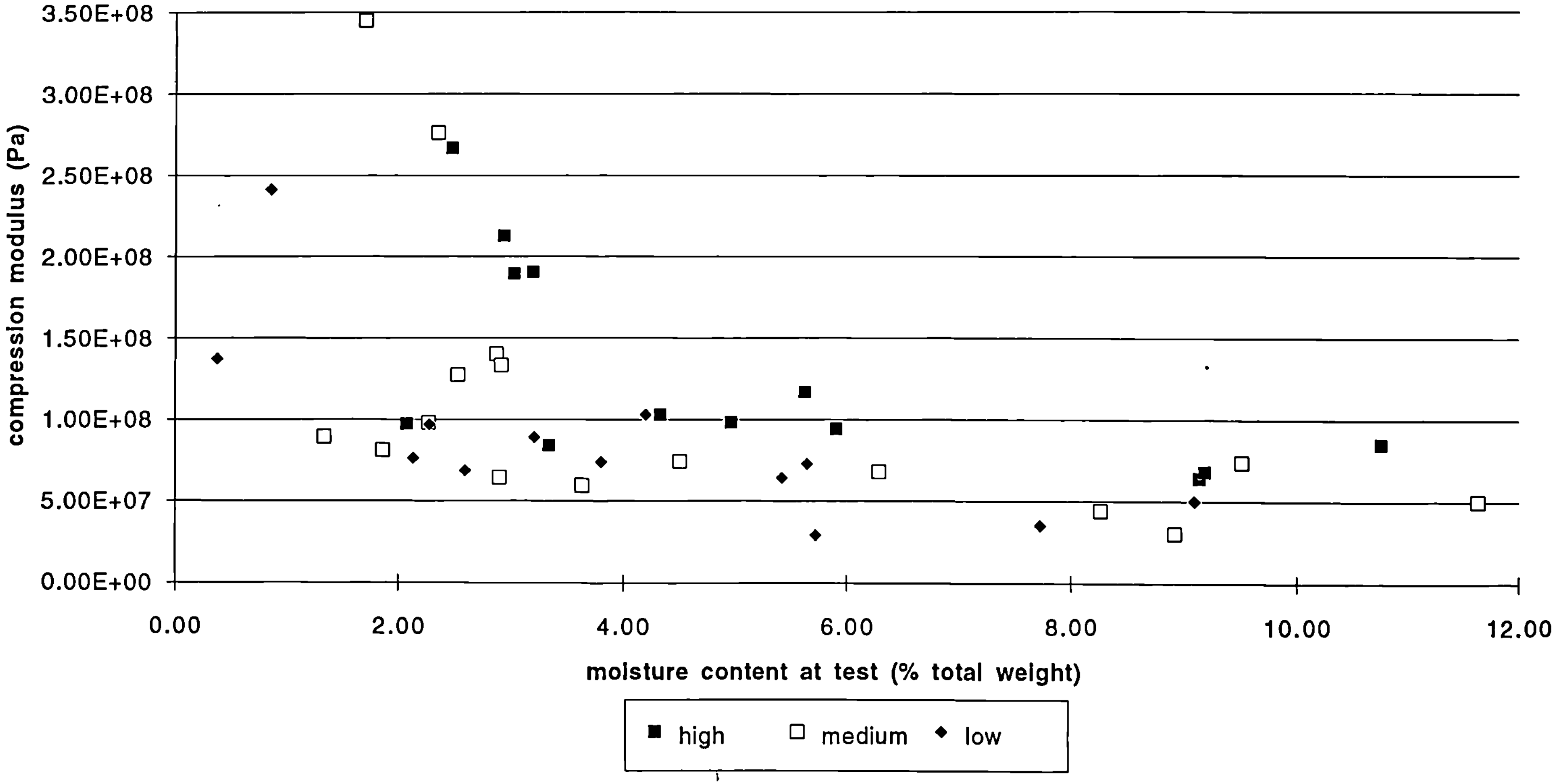


figure 6.17a

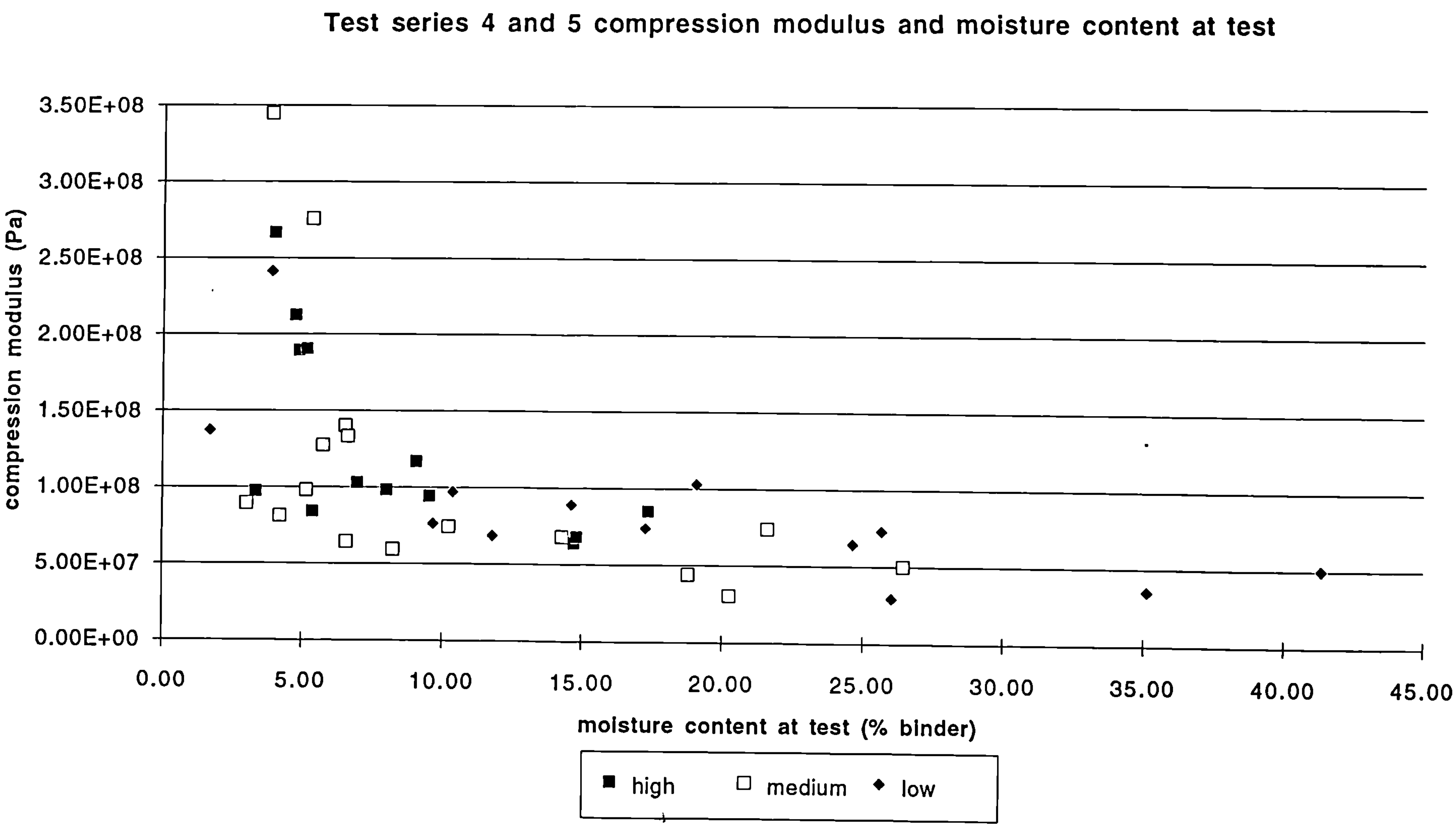

Test series 4 and 5 compression modulus and moisture content at test
compression modulus (Pa)
3.50E+08
3.00E+08
2.50E+08
2.00E+08
1.50E+08
1.00E+08
5.00E+07
0.00E+00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
moisture content at test (% binder)
■ high
□ medium
◆ low

figure 6.17b

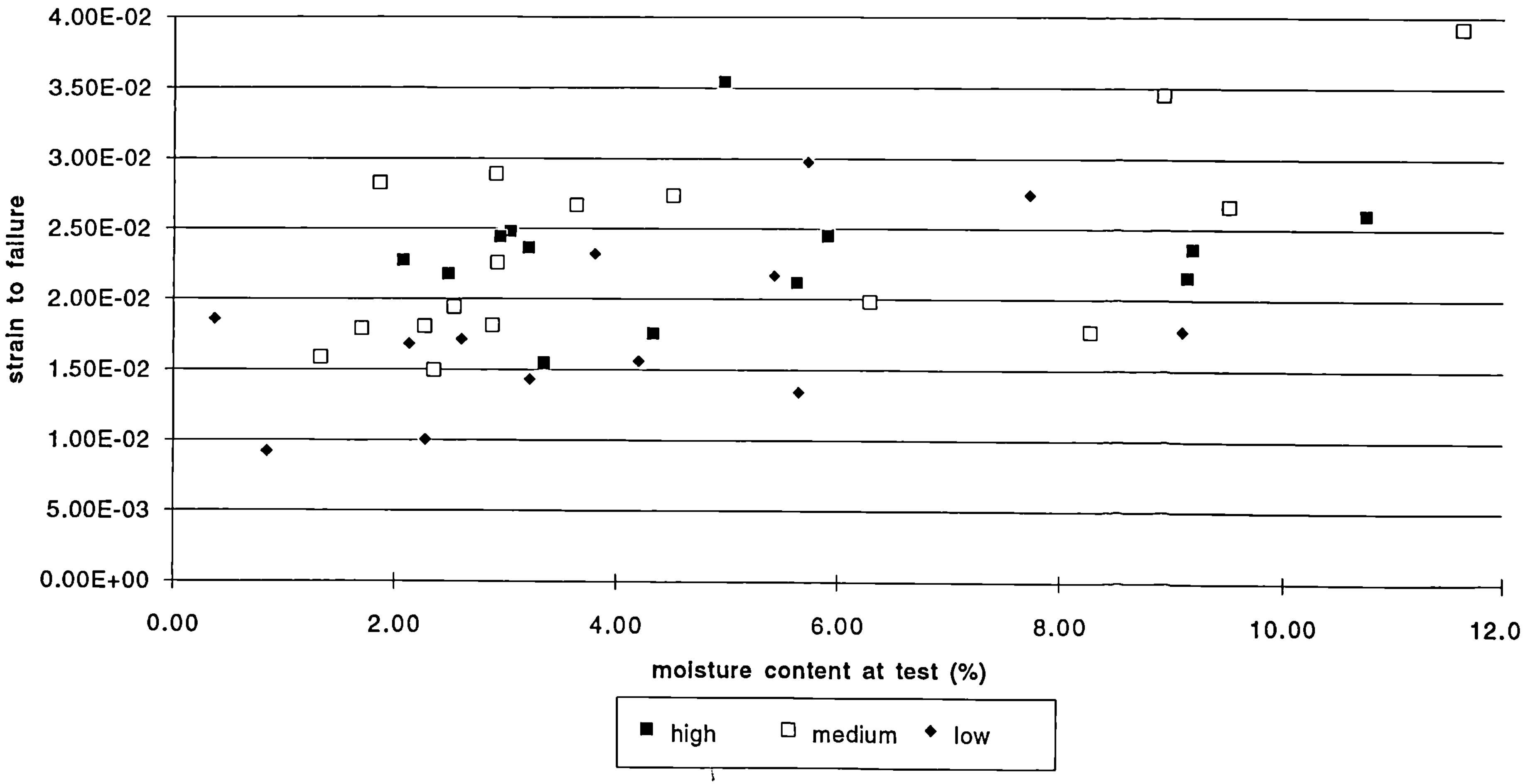

Test series 4 and 5 strain to failure and moisture content at test

figure 6.18

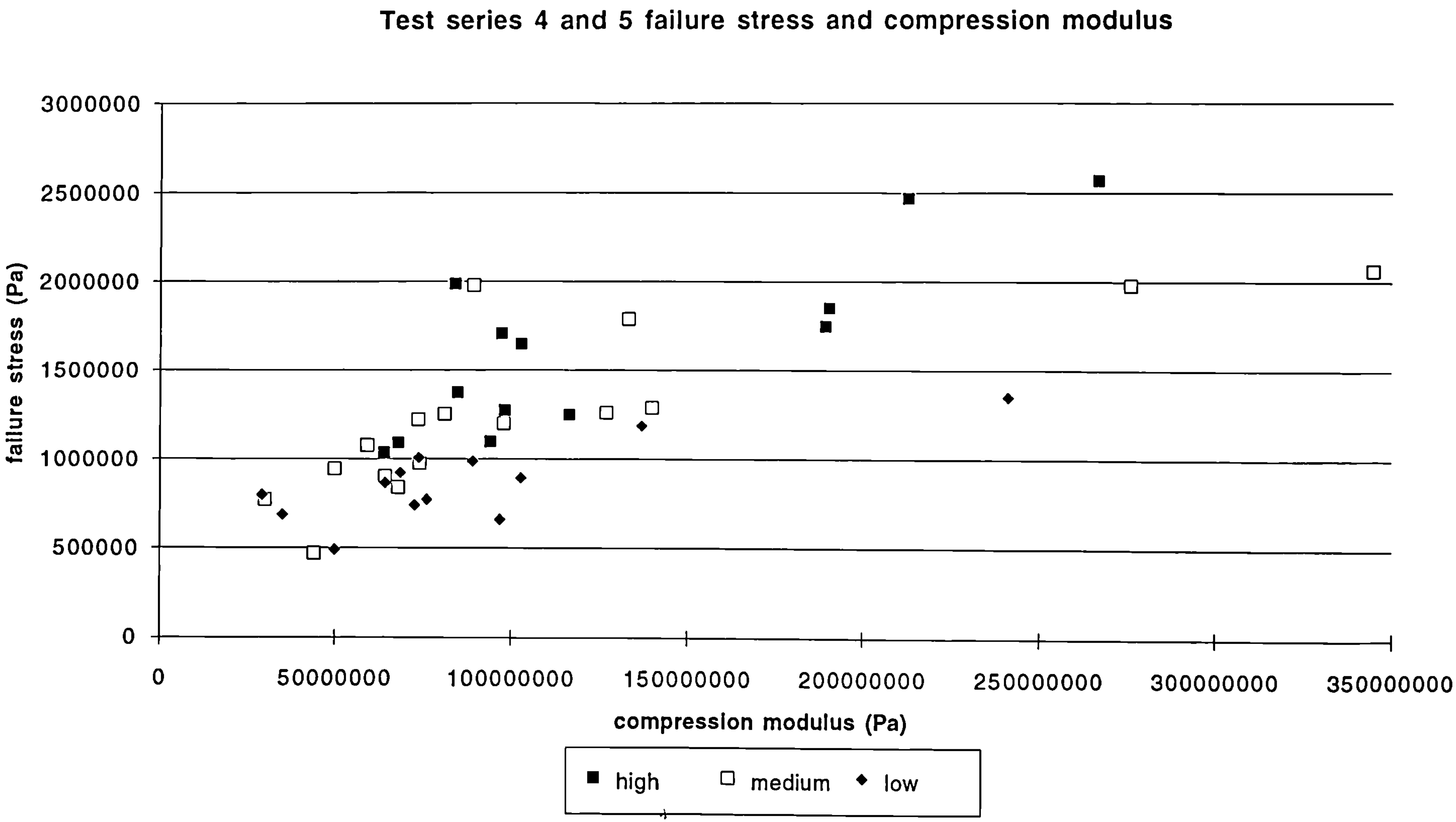

Test series 4 and 5 failure stress and compression modulus
failure stress (Pa)
3000000
2500000
2000000
1500000
1000000
500000
0
0
50000000
100000000
150000000
200000000
250000000
300000000
350000000
compression modulus (Pa)
■ high
□ medium
◆ low

figure 6.19

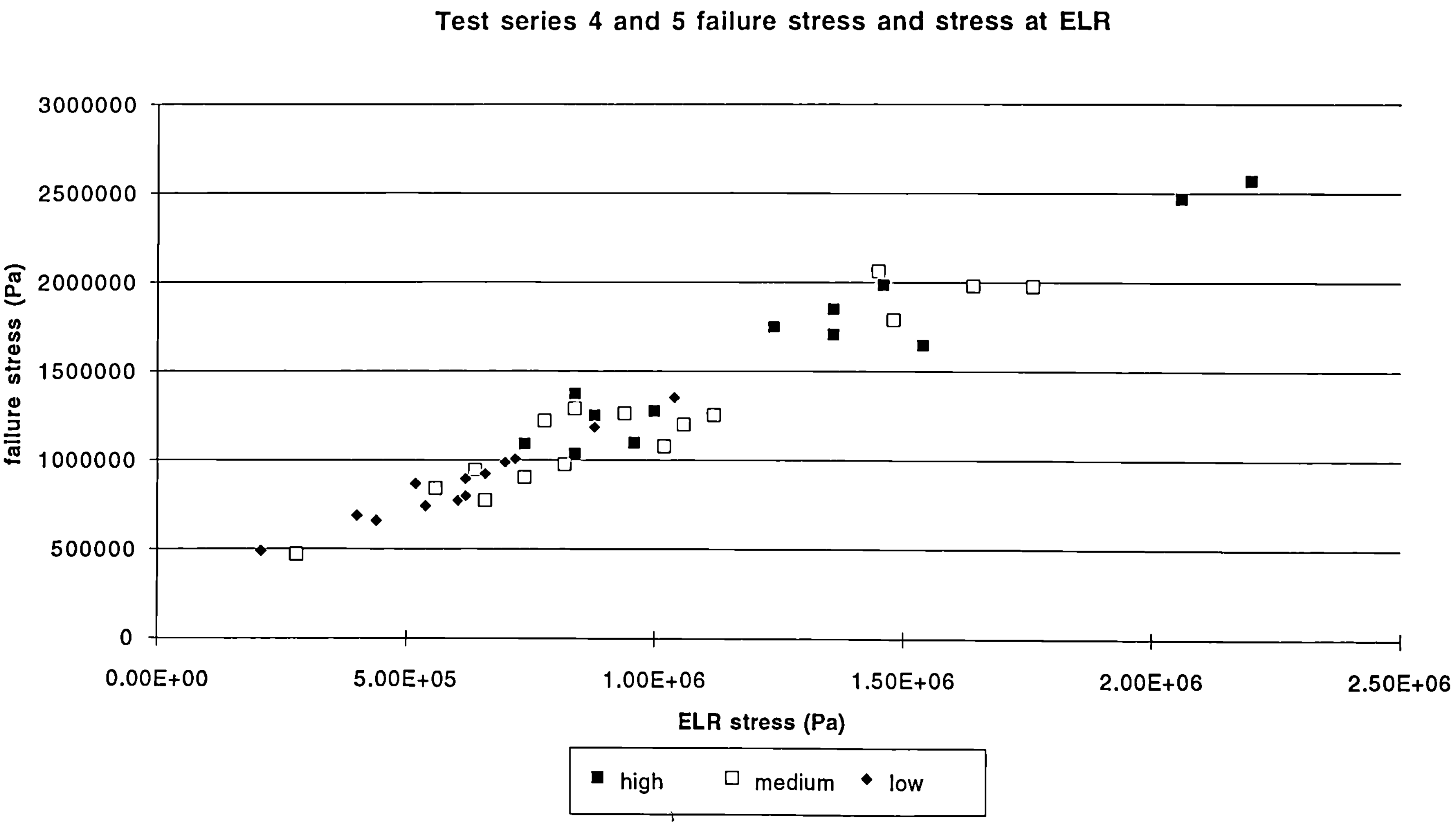

Test series 4 and 5 failure stress and stress at ELR
failure stress (Pa)
3000000
2500000
2000000
1500000
1000000
500000
0
0.00E+00
5.00E+05
1.00E+06
1.50E+06
2.00E+06
2.50E+06
ELR stress (Pa)
■ high
□ medium
◆ low

figure 6.20

Test series 4 and 5 failure stress and strain to failure

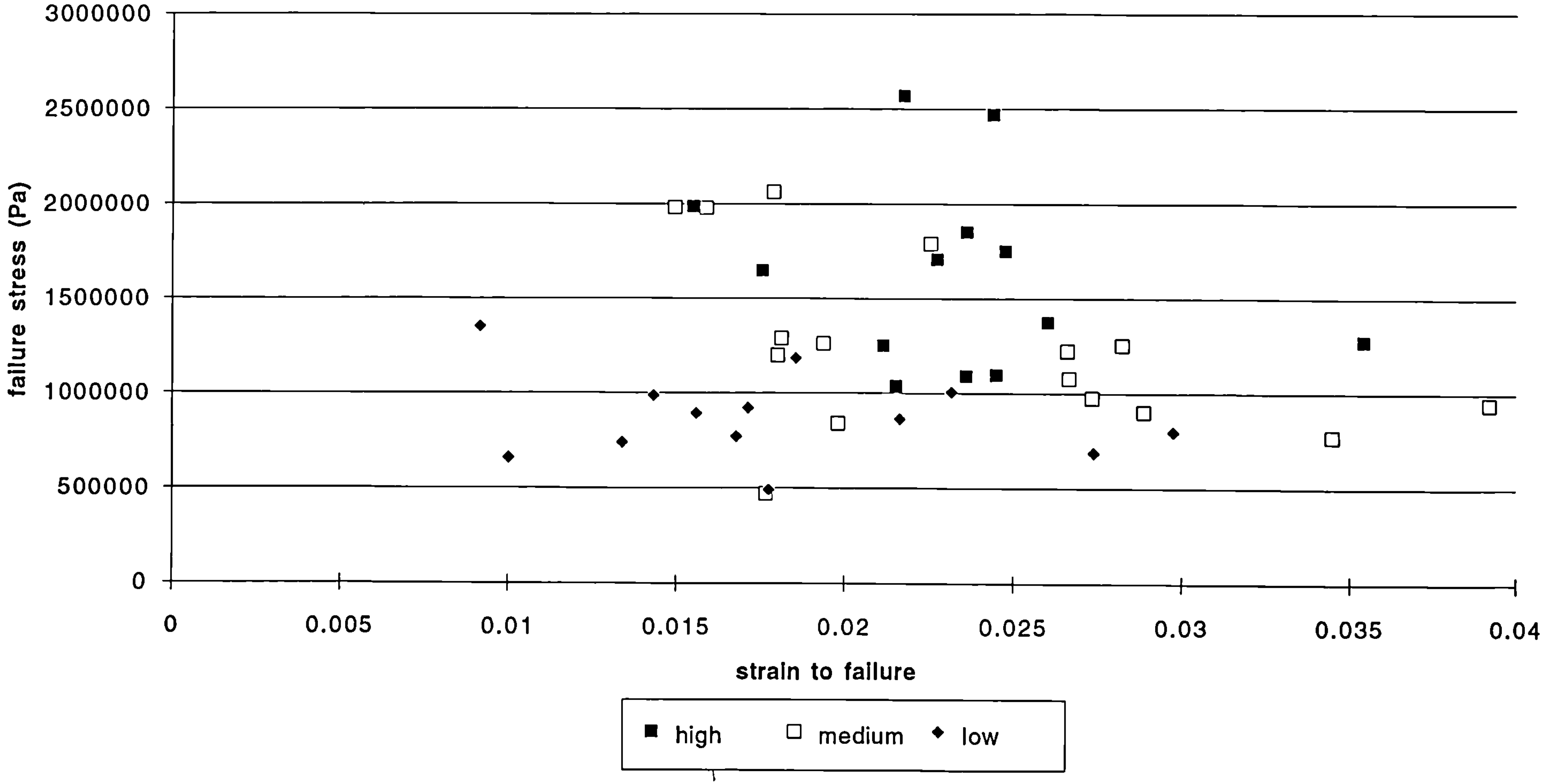


figure 6.21

Test series 4 and 5 compression modulus and strain to failure

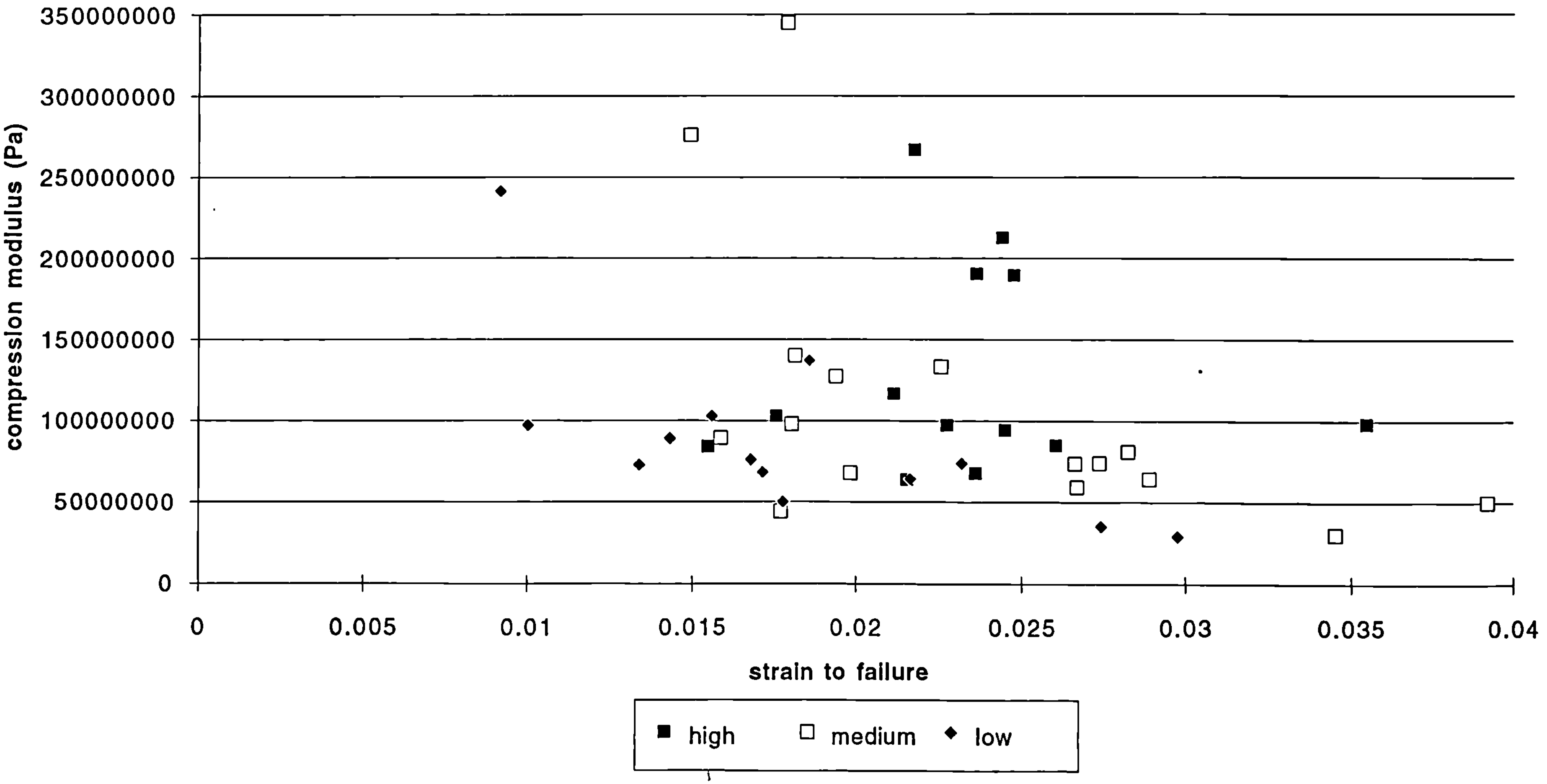
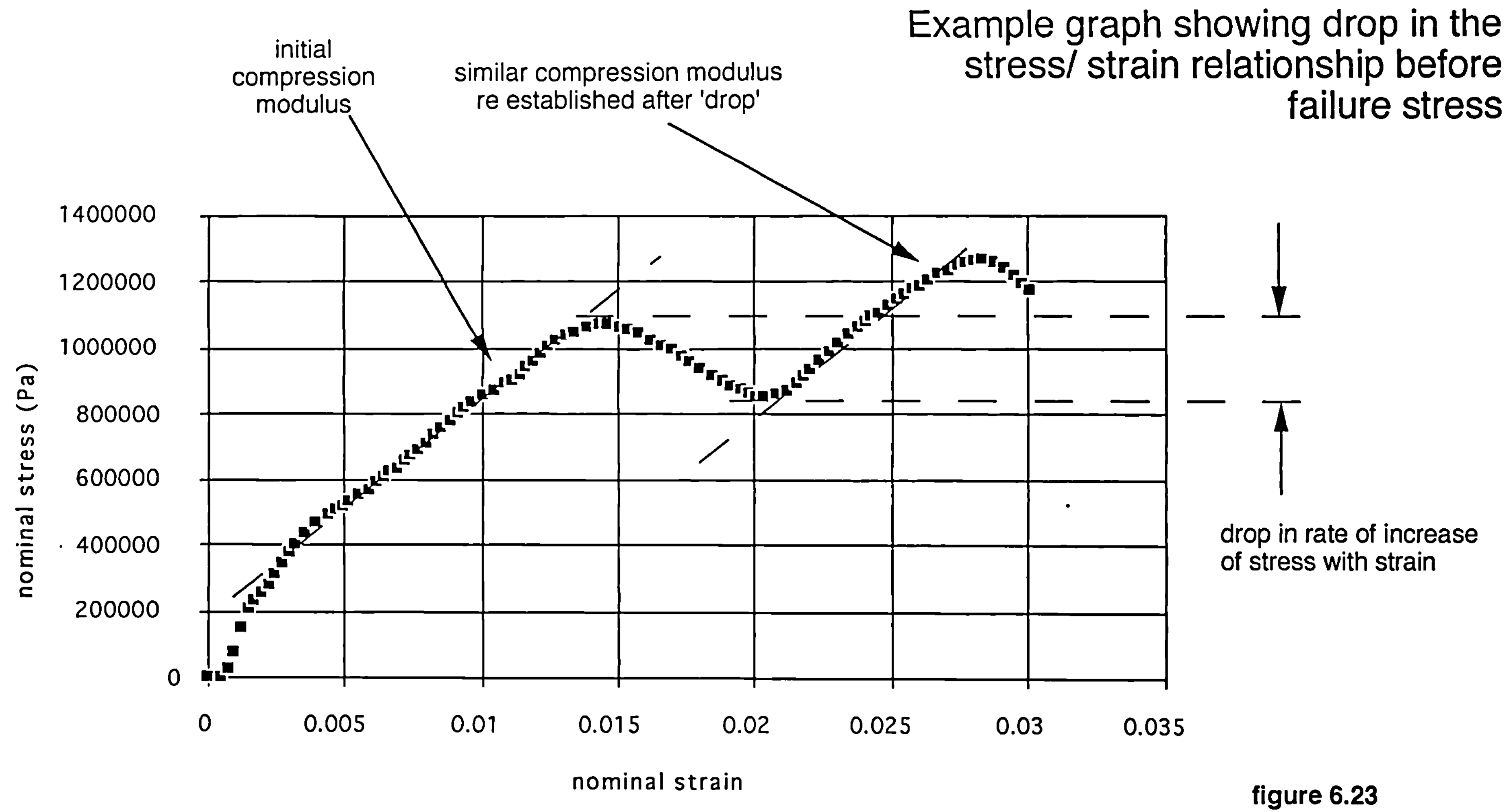


figure 6.22



Example graph showing drop in the stress/ strain relationship before failure stress

figure 6.23

Example stress/ strain graph showing a marked change in compression modulus

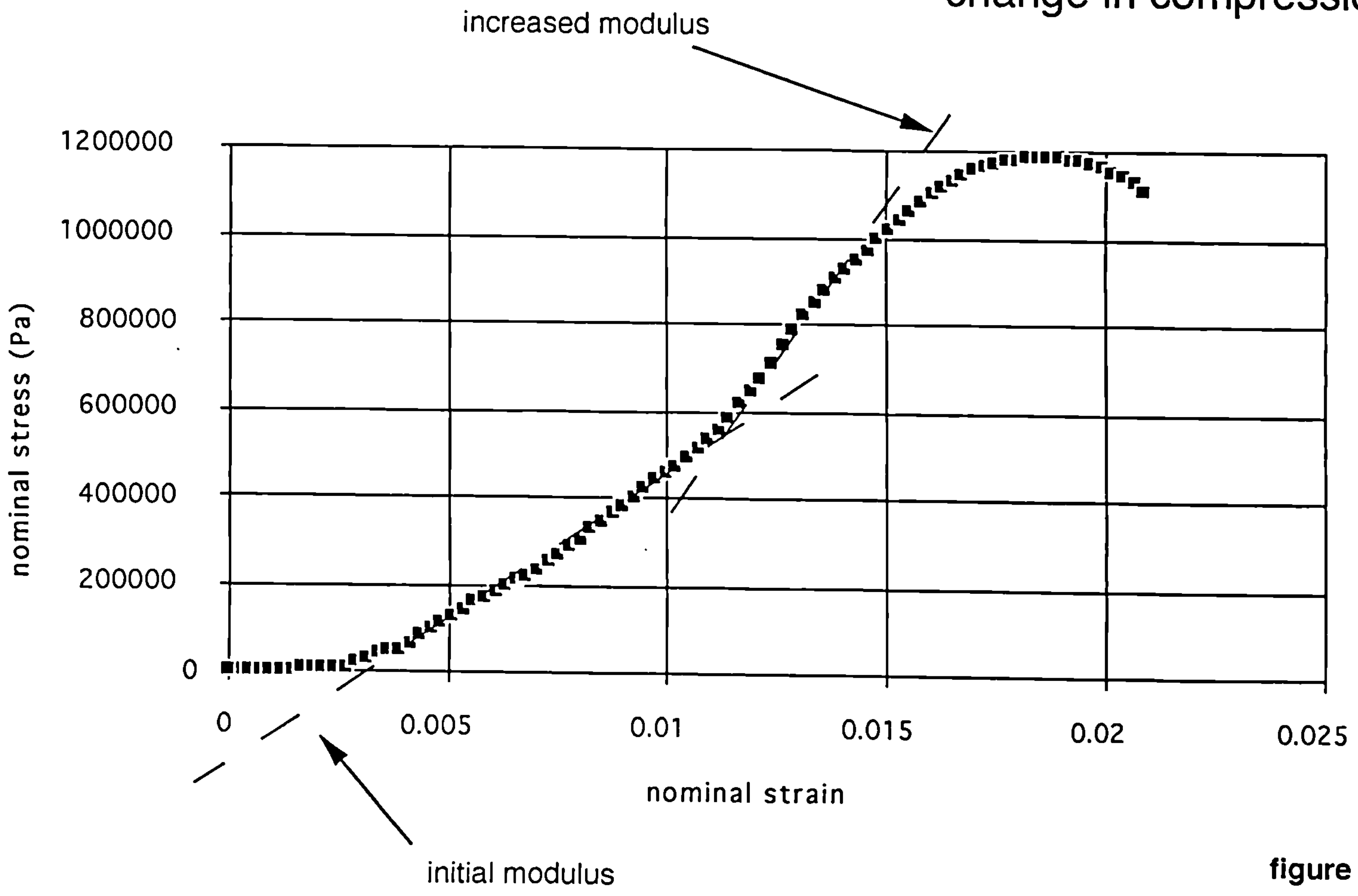
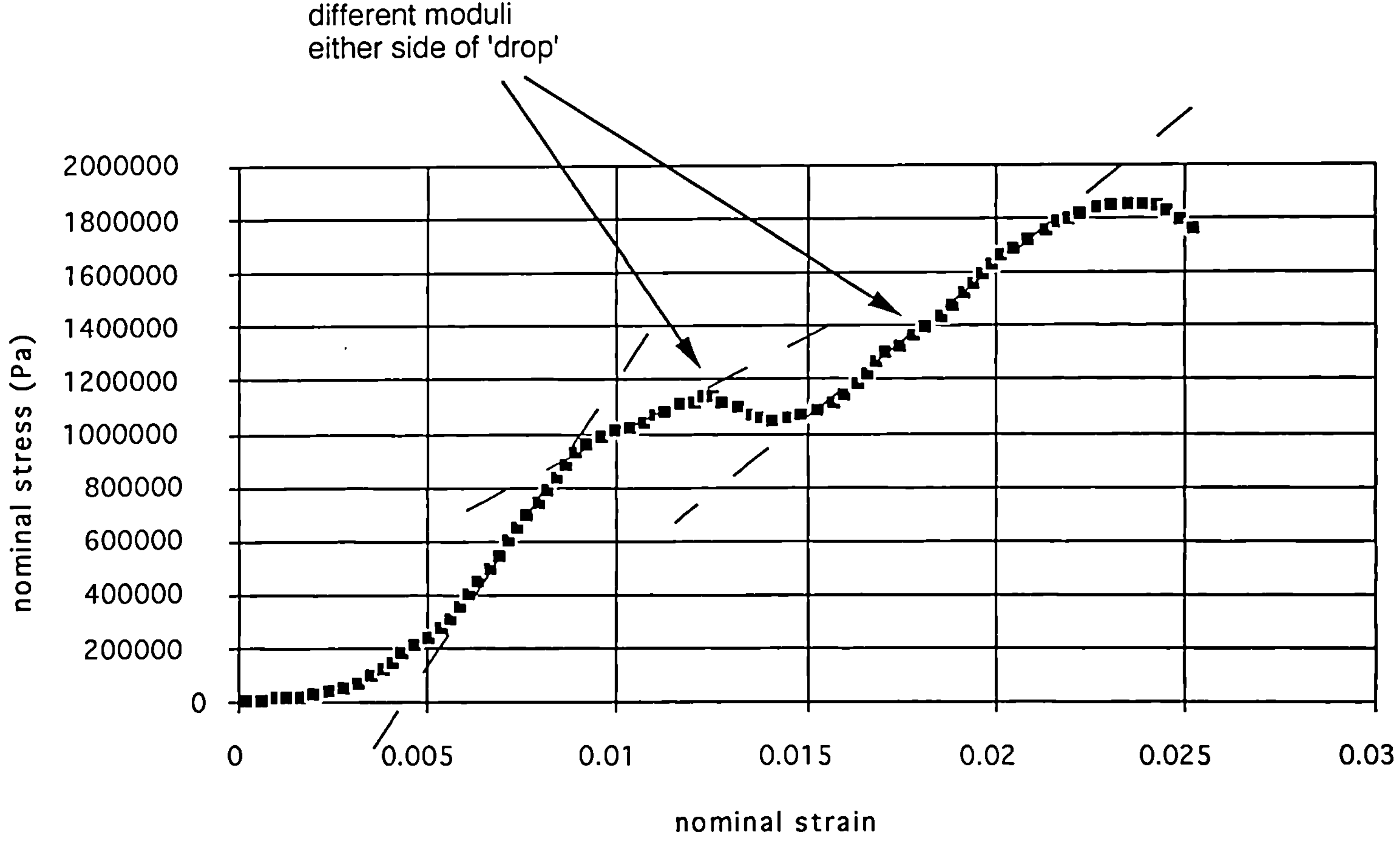


figure 6.24

Example graph showing a dropin the stress/ strain relationship and a change in compression modulus



different moduli either side of 'drop'

figure 6.25

Example graph with no drop in stress/strainrelationship and no change in compression modulus

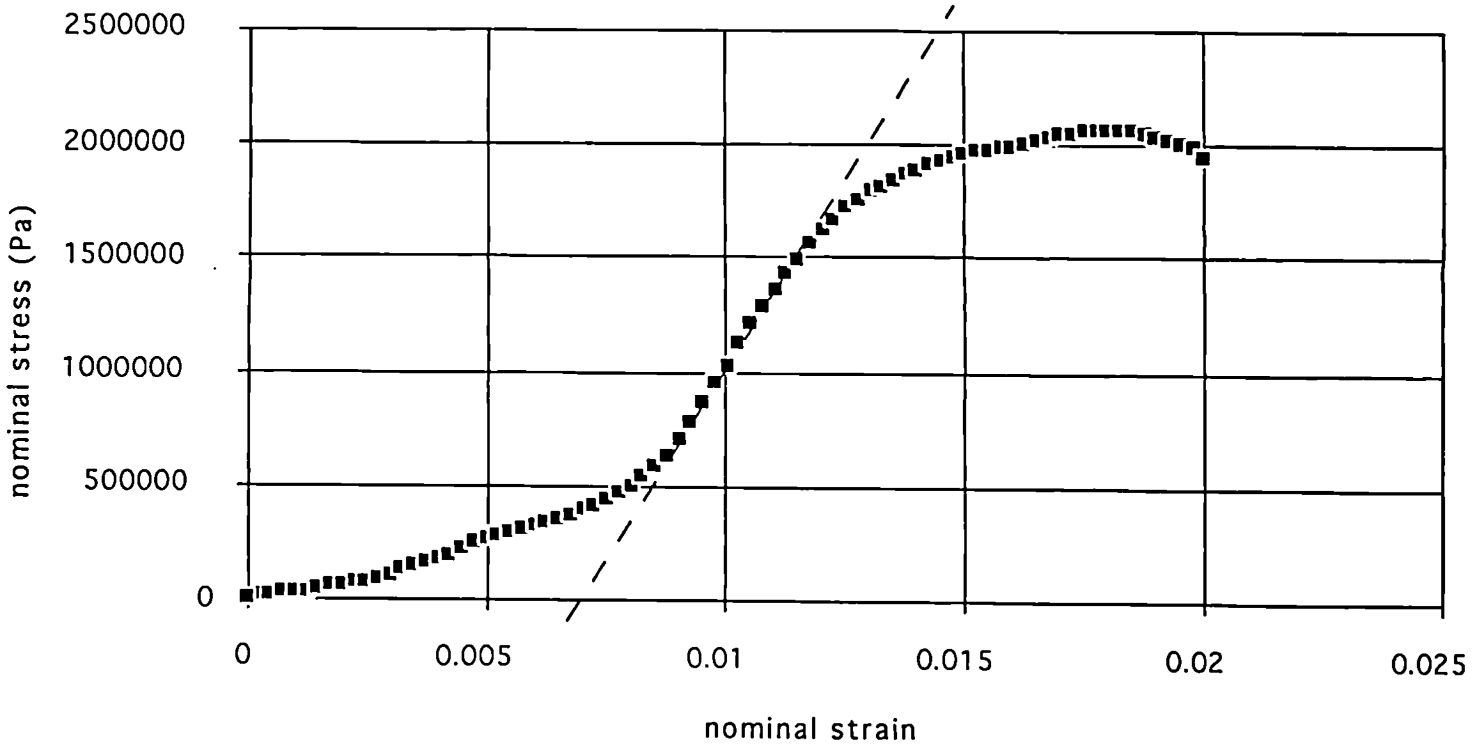


figure 6.26

Moisture content at test of test series 4 and 5 samples

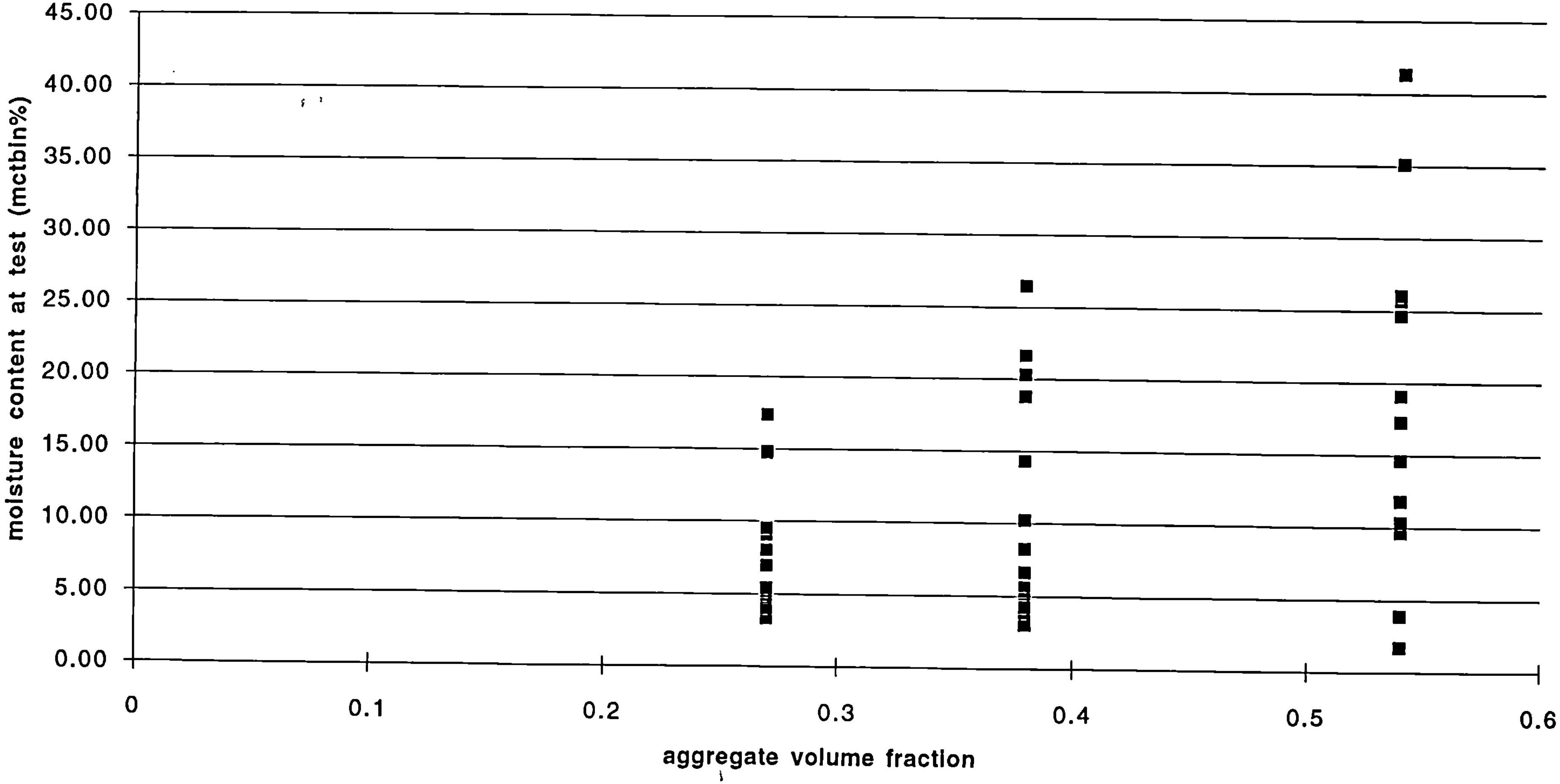


figure 6.27

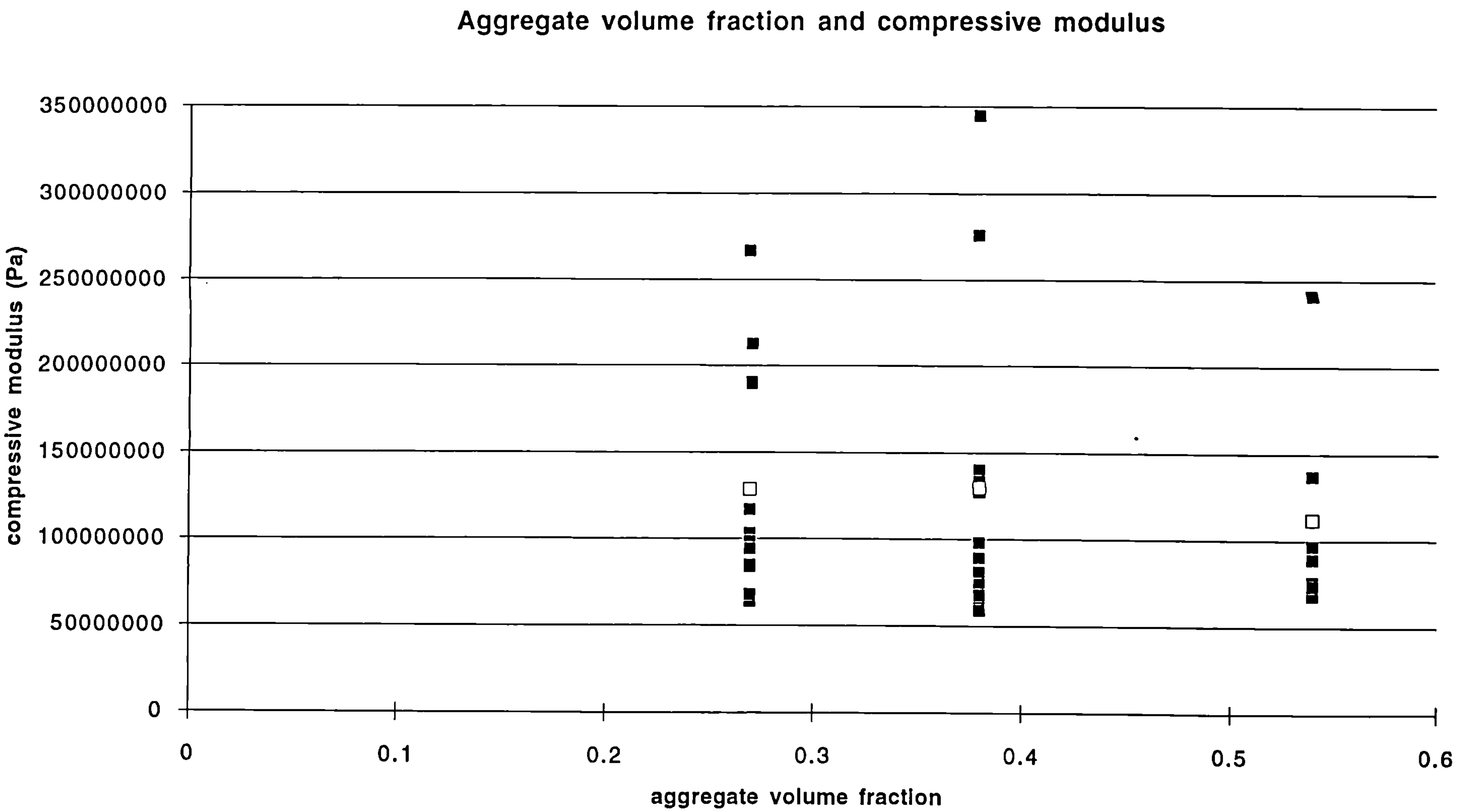

Aggregate volume fraction and compressive modulus
compressive modulus (Pa)
350000000
300000000
250000000
200000000
150000000
100000000
50000000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
aggregate volume fraction

figure 6.28

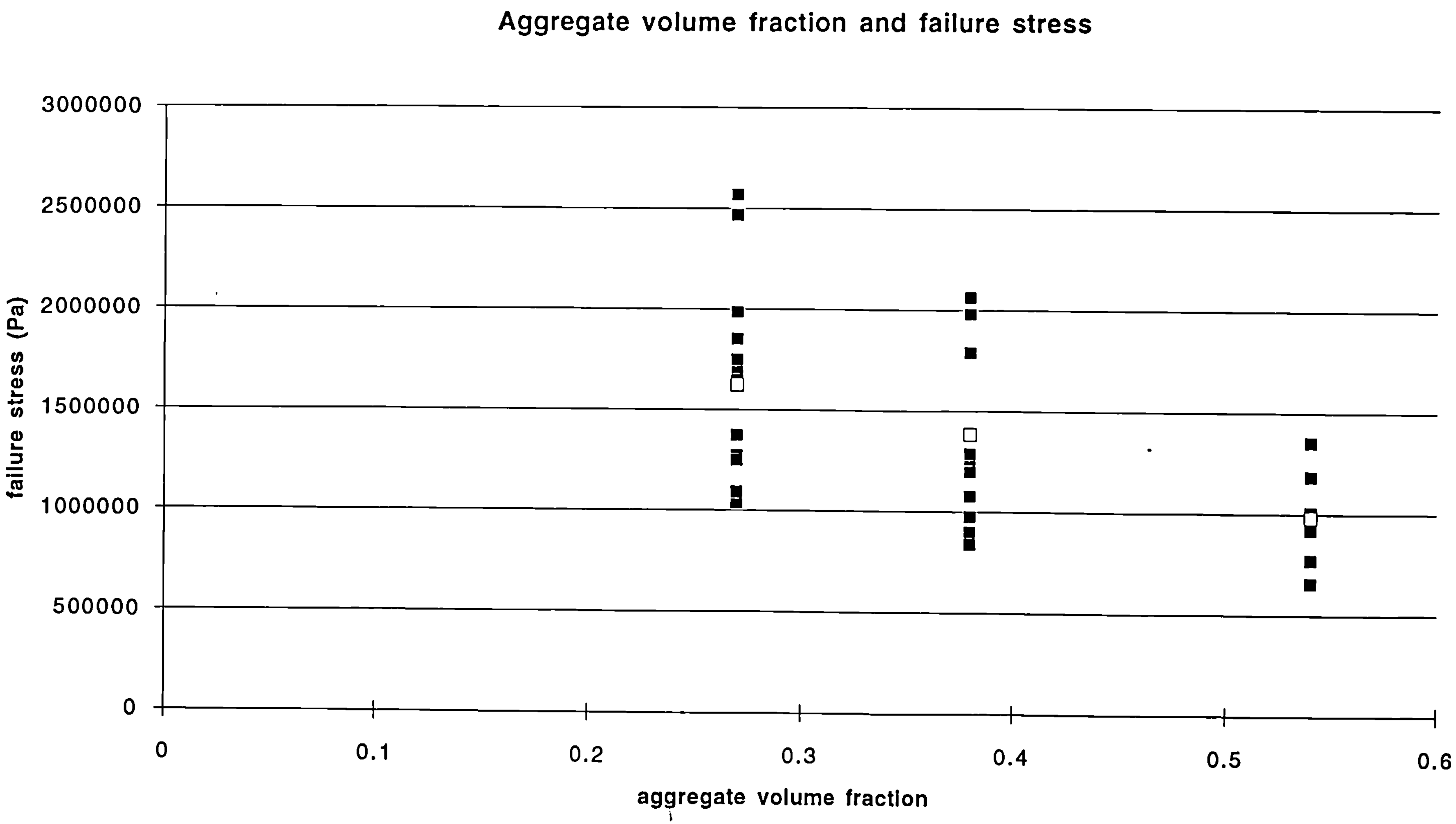

Aggregate volume fraction and failure stress
failure stress (Pa)
3000000
2500000
2000000
1500000
1000000
500000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
aggregate volume fraction

figure 6.29

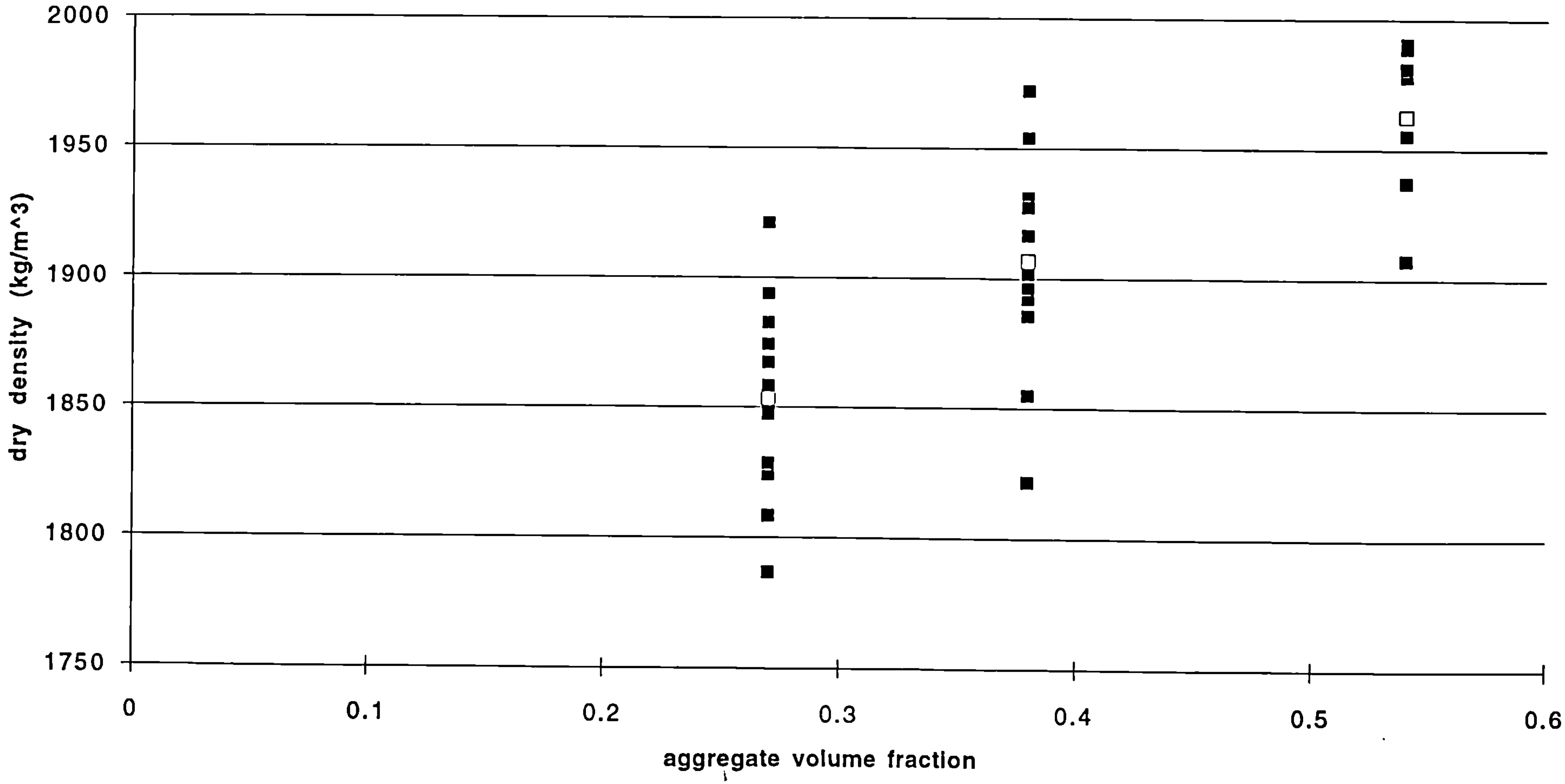

Aggregate volume fraction and dry density

figure 6.30

Drying progress of test series 4 and 5 cylinders

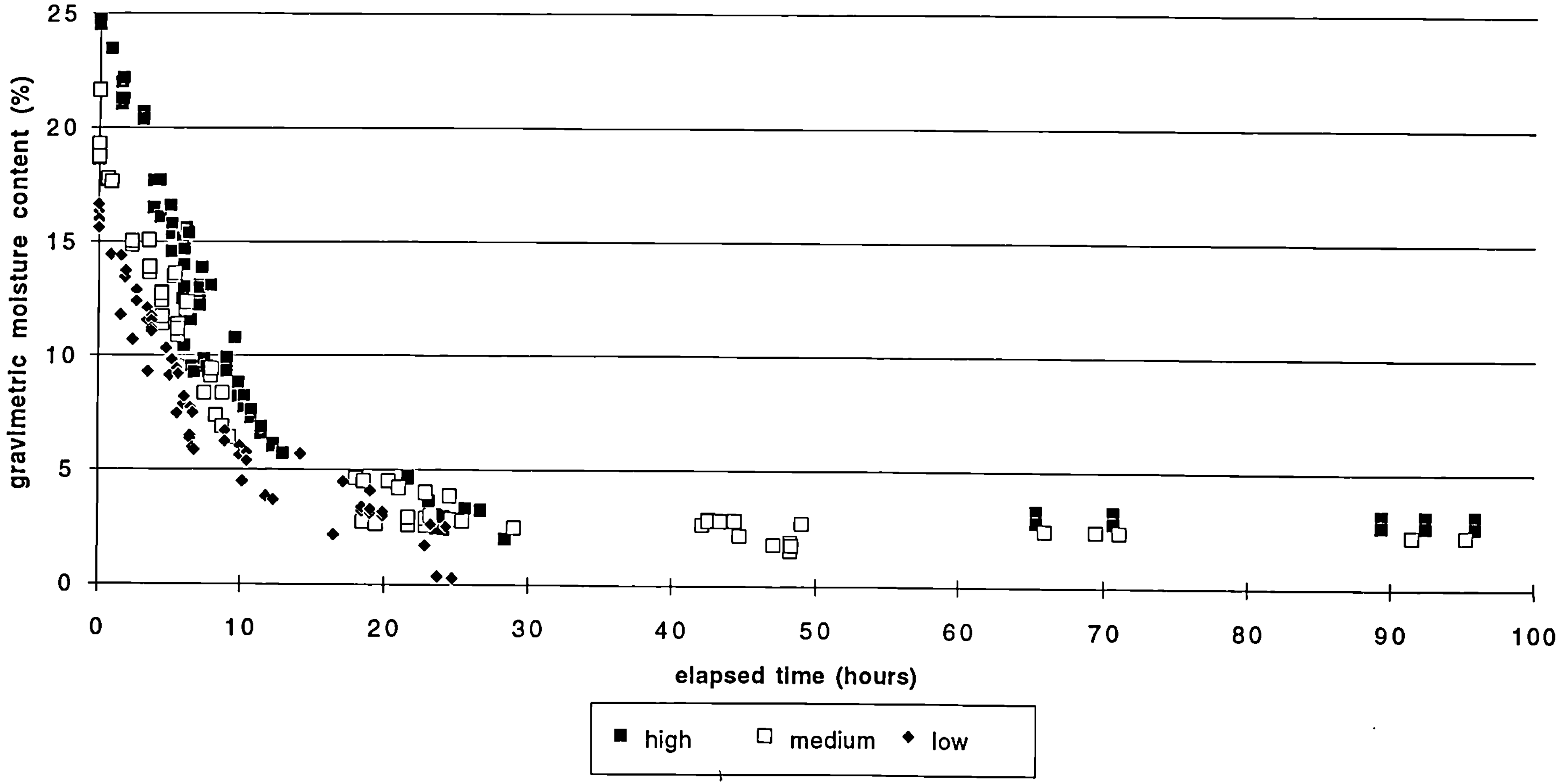


figure 6.31

Drying progress of test series 4 and 5 cylinders

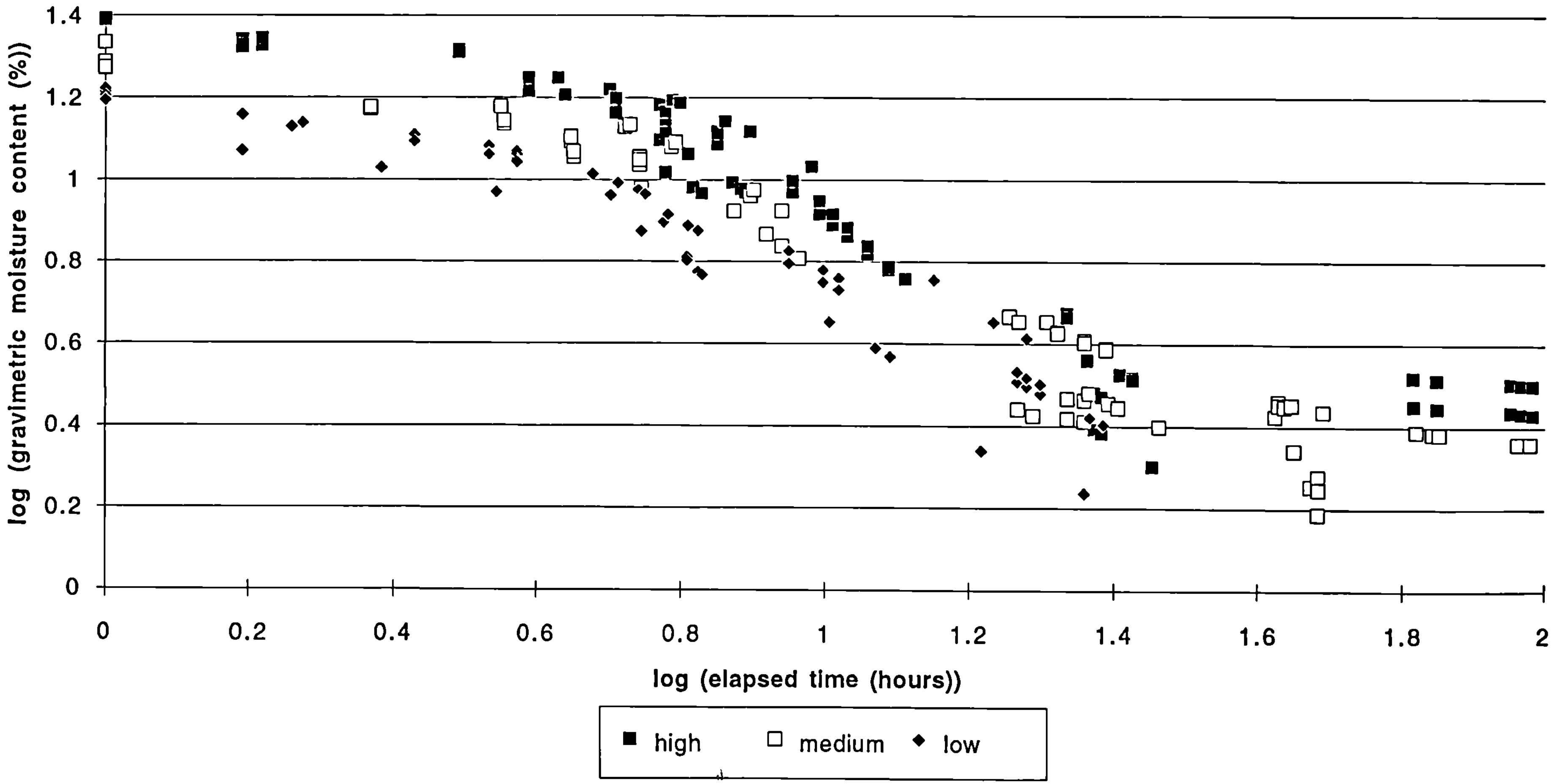


figure 6.32

Rate of drying of test series 4 and 5 cylinders

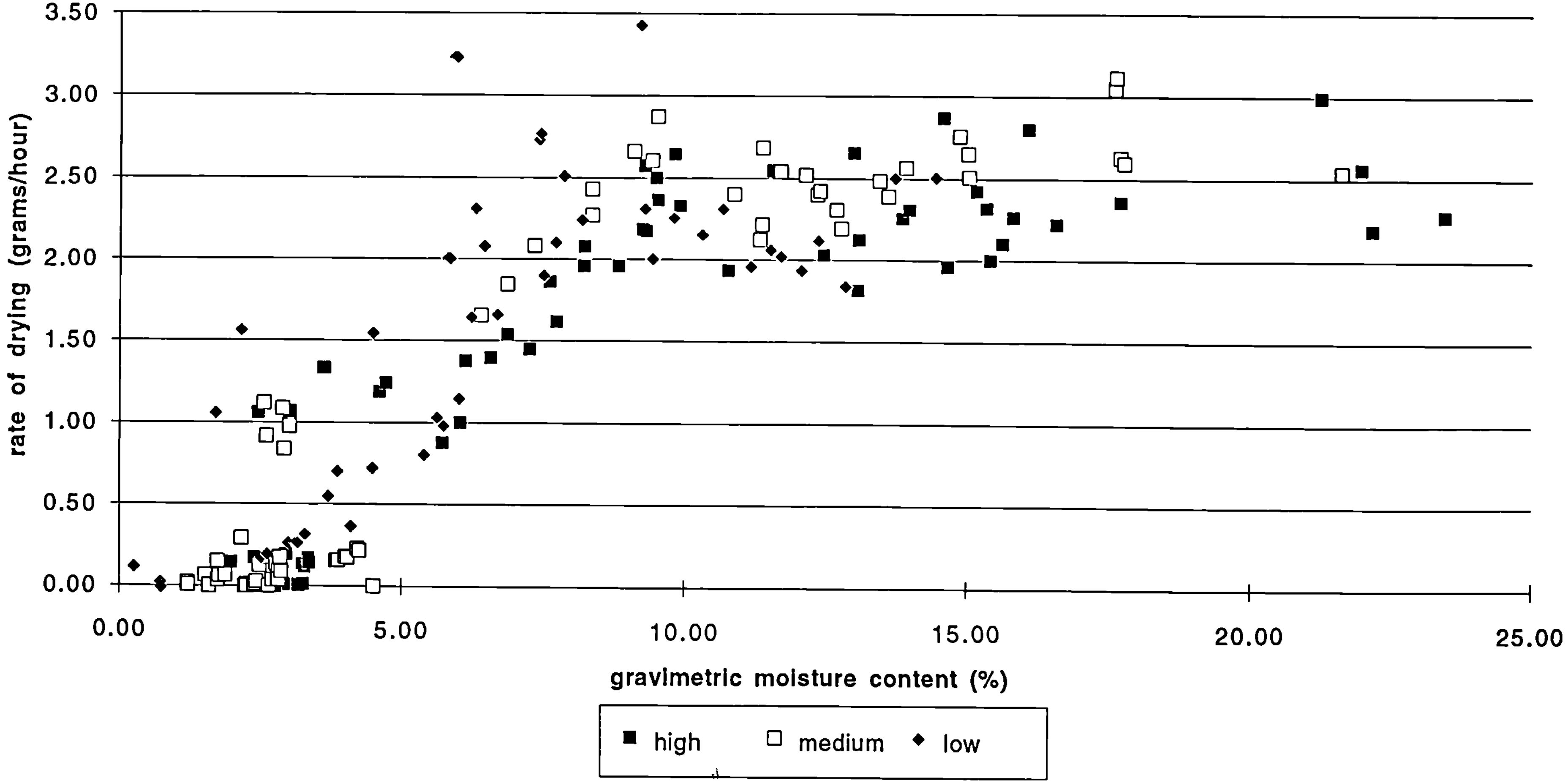


figure 6.33

Initial drying progress of 2nd and 3rd lifts: average TDR readings of both lifts at similar elapsed times from manufacture

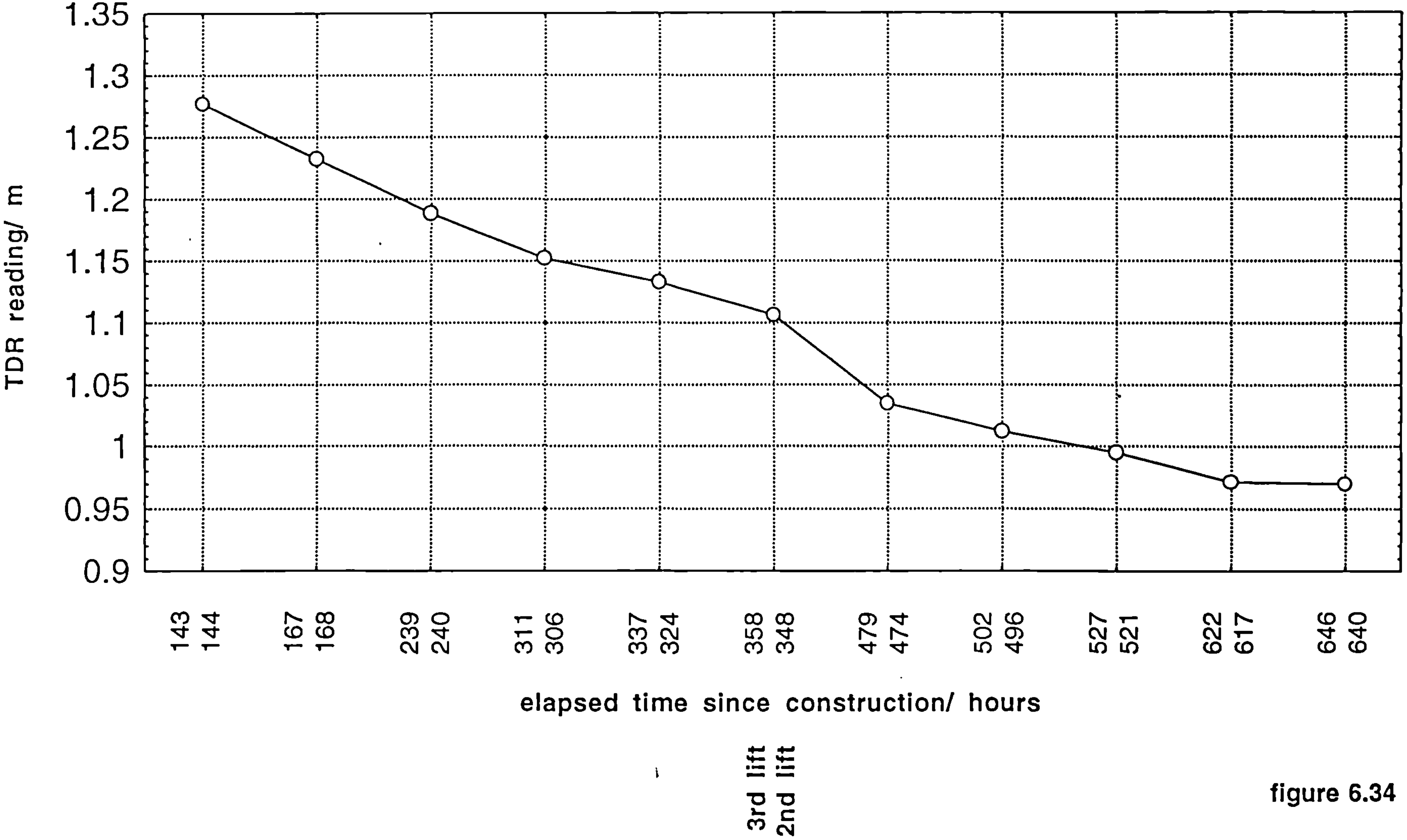


figure 6.34

Initial drying progress of 2nd and 3rd lifts: average TDR readings for each lift at similar elapsed times from manufacture

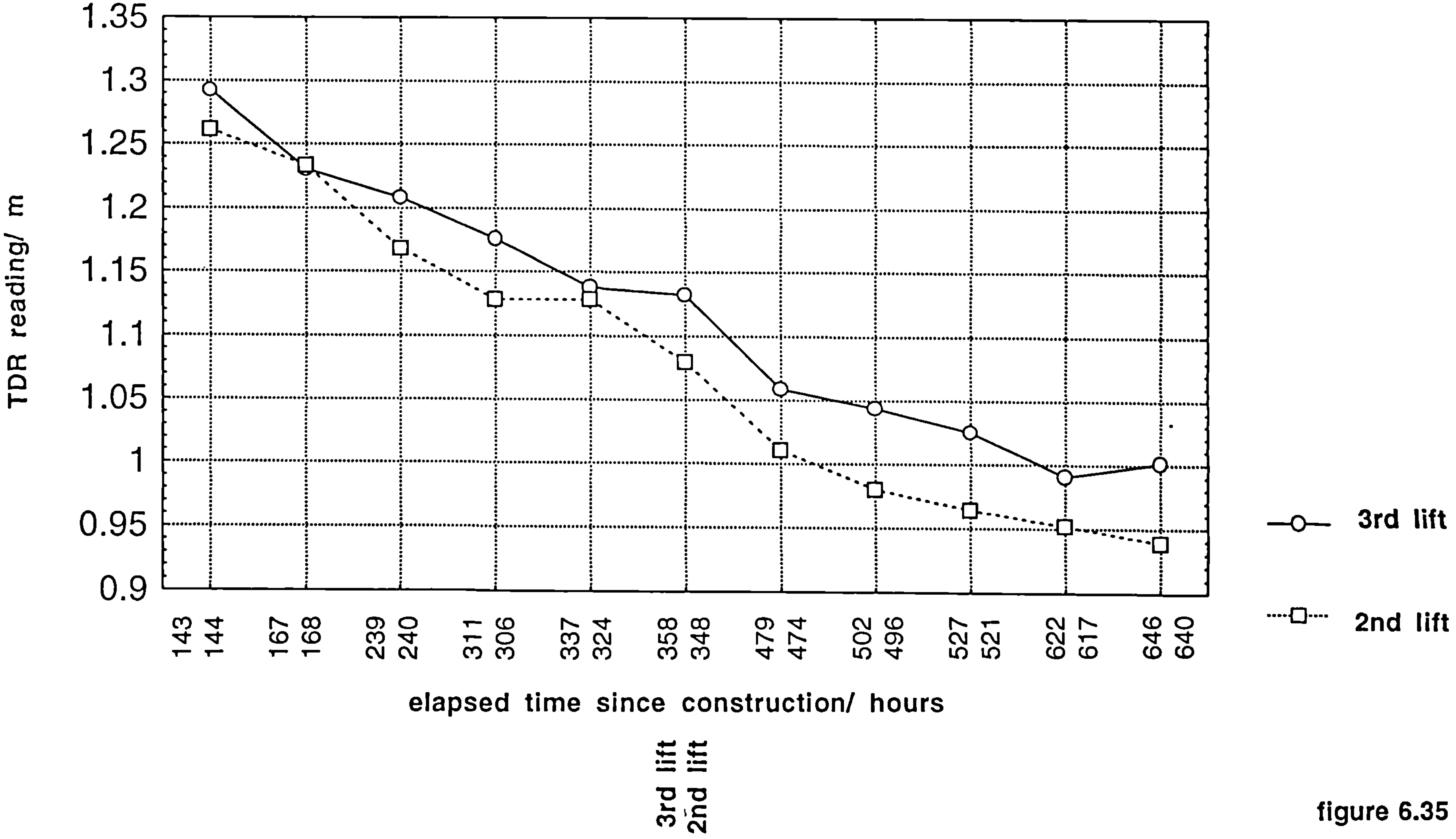


figure 6.35

Initial drying progress of 2nd and 3rd lifts: average TDR readings of vertically alinged probes of both lifts

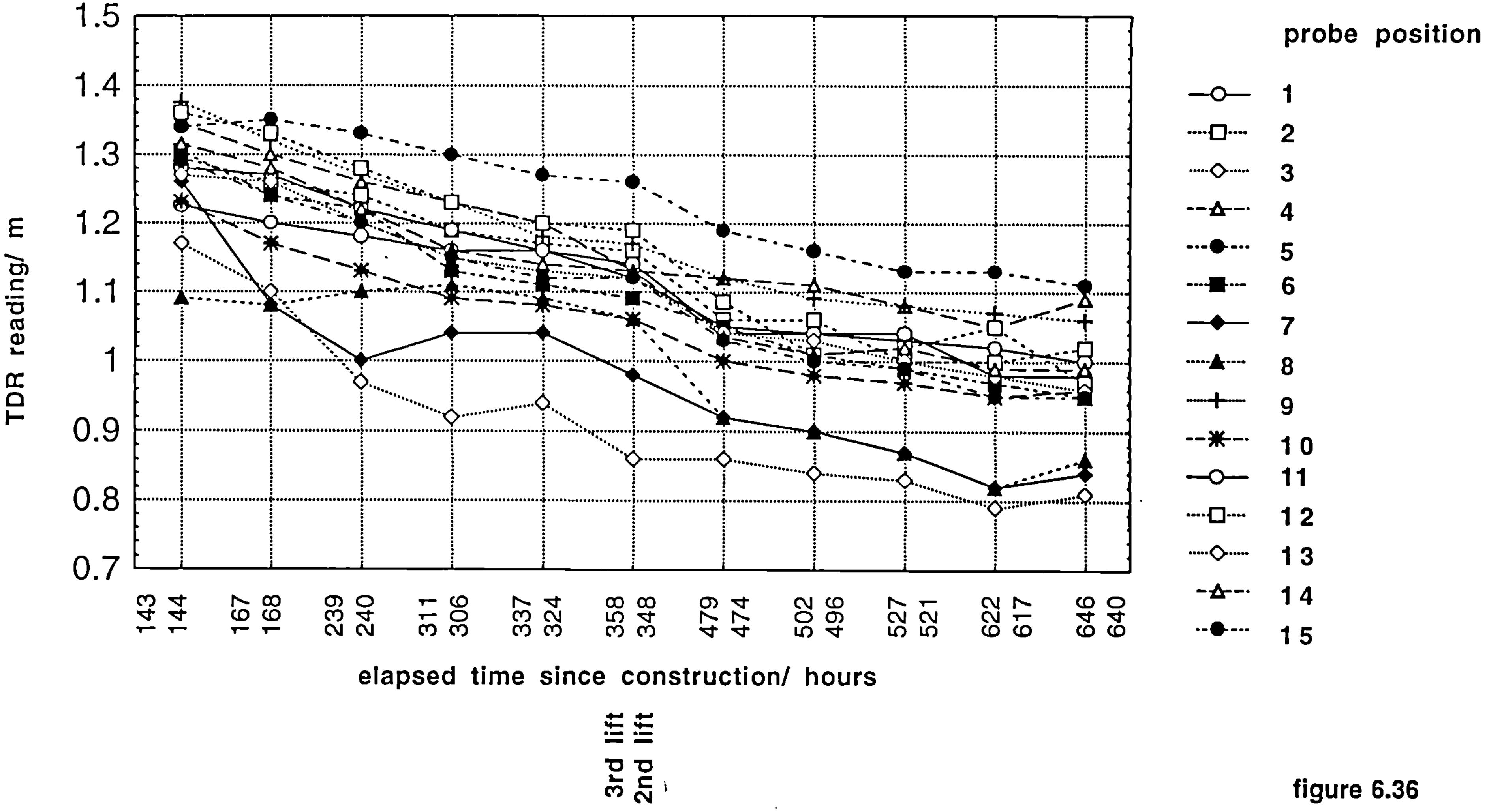
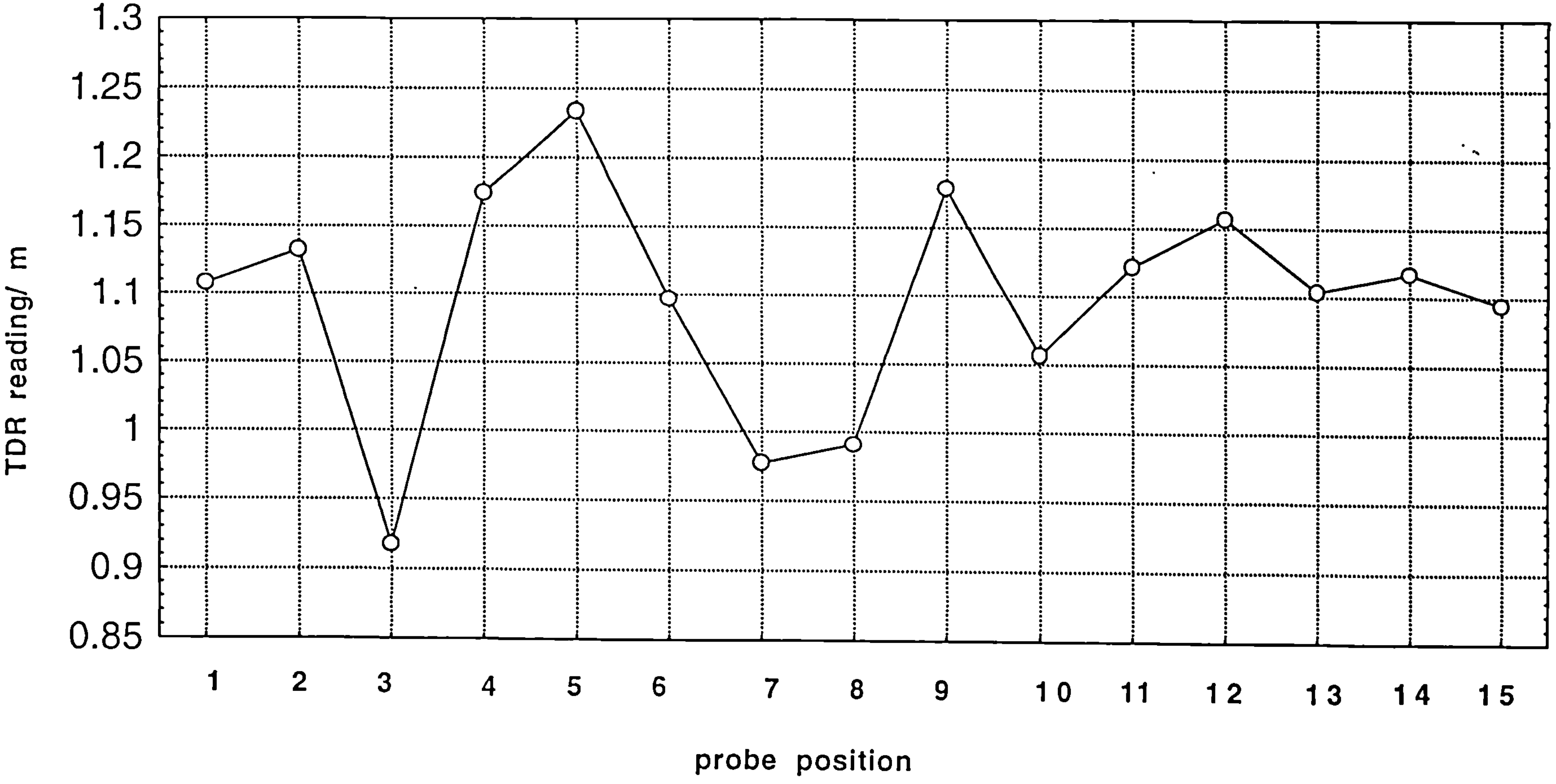
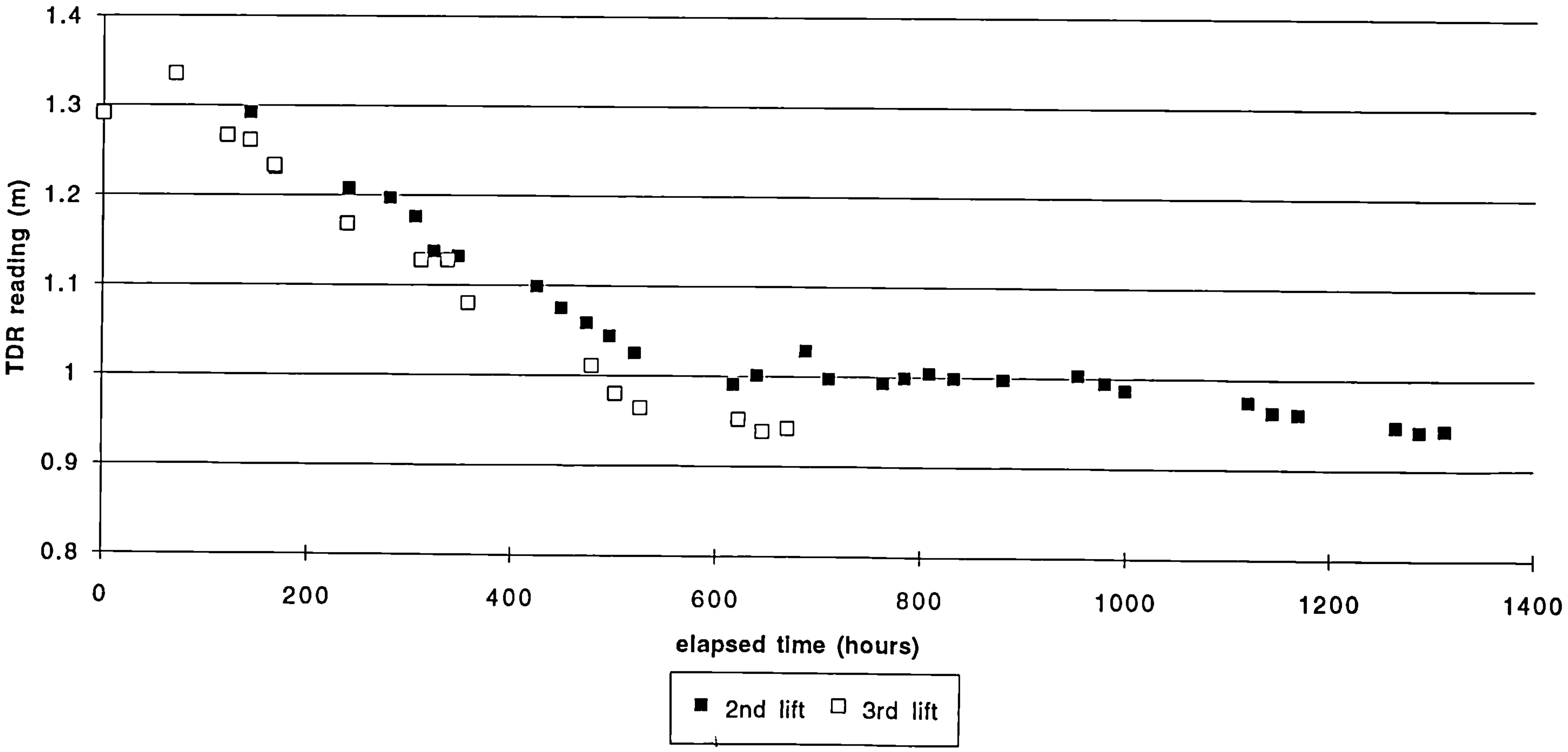


figure 6.36



Initial drying progress of 2nd and 3rd lifts: average TDR readings of vertically aligned probes for all comparable times

figure 6.37



Initial drying progress of 2nd and 3rd lifts: average lift TDR readings and time elapsec manufacture

figure 6.38

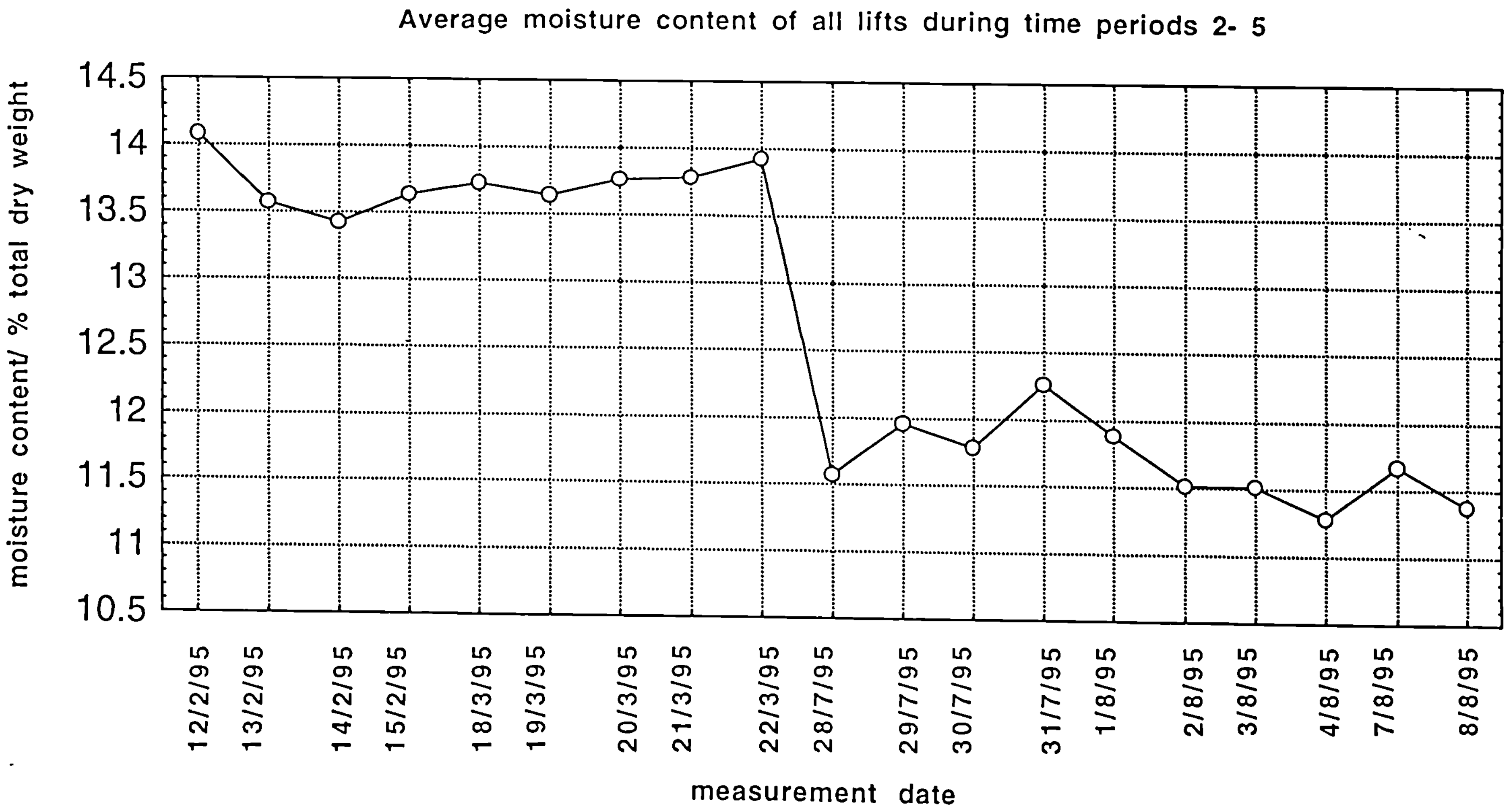

Average moisture content of all lifts during time periods 2- 5
moisture content/ % total dry weight
14.5
14
13.5
13
12.5
12
11.5
11
10.5
12/2/95
13/2/95
14/2/95
15/2/95
18/3/95
19/3/95
20/3/95
21/3/95
22/3/95
28/7/95
29/7/95
30/7/95
31/7/95
1/8/95
2/8/95
3/8/95
4/8/95
7/8/95
8/8/95
measurement date

figure 6.39

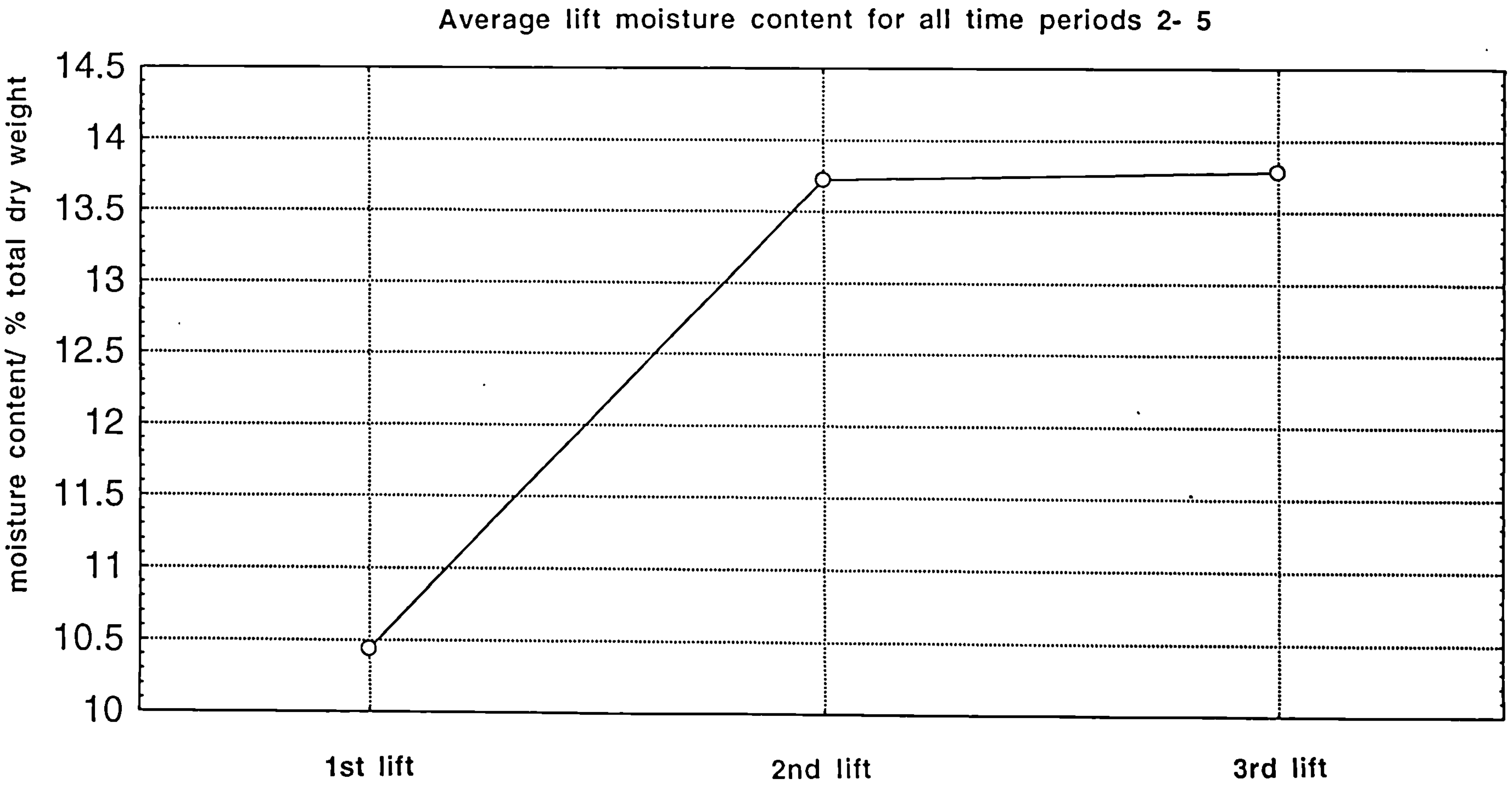

Average lift moisture content for all time periods 2- 5
moisture content/ % total dry weight
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
1st lift
2nd lift
3rd lift

figure 6.40

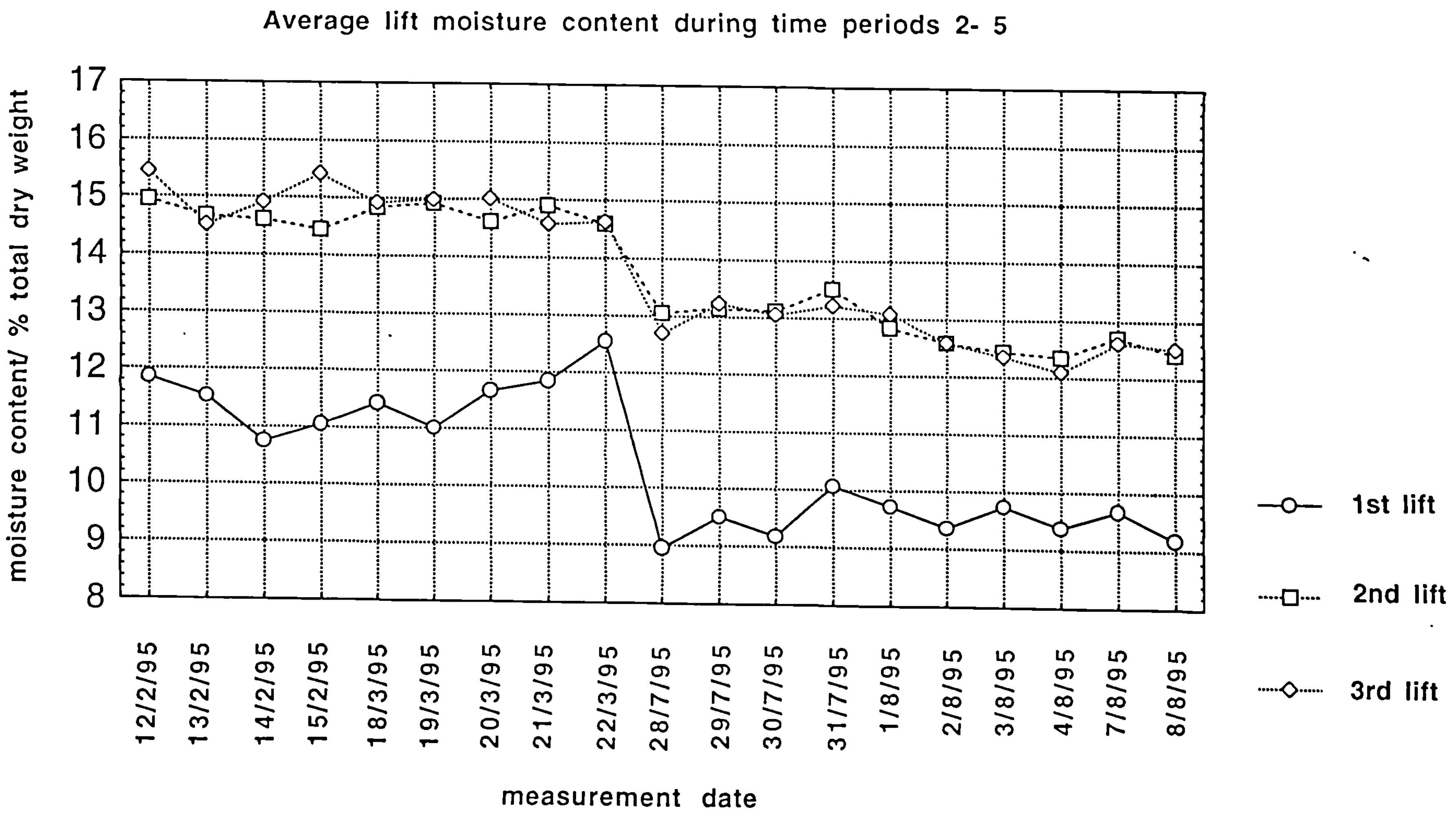

Average lift moisture content during time periods 2- 5
moisture content/ % total dry weight
17
16
15
14
13
12
11
10
9
8
12/2/95
13/2/95
14/2/95
15/2/95
18/3/95
19/3/95
20/3/95
21/3/95
22/3/95
28/7/95
29/7/95
30/7/95
31/7/95
1/8/95
2/8/95
3/8/95
4/8/95
7/8/95
8/8/95
measurement date
1st lift
2nd lift
3rd lift

figure 6.41

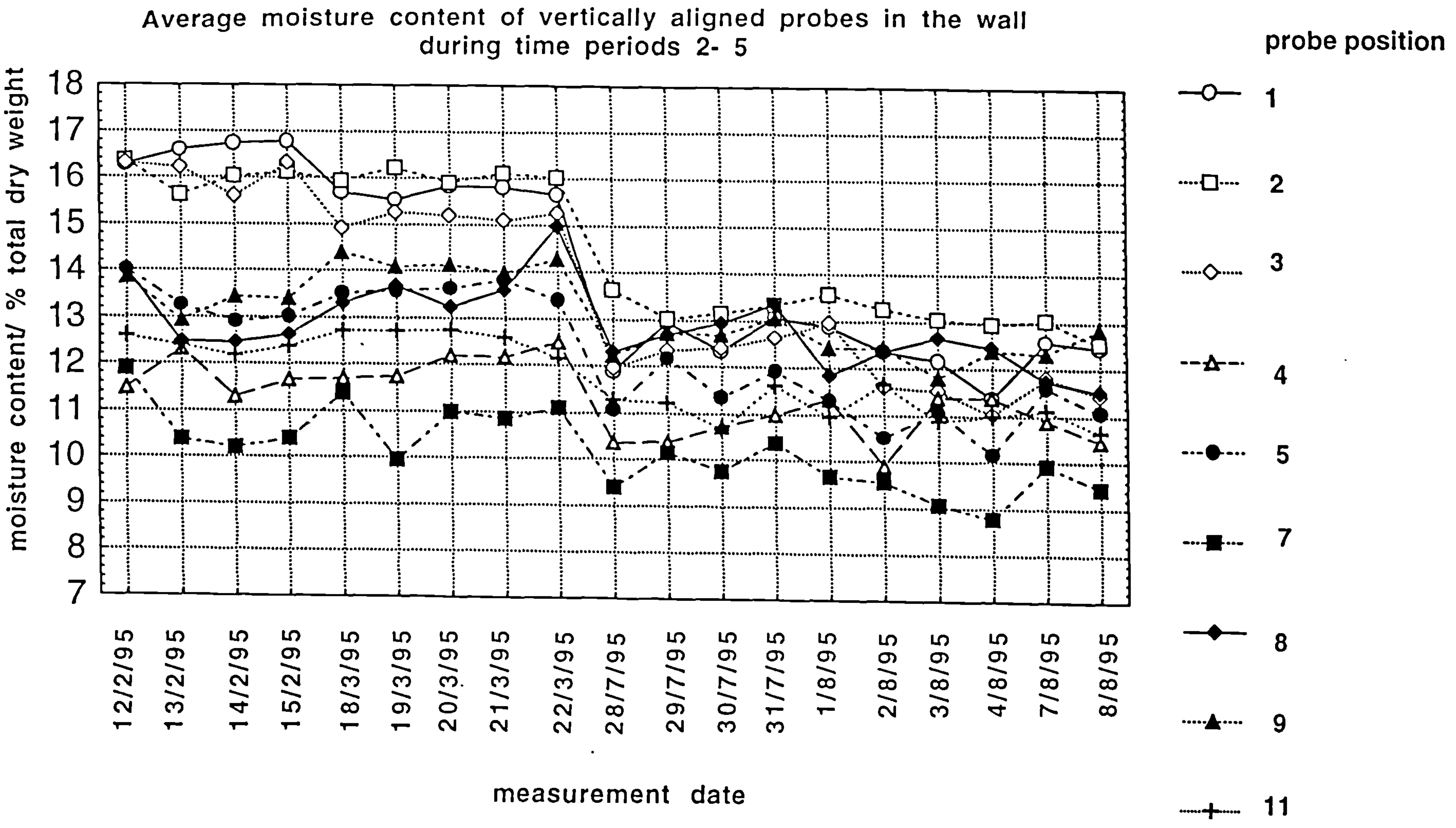

Average moisture content of vertically aligned probes in the wall
during time periods 2- 5
moisture content/ % total dry weight
18
17
16
15
14
13
12
11
10
9
8
7
12/2/95
13/2/95
14/2/95
15/2/95
18/3/95
19/3/95
20/3/95
21/3/95
22/3/95
28/7/95
29/7/95
30/7/95
31/7/95
1/8/95
2/8/95
3/8/95
4/8/95
7/8/95
8/8/95
measurement date
probe position
1
2
3
4
5
7
8
9
11

figure 6.42

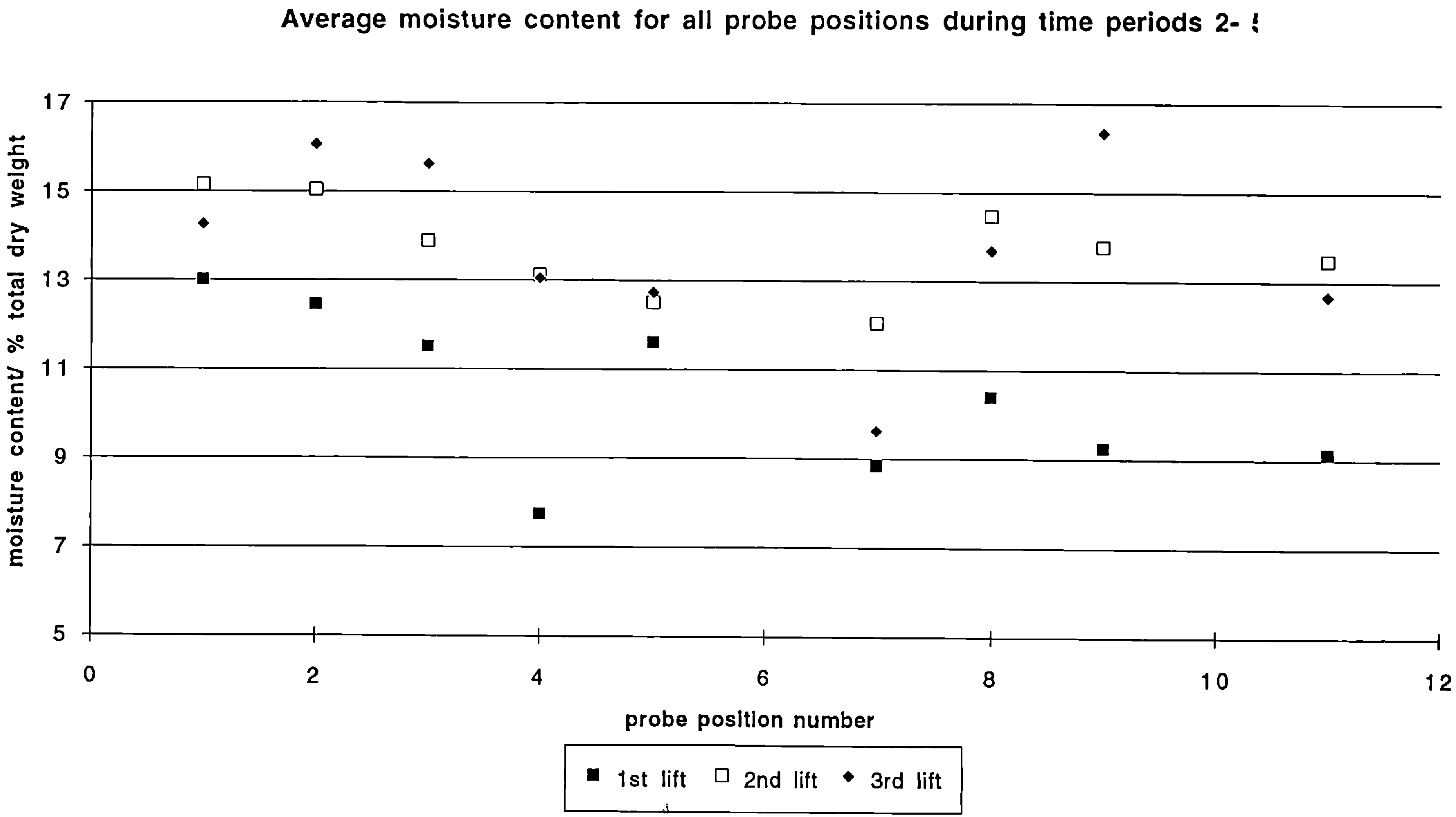

Average moisture content for all probe positions during time periods 2- !
moisture content/ % total dry weight
17
15
13
11
9
7
5
0
2
4
6
8
10
12
probe position number
■ 1st lift
□ 2nd lift
◆ 3rd lift

figure 6.43a

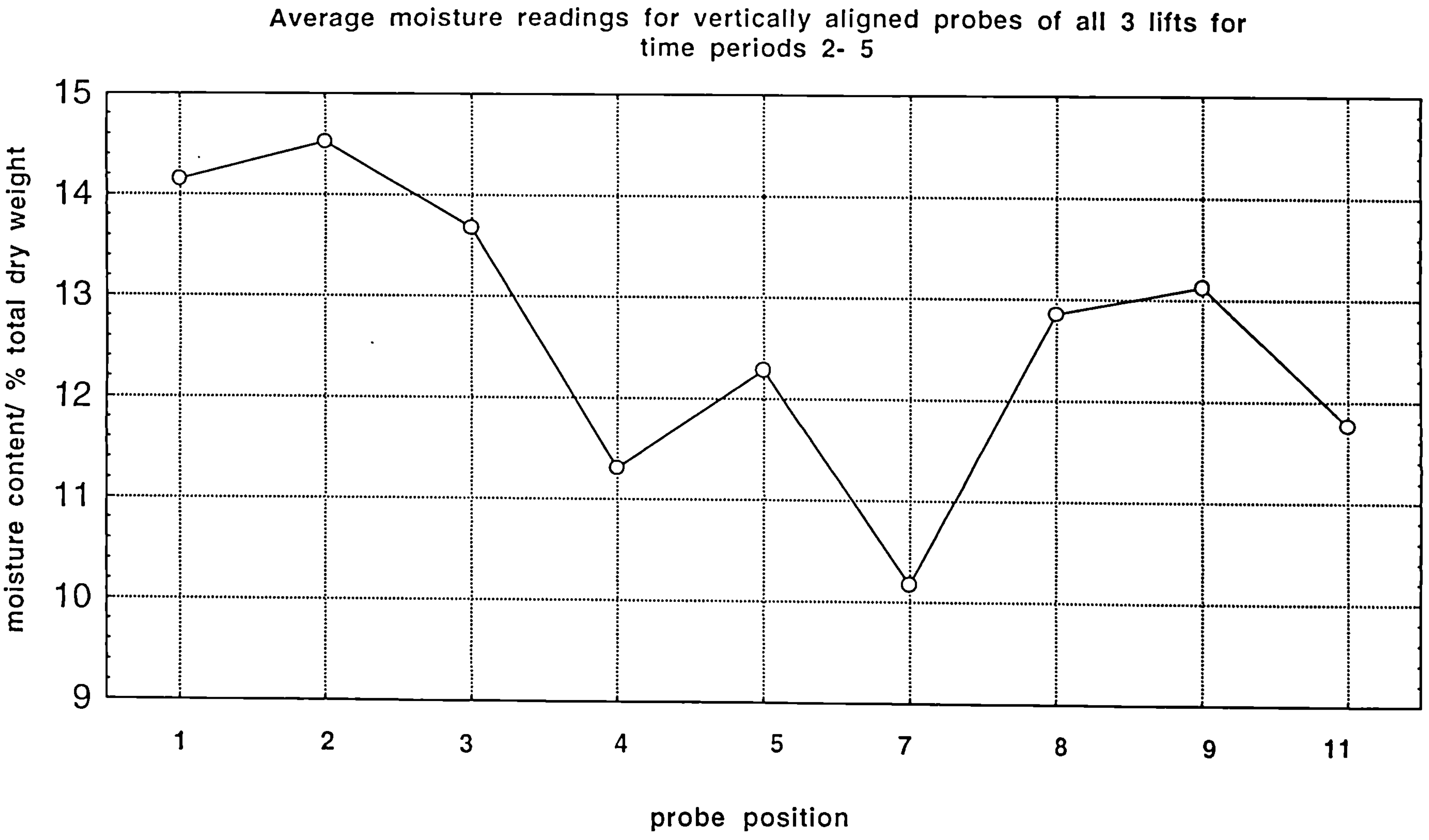

Average moisture readings for vertically aligned probes of all 3 lifts for time periods 2- 5
moisture content/ % total dry weight
15
14
13
12
11
10
9
1
2
3
4
5
7
8
9
11
probe position

figure 6.43b

Difference between average moisture content readings of individual probe positions during time periods 2- 3 and 4- 6.

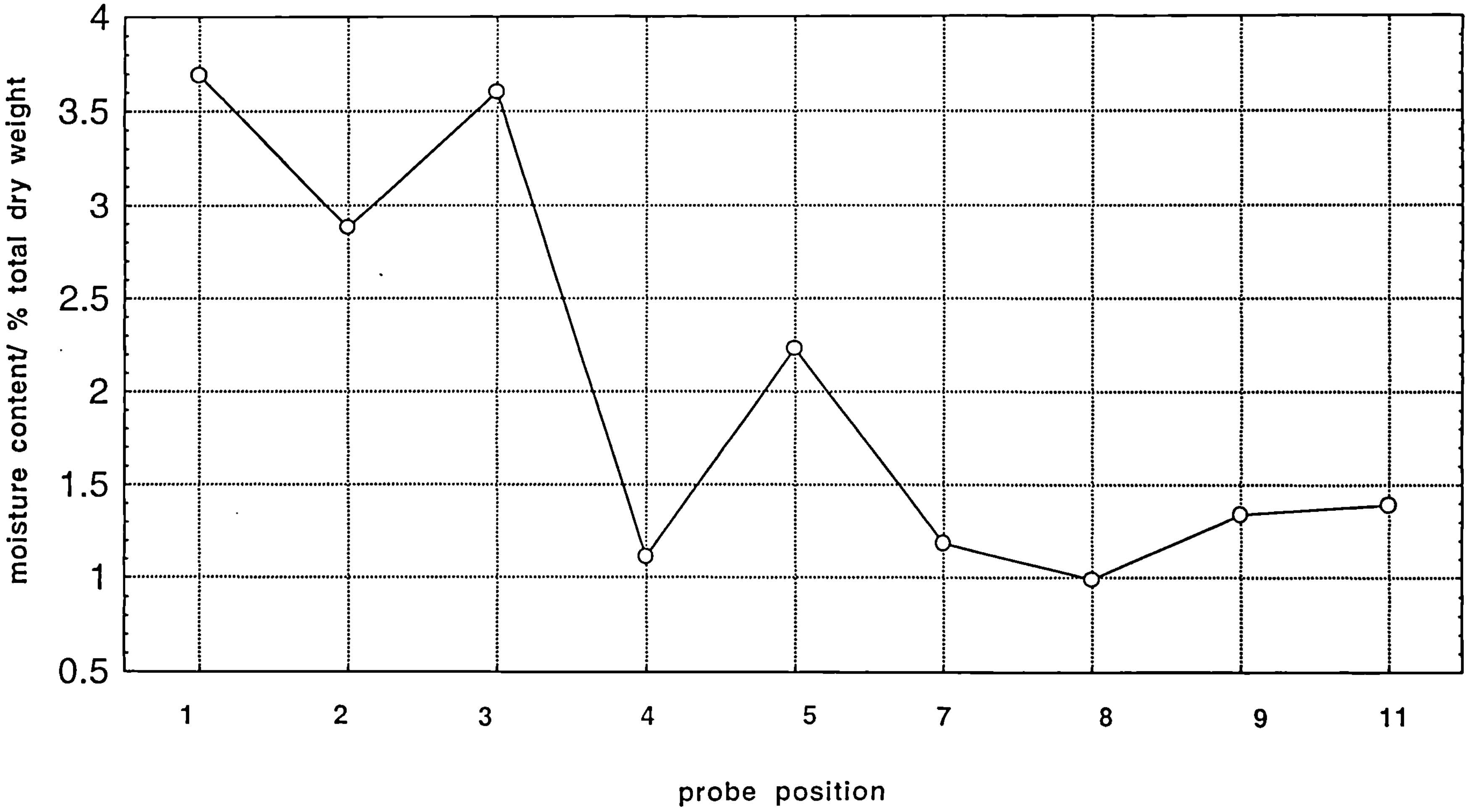


figure 6.44

Chapter 7: Discussion

This chapter will consider:

7.1) discussion of results of compression tests upon cob and cob matrix material

 7.1.1) the effect of moisture content on the failure mechanisms of cob matrix material

7.2) discussion of the drying process of cob and cob matrix material

 7.2.1) the drying process of cob and test series four and five results

 7.2.2) the moisture content history of the experimental cob wall

7.3) the statistical analysis of data and experimental design.

7.1) Discussion of results of compression tests upon cob and cob matrix material

7.1.1) The effect of moisture content on the failure mechanisms of cob matrix material

During this discussion of the results of the different test series the terms 'compression modulus', 'stress at ELR (stress at the 'end of linear stress/ strain response'), 'strain at ELR' (strain at the 'end of linear stress/ strain response'), 'failure stress' and 'failure strain' will be used. These terms are defined in chapter 4 section 4.1, and are shown on the typical stress/ strain graph in shown in figure 7.1. Figure 7.1 also illustrates the phases of the compression test discussed below.

Figure 7.2 illustrates the four failure mechanisms of cob and cob matrix material. The particular mechanism by which these materials fail is determined by the moisture content of their binder fraction at the time of testing. The transition between some failure mechanisms is gradual and it is possible for samples to fail due to combinations of these mechanisms.

The phases of compression testing of cob matrix material

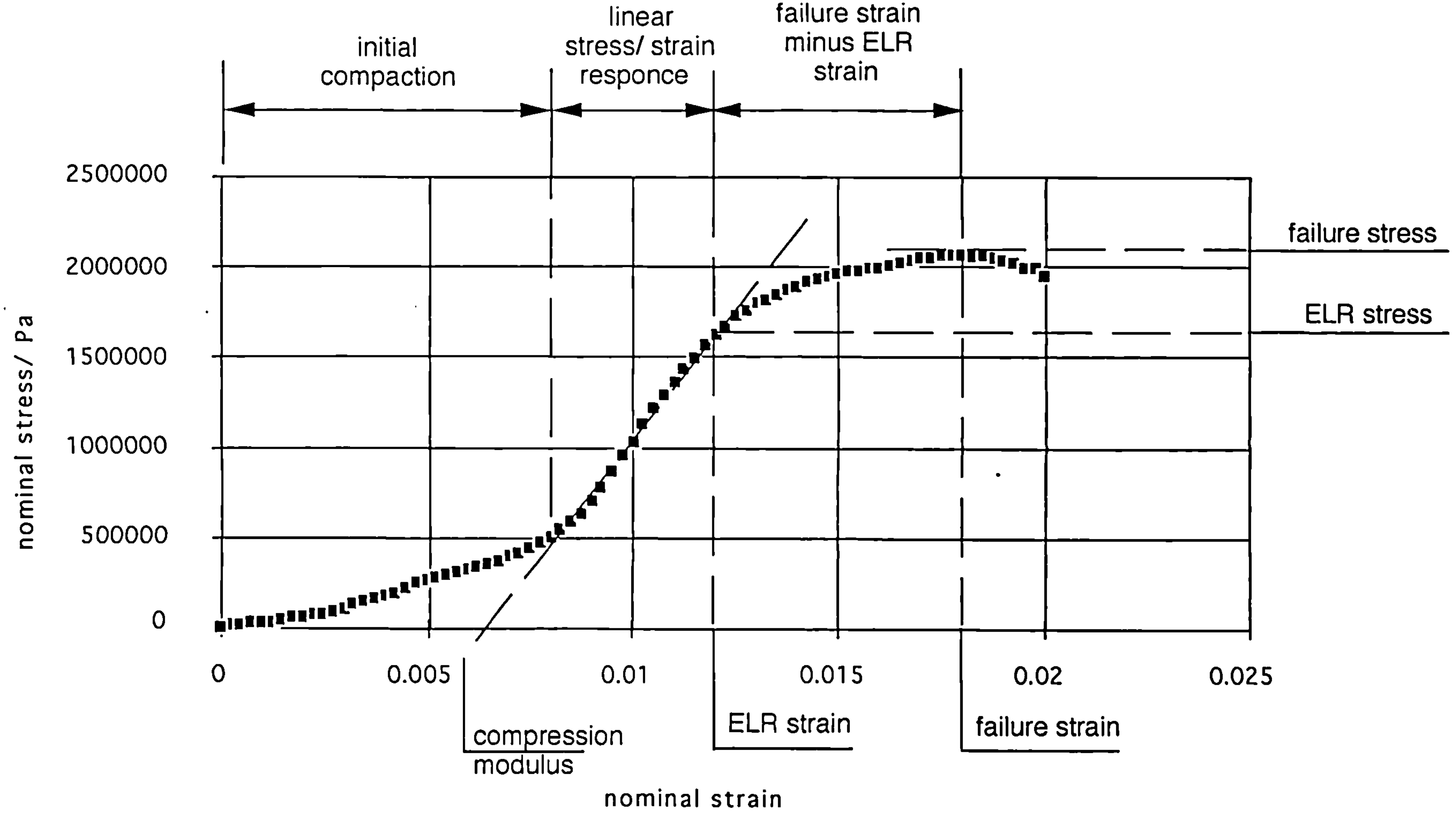


figure 7.1

The effect of moisture content on the failure mechanisms of cob matrix material

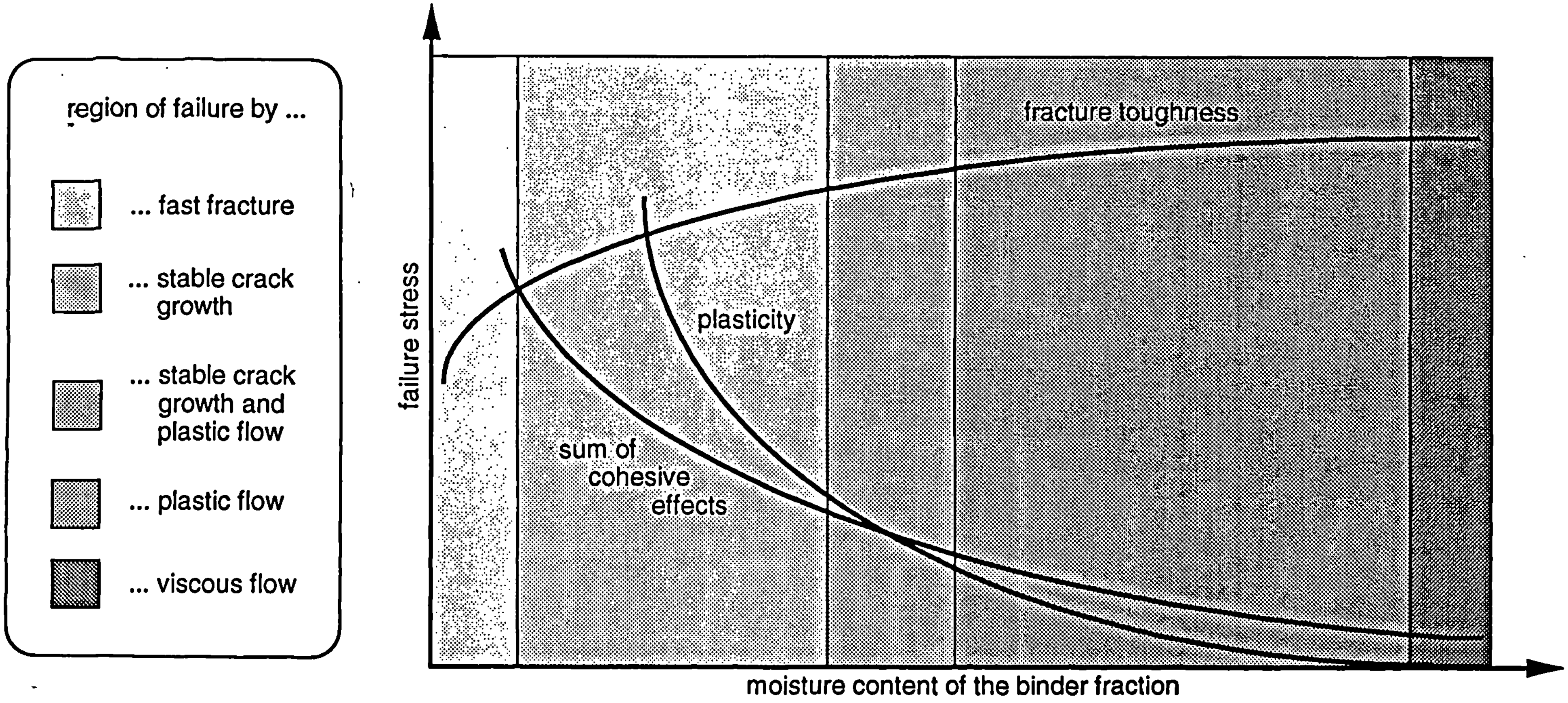


figure 7.2

The failure mechanisms of cob and cob matrix material are considered by discussing the behaviour during compression testing of 'low' and 'high' moisture content.

The stress/ strain graph of a 'low' moisture content sample in compression is described below in three phases. The mechanisms by which such a sample fails, by stable crack growth, or by a combination stable crack growth and plastic flow, is also discussed in three phases.

i) Initial compaction of the sample.
ii) A linear stress/ strain response of the sample to the continuing application of load.
iii) Increasing crack growth within the sample: both the initiation and propagation of new cracks, and the propagation of existing cracks. This phase of testing terminates with the 'failure stress' of the sample.

Initial compaction of the sample occurs during the first phase of loading. This compaction is due to the compression of weak volumes of material in the test sample (macro voids) and the compression of 'high points' on the faces of the test specimen. The sample is permanently compressed by this process.

During the initial phase of the compression test energy transferred to the sample by the test machine is being expended by the repacking of particles of the sample. Therefore the gradient of the stress/ strain graph is low relative to the maximum value that this gradient will attain once the initial compaction of the sample is complete.

The rate of initial compaction of the sample gradually diminishes. As it does so the gradient of the stress/strain graph increases to the maximum value it will achieve during the test. The maximum gradient is typically maintained for a significant portion of the test resulting in a marked linear stress/ strain response. It is from the gradient of this linear response that the compression modulus of the sample is calculated. In this phase of the test the bonds within the material, due to real and apparent cohesion, are under increasing stress, but the majority of them are not failing. Some bonds will fail, initiating cracks, but at this stage of the test there is not enough energy, due to the applied load, to cause them to propagate sufficiently to cause the gradient of the stress/ strain graph to decrease. The majority of energy transferred to the sample by the test machine is being stored in the deformation of the bonds within the binder fraction of the sample. The deformation of the sample over this linear phase is assumed to be elastic: that is the deformation of the sample incurred in this second phase of the test would be recovered if the load was removed from the sample.

At the end of the linear stress/ strain response a significant proportion of bonds within the material are failing. New cracks are initiated and existing cracks begin to propagate. This cracking within the material causes the gradient of the stress/ strain response of the sample to decrease from the maximum value attained in the linear stress strain response phase. As the compression of the sample progresses, less additional energy is necessary to break the increasingly stressed bonds within the material. Energy is dissipated within the sample by the propagation of cracks. From experimental observation it is apparent that the rate of decrease of the stress/ strain gradient increases in proportion to the amount of cracking within the test sample.

The phase of increasing crack growth within the sample terminates with the maximum stress ('failure stress') achieved by the sample. At this point in the test crack linkage has separated the sample into discrete pieces. Deformation of the sample can now occur by movement of these segments along 'failure planes'.

From this description of the stress/ strain relationship in compression of samples of 'low' moisture content cob and cob matrix material, it is apparent that the failure stress and stress at ELR are closely related because the ELR defines the point at which the material is susceptible to failure. This is illustrated in the plots of the failure stress and stress at ELR of the experimental samples in figures 6.12 and 6.20.

The failure stress is a function of the amount of binder fraction that has to be cracked to reach a state of crack linkage. This is apparent from the significant correlation between mix type and failure stress (figure 6.29).

The rapidity with which the state of crack linkage of the binder fraction of a sample is reached depends upon the number of cracks and nucleation sites for cracks in the material: this is dependent upon the degree of strain magnification, and the toughness of the binder fraction. Both of these properties are influenced by the moisture content of the binder fraction.

The properties of the binder fraction at 'low' moisture contents are such that samples of cob and cob matrix material fail by stable crack growth. A sample of cob or cob matrix material which is tested at a low moisture will achieve a maximum stress, at which the sample is considered to have failed. However, a sample which is tested with a 'high' moisture content will not achieve a maximum stress value: instead the stress/ strain response will be linear, but not elastic, with a very low gradient indicating a very low resistance to deformation. For such samples of cob and cob matrix material failure is entirely by plastic flow. This occurs because the energy necessary to overcome the real and apparent cohesion within such wet material is very low.

In such cases another definition of the failure of the material must be applied. Robert Saxton at the University of Plymouth has suggested arbitrarily defining the failure of wet cob as a deformation of 10% of the original sample length (10% strain)[1] . This definition is based upon the compression properties required of cob for efficient construction. Saxton is suggesting that cob at a moisture content such that the material exhibits 10% strain will inhibit construction: too much material will be forced to 'flow' horizontally such that it overhangs the plinth on which the wall is being constructed. Such material will have to be removed during the 'parring down' process (chapter 3, section 3.7).

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[1] presentation made at a 'Cob Awareness Seminar' organised by the University of Plymouth Centre for Earthen Architecture, Exeter, September, 1993.

Until this point two distinct failure modes have been discussed (figure 7.2):

i) failure by plastic flow exhibited by 'high' moisture content samples with no elasticity but the ability to (nominally) continuously deform plastically causing; and

ii) failure by stable crack growth exhibited by 'low' moisture content samples with no plasticity but the property of elasticity.

Because the moisture content of the test samples is not uniformly distributed through out their volume, the transition between the regions of failure by plastic flow and stable crack growth does not occur suddenly at a particular moisture content. Instead the degree of plasticity of the sample gradually increases. Between the non plastic state and the state of unlimited plasticity the material will posses limited plasticity. The property of limited plasticity allows particles to move over one another until they form assemblages with a degree of cohesion which is too great to be deformed plastically: failure of such assemblages then occurs by the propagation of cracks through them.

Therefore samples tested at intermediate moisture contents, between the high and low moisture contents discussed previously, will exhibit both plastic flow and stable cracking failure mechanisms (figure 7.2). The degree to which each of these mechanisms is responsible for the failure of the samples is determined by the moisture content of the binder fraction of the sample under test. When a sample of intermediate moisture content is compressed it follows the three phases of behaviour described in the discussion of testing of low moisture content samples. However, the initial compaction of the sample is augmented by limited plastic flow. Such a sample will not achieve as great a compression modulus or point of ELR as a similar sample tested at a lower moisture content. Plasticity is not the only property of the binder fraction to decrease with decreasing moisture content: the 'toughness' of the binder fraction does too. The decrease in this property could, in theory, cause the failure of a sample by 'fast fracture'. This is discussed below.

'Toughness' is a measure of the energy absorbed in the creation of new surface area as a crack propagates through a material. The propagation of a crack through stressed material also relieves stress in the material, releasing energy as it does so. 'Fast fracture' will occur if the energy absorbed in the creation of new surface area is less then the energy released by the relaxation of the material through which the crack is propagating (Ashby & Jones 1980, pg. 121 et seq.). The occurrence of failure by fast fracture is therefore dependent upon the toughness of binder fraction, and the amount of energy stored in the sample due to its deformation. The magnitude of stored energy in a test sample due to elastic deformation is proportional to the point of ELR of the material in compression, the toughness of the binder fraction is determined by its moisture content.

When the moisture content of the binder fraction is low, it has low toughness and 'brittle' fracture properties: that is the material does not deform greatly before the bonds within it are broken. This behaviour is responsible for the low strain to failure achieved by samples with a low moisture content. The toughness of the binder fraction increases with increasing moisture content and it changes from exhibiting brittle fracture properties to possessing 'ductile' fracture properties. Ductile fracture, unlike brittle fracture, is associated with deformation of the material before the bonds within it are broken. Ductile fracture behaviour and the property of plasticity are responsible for the large strain to failure achieved by samples with a high moisture content. This change in properties is important because the ductile fracture process absorbs more energy then a brittle fracture process. The practical significance of the change in fracture properties of the binder fraction with moisture content is that the energy required to propagate cracks through wet binder fraction is greater then that required to propagate cracks through dry binder fraction. Therefore, although the compression modulus and stress at ELR of a sample will increase with decreasing moisture content, less energy is required to produce a state of crack linkage once the point of ELR has been reached.

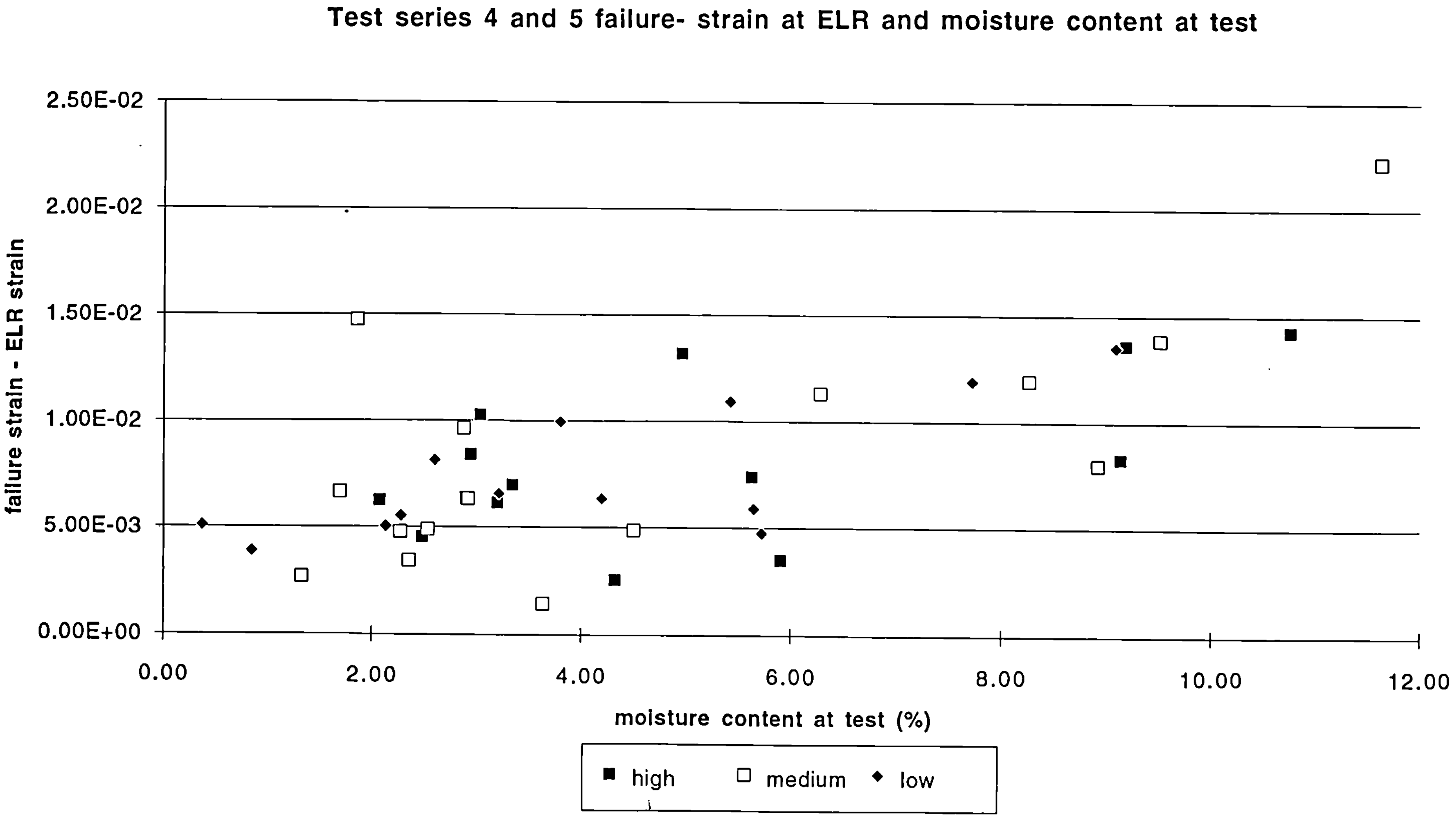
Figure 7.3 is a plot of the failure strain minus the strain at ELR against the moisture content at test of the sample. This figure illustrates the diminishing amount of energy necessary to cause crack linkage at the point of ELR with decreasing moisture content. The logical extension of this trend is the point where no additional energy is needed, beyond the point of ELR, to reach a state of crack linkage: the energy to continue crack propagation is supplied by the relive of stressed material by the cracking process. Failure would then be by 'fast fracture'. Although none of the samples tested failed by fast fracture this mechanism has been included in figure 7.2 to show the limit of the trend which the samples exhibited.

Increasing the moisture content of the binder fraction has two important effects: it reduces the internal friction of the binder fraction; and it decreases the degree of real cohesion within the material. The reduction of real cohesion dictates that, although crack propagation in the binder fraction becomes increasingly more costly in energy terms with increasing moisture content, the cracking process can occur at a lower stress. Further more, as the moisture content of the binder fraction increases, the failure mechanism will change from the propagation and linkage of cracks to one of plastic flow and, at even higher moisture contents, to viscous flow. The change from failure by stable crack propagation to failure by fast fracture, if a sample could be dry enough for this to occur, would be abrupt. The change from failure by stable crack propagation to failure by plastic flow, will occur as a gradual transition with some samples exhibiting both forms of failure. The moisture content at which the failure mechanism of the cob matrix material changes is determined by the following.

a) The proportion of binder and aggregate fractions in the material. This determines:

i) the surface area of the material to be lubricated by the moisture content to achieve a plastic state; and

ii) the magnitude of real cohesion which must be eroded to reach a viscous state.



Test series 4 and 5 failure- strain at ELR and moisture content at test

figure 7.3

b) The mineralogical nature of clay in binder fraction. This will determine the proportions of adsorbed and free water in the material. Since free water is a more effective lubricant than adsorbed water, because it is less viscous, the proportion of adsorbed to free water will determine the efficiency of the moisture content as a lubricant.

An indication that the range of moisture content over which plasticity occurs is dependent upon the surface area of the mix, is illustrated by the moisture contents at which the samples of test series 4 and 5 were manufactured. The target moisture contents for the production of these samples was established experimentally, as described in chapter 5. These moisture contents differed between mix types so as to achieve a similar consistency of the samples during manufacture. It has been found that the amount of water added to achieve the same consistency varied approximately in proportion to the calculated surface area of each mix. This is shown below in table 7.1.

mix type	target moisture content (%)	total particle surface area (m^2)	water added/ total particle surface area (%/ m^2)
high	26	6.76	3.85
medium	20	6.12	3.27
low	17	4.53	3.75

table 7.1
Variation of moisture content at production with calculated mix surface area.
(Note: total particle surface area is given for an average weight cylinder in square meters)

In chapter 6 the stress/ strain relationship of test series 4 and 5 samples was discussed. The form of these graphs illustrated four distinct types of behaviour. These were:

i) samples showing a 'drop' in the rate of increase of stress with strain before the failure stress was achieved (figure 6.23);
ii) samples showing a marked change in compression modulus during the test (figure 6.24);
iii) samples displaying the behaviour in both (i) and (ii) (figure 6.25); and
iv) samples displaying none of the behaviour in (i) to (iii) (figure 6.26).

The behaviour described by the categories (i), (ii) and (iii) above is caused by the failure of weak regions in the material before failure of the remainder of the sample. Regions of weak material within test samples are caused by strain magnification resulting from the presence of macro voids and/ or an unfavourable, for the achievement of a high failure stress, distribution of binder and aggregate particles. The distribution of weak material in the sample determines which type of behaviour the sample will exhibit. The failure of a highly localised region of weak material within otherwise strong material will cause a drop in the rate of increase of stress with strain (behaviour (i)). The failure of more evenly distributed weak material will result in samples showing a marked change in rigidity during the test (behaviour (ii)). It is possible for a sample to contain weak material distributed in both these forms: when this is the case samples display both types of behaviour described in (i) and (ii). These premature failures did not initiate the failure of the entire specimen, because stronger material was able to resist the compression force applied by the test machine once the weak region had failed. The stress/ strain relationship of a sample containing a weak region is affected by: the uniformity of properties within the weak region and in remainder of sample; and the difference in strength between the weak region and the remainder of the sample.

The stress/ strain relationship of samples containing fibre, those in test series 1 and 2, did not display a sudden drop in the rate of increase in stress with strain before the failure stress was achieved; a marked increase in compression modulus; or combinations of these behaviours. This is because the fibre content of cob restricts relative movement of the material within the sample. In this way failure of a weak region in the material is prevented and the distribution of stress throughout the material is more uniform. As discussed previously, fibre content also contributes to crack stopping in the material.

From the above discussion it might be thought that the moisture content of material at the extreme 'wet end' of the region of failure by stable crack growth would be defined by the plastic limit introduced in chapter 5. This is not the case because the plastic 'limit' is not the moisture content of the material at which plastic flow is impossible. From the description of the plastic limit test given in chapter 5 it is apparent that this test measures the moisture content at which the material can just under go a particular degree of plastic deformation without cracking: that is enough plastic flow to reduce the diameter of the cylinder of material from 6 mm to 3 mm by the rolling process. The transition from the region of failure by plastic flow to that of failure by stable cracking of cob and cob matrix samples occurs when even such limited plastic deformation is impossible. The moisture content at the plastic limit (table 6.3) is therefore higher than the moisture content of material at the transition between the regions of failure by plastic deformation and stable cracking. The relevance of the plastic limit to identifying the change in failure modes is further diminished because the plastic limit is found using only the fines material of a soil. The fines material will have a greater surface area per unit weight than the material from which it has been removed. The plastic limit of the fines material, therefore, is not representative of the plastic limit of the material from which the fines has been removed.

An indication of the range of moisture content of the different failure regions can be determined by examining the scatter in the data of test series 4 and 5. This is due to the varying degrees to which the different failure modes are affected by the particular arrangement of particles in an individual sample.

Within the region of failure by plastic flow the property dominating the failure is plasticity. The plasticity of the test series 4 and 5 samples was determined by the moisture content and surface area of the material: it is therefore independent of the distribution of particles within a particular sample. However, in the transition region between the failure mechanisms of plastic flow and stable crack growth, the particular arrangement of particles in an individual sample begins to affect the failure of the sample: the formation of assemblages of particles whose cohesion is too great for the plasticity mechanisms to operate is dependent upon the particular arrangement of the particles.

As the moisture content of test samples decreases further the failure mechanism changes to one of stable cracking. This failure mode is more sensitive to the particular arrangement of particles in an individual sample than failure in the transition zone; or in the regions of plastic or viscous flow. Failure by stable crack growth is realised when a state of crack linkage is achieved. The nucleation of cracks and their propagation through the material is affected by the degree of strain magnification. The crack stopping abilities of the cob matrix material are dependent upon the progress of a crack being interrupted by an aggregate particle (cob material, in addition to this mechanism of crack stopping, benefits from crack stopping by the fibre fraction) (figure 3.5). The degree of strain magnification and particulate crack stopping are all dependent upon the particular arrangement of particles, and the moisture content in the test samples. Because the arrangement of particles, and the distribution of the water of a particular moisture content vary randomly between nominally identical samples, the scatter of results increases with a change in the failure mode from plastic flow to stable crack growth.

From the plots of failure stress, stress at ELR and compression modulus against the moisture content at test of the samples in test series 4 and 5 (figures 6.15 to 6.17) it can be seen that scatter of the results of the high and medium cylinders increases noticeably at about 3% moisture content by total weight. It is proposed that below this moisture content cob matrix material fails by stable crack growth.

The relationship between the moisture content and compression modulus of the binder fraction has been investigated using the rule of mixtures, considered in chapter 3. The calculated maximum and minimum compression moduli of the binder fraction are shown below (table 7.2).

	maximum	minimum
compression modulus of the binder fraction	2.05×10^8 Pa	1.26×10^7 Pa
moisture content % by weight of binder fraction	2	26

table 7.2
Calculated values of maximum and minimum compression modulus of the binder fraction.

This calculation assumes that the compression modulus of the aggregate fraction is 79.4×10^9 Pa. This is the average of a range of values of the compression moduli of aggregate material quoted by Mehta (1986, pg. 238).

Figure 7.4 shows the calculated compression modulus of the binder fraction for the cylinders in test series 4 and 5, and their moisture content, expressed as a percentage of the binder fraction weight.

The assumption of a compression modulus for the aggregate fraction makes the calculated compression moduli of the binder fraction approximate. However, because the compression modulus of the aggregate fraction is independent of moisture content, the calculation does illustrate the form of the relationship between the compression modulus of the binder fraction and its moisture content.

The large difference in compression moduli of the aggregate and binder fractions emphasises the potential for strain magnification that exists in cob and cob matrix material.

Test series 4 and 5 calculated compressive modulus of the binder fraction and mo
content

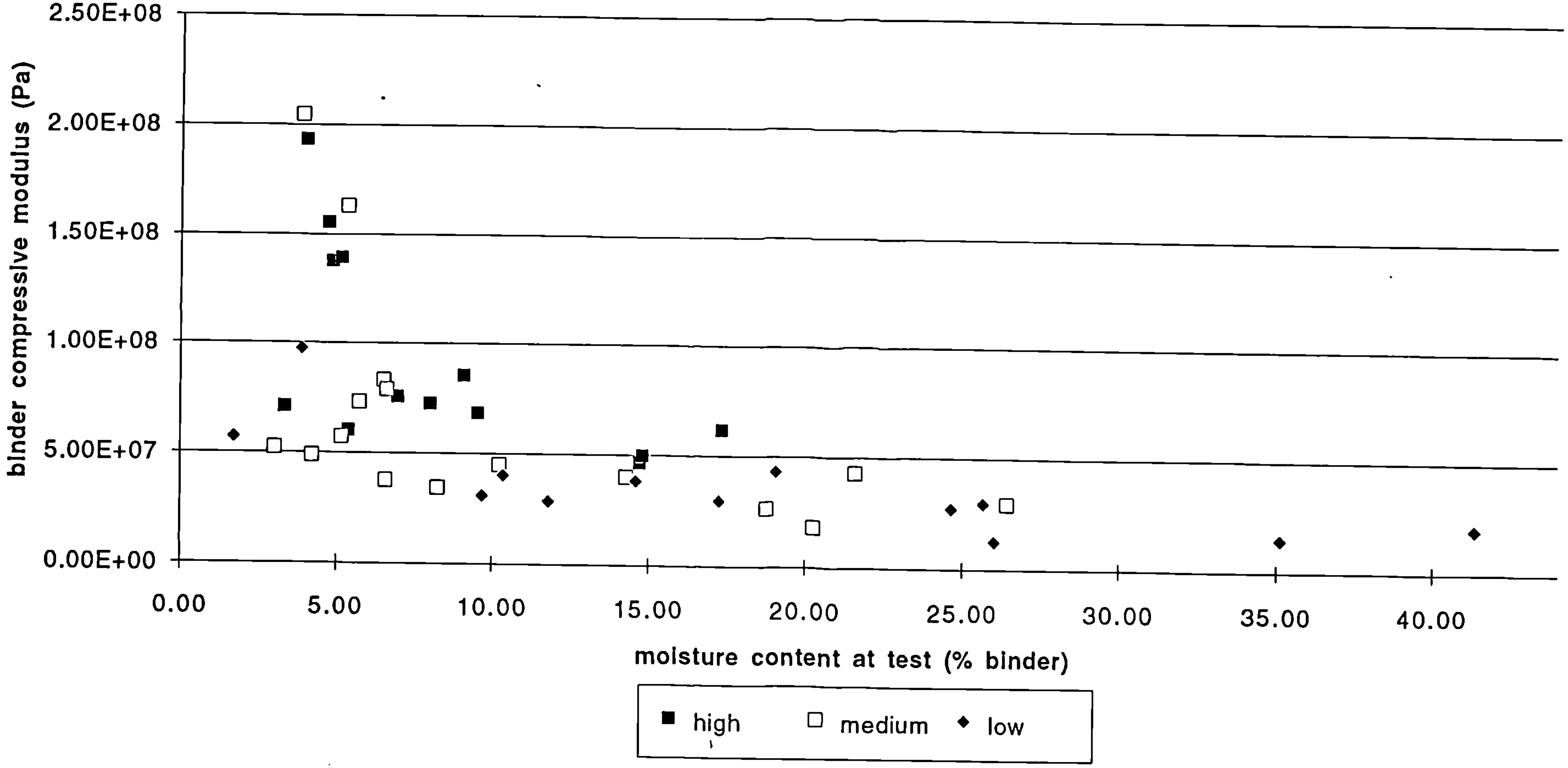


figure 7.4

The degree of strain magnification will not only be affected by the difference in the compression moduli of the aggregate and binder fractions, but also by the void content of the material: this is because voids have a compression modulus of zero. The tests conducted on cob matrix material did not include measurement of void size distribution of the samples. However, the void content of each mix type may be approximated by examining the change in the average dry density over a similar range of moisture content for each mix type (figure 6.30). Analysis of the data shown in figure 6.30 indicates that there is a statistically significant change in average dry density with mix type. Because the density of each mix type is nominally identical, chapter 6 section 6.2, this result indicates the following hierarchy (table 7.3) of void content for the mix types of test series 4 and 5.

mix type	void content
high	highest
medium	intermediate
low	lowest

table 7.3
Hierarchy of void content of test series 4 and 5 mix types.

This hierarchy of void content is compatible with the prediction that voids within the binder fraction, 'micro voids' described in chapter 3 section 3.6.2, will be responsible for the bulk of the porosity of a cob matrix material.

It is proposed that the effect of strain magnification due to the proportion of aggregate and binder fractions in cob matrix material can be estimated using the index:

$$\text{strain magnification index} = \frac{\text{total particle volume}}{\text{total particle surface area}} \quad \text{m}$$

This does not include the effect of the void content upon strain magnification and assumes that there is a uniform distribution of aggregate and binder fractions. A low value of this index indicates low strain magnification in the earth mix. The values of this index are given below (table 7.4) for the samples of test series 4 and 5.

mix type	strain magnification index (m)	degree of strain magnification
high	0.0552	lowest
medium	0.0914	intermediate
low	01831	highest

table 7.4
Hierarchy of strain magnification of test series 4 and 5 mix types.

In chapter 3 the following concepts were introduced: that the aggregate fraction brought to an earth mix the 'potential' for the material to develop compression modulus, and that the degree to which this potential was realised was dependent upon an 'efficiency factor'. The rule of mixtures predicts that, as the volume fraction of the cob matrix material increases, the compression modulus of the composite will also increase. However, the analysis of the results of test series 4 and 5 show that this is not the case: there is no statistically significant change in the compression modulus of the samples despite the large difference in aggregate volume between the three mix types (figure 6.28). This effect is due to the different efficiency factors of the three mixes.

The low mix has a greater potential compression modulus than the medium or high mixes due to its large aggregate volume fraction. However, over a similar range of moisture content, samples of both the medium and the high mixes achieve greater compression moduli than samples of the low mix (figure 6.28). This is because the high and medium mixes have a greater efficiency factor than the low mix and are able to realise more of their potential compression modulus: there is a sufficient quantity of binder fraction to hold the aggregate together. It also apparent from figure 6.28 that the greatest compression modulus was achieved by a sample of medium mix. This is because the medium mix had the most effective combination of efficiency factor and potential compression modulus.

The relationship between the compression modulus of cob matrix material and aggregate volume fraction can be calculated using the rule of mixtures equation and the following information:

- the average experimental compression modulus of the high mix samples of test series 4 and 5; and
- an assumed compression modulus of 79.4×10^9 Pa for the aggregate fraction (as above).

The results of these calculations are shown in figure 7.5. Also shown on this figure are the average compression moduli from figure 6.28. From figure 7.5 it can be seen that, of the three mix types, the results of low mix samples appear to deviate from the rule of mixtures prediction to the largest degree. This is due to the effect of the efficiency factor of the low mix. For this reason the calculated values of the compression modulus of the binder fraction of the low mix deviate from those of the high and medium mixes (figure 7.4). The position of the low mix in the hierarchies of void content and strain magnification (tables 7.3 and 7.4), suggests that the degree of strain magnification has a greater influence upon the efficiency factor than the void content of the material.

Rule of mixtures calculation and average observed compression modulus (E) of cob material

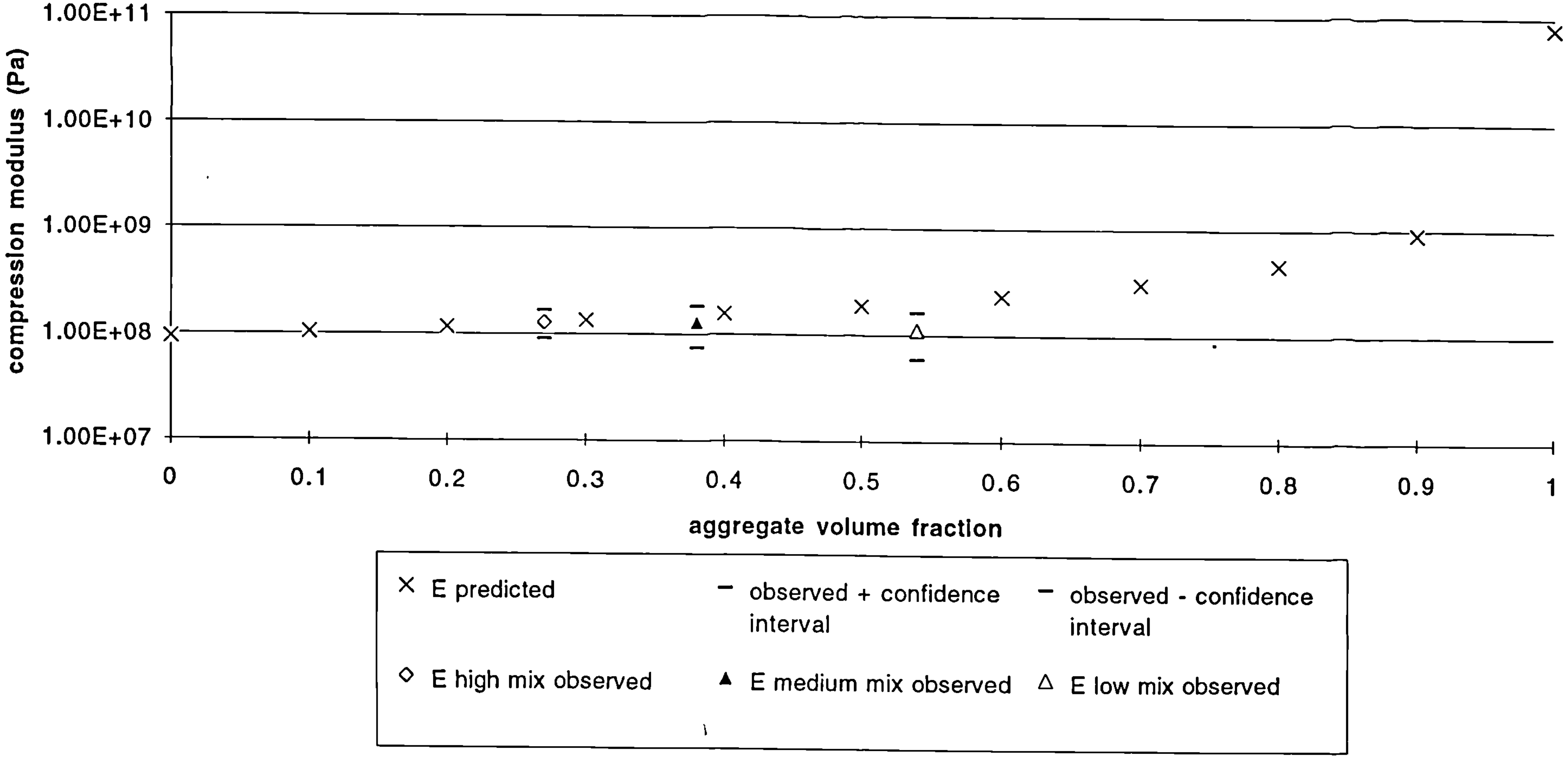


figure 7.5

7.2) Discussion of the drying process of cob and cob matrix material

7.2.1) The drying process of cob and test series four and five results

Cob and cob matrix material dries by the evaporation of water it contains. The evaporation process is dependent upon the molecules of water possessing enough energy to escape the liquid phase and enter the vapour phase. The rate of evaporation of a liquid into a vapour may be increased by (Whelan & Hodgson 1978, pg. 205):

i) increasing the surface area of the liquid;
ii) increasing the energy of the molecules of the liquid; and
iii) reducing the number of molecules above the liquid by reducing the vapour pressure.

Evaporation occurs at all temperatures but is faster at high temperatures due to (ii) above. The cylinders of test series 4 and 5 were dried at a nominally constant temperature providing the water molecules in the material with a constant amount of energy to over come the resistance to their evaporation- the vapour pressure near the surface of the evaporating water. Despite the environment of the humidity oven being constant the drying progress of the cylinders was not constant as the resistance to evaporation increased as the drying process progressed. Figure 7.6 shows the 'ideal' form of the relationship between the rate of change of mass due to the evaporation of water, and the moisture content of the material. The figure illustrates how the 'critical moisture content' separates a region of constant rate of drying from a region in which the rate of drying is falling. This moisture content is the same as the 'shrinkage limit' of the limits illustrated in figure 5.1. Figure 6.33 is a graph of the rate of change of mass against the moisture content for the cylinders of test series 4 and 5. It illustrates the constant rate drying process at moisture contents greater than the critical moisture content; the falling rate drying process at moisture contents less than the critical moisture content; and the critical moisture content of the materials occurring at approximately 9% gravimetric moisture content.

The region of drying at a constant rate occurs because:

i) the evaporation of the liquid water into water vapour occurs only at the surface of the sample as the interior of the sample is saturated;
ii) water is continually available at the surface of the sample because the sample is able to contract as it dries; and
iii) the vapour pressure around the samples is nominally constant, being regulated by the humidity oven in which the samples are drying.

During the region of constant rate drying the moisture content of the sample is uniform throughout its volume. Once the critical moisture content has been reached water is no longer available at the surface of the sample as it has reached the limit of its capacity for contraction (shrinkage limit). Therefore, further evaporation must occur from water filled pores within the material. As water evaporates from these pores it increases the vapour pressure within the sample. This vapour pressure can only be reduced by the molecules of water vapour escaping the interior of the sample by diffusing through the air filled pores of the binder fraction into the oven interior. The driving force for this diffusion is the negative 'vapour pressure gradient' between the sample interior and the oven interior (that is, the vapour pressure in the sample is greater than that in the humidity oven). This is an example of 'Fickian diffusion' (Newey & Weaver 1990). As the evaporation process continues the liquid water available for evaporation 'retreats' into the sample: the 'vapour transport paths' along which diffusing water vapour has to travel to reach the oven interior, therefore, become longer and more tortuous. The affect of this is to decrease the rate at which the vapour pressure within the sample can be relieved. The resulting increase in vapour pressure within the sample is the cause of the decrease in the rate of evaporation illustrated in figures 7.6 and 6.33.

The different rates of drying and the critical moisture content of cob matrix material

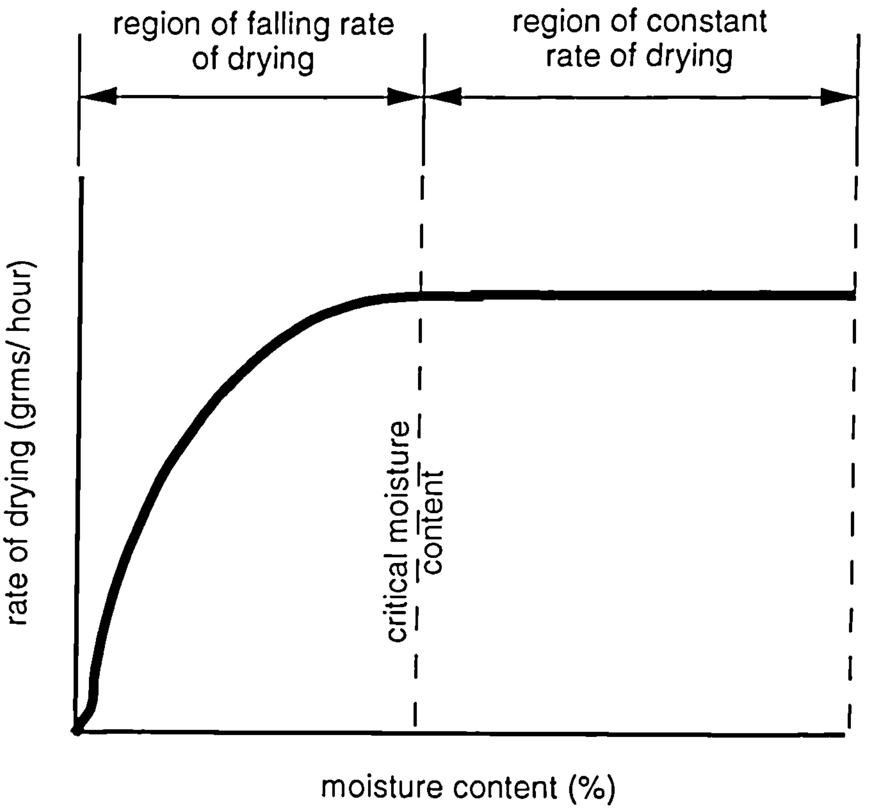


figure 7.6

In chapter 6 it was shown that the drying progress of the test series 4 and 5 samples did not differ in a statistically significant way. As the evaporation process by which drying takes place is dependent upon the porosity of the binder fraction, the similarity of the drying progress of the test 4 and 5 samples is evidence that the porosity of each of these materials was above a level which would inhibit the drying process.

The amount of energy necessary to evaporate the water contained in the material is dependent upon the size of the pore in which the water is held. "When water drains out of soil under the force of gravity or is removed by evaporation or transpiration it is held at a suction (a reduced or negative pressure) due to the adhesion of water molecules to particle surfaces and the cohesion forces acting between water molecules." (Rowell 1994, pg. 88).

'Free' water, which is not adsorbed to particle surfaces, is held in soil pores by a force resulting from the surface tension of the water. Surface tension acts along the surface of the water at the point of contact between the water and the pore wall. The magnitude of this force is related to the radius of the pore containing the water and the angle that the meniscus of the water makes with the pore wall. The relationship between these variables may be manipulated to show that the suction force, S, necessary to empty a pore of radius r is given by the equation: $S = 0.15/ r$; where S is in pascals and r in meters (Rowell 1994, pg. 88). This relationship is used in the experimental measurement of soil water suction to approximate the radius of pores emptied at a particular pressure difference. From this relationship it is apparent that the pressure difference necessary to empty pores within the soil is inversely proportional to the pore diameter. This relationship dictates combinations of environmental humidities and temperatures necessary to remove all free water from cob or cob matrix material. If these materials are at equilibrium with an environment with a combination of temperature and humidity which is insufficient to cause the evaporation of water from the finest pores of the materials, then free water will remain held in these fine pores. It is apparent from figure 6.31 that the environment of the humidity oven did not provide sufficient driving force to cause the evaporation of all the water held in the samples.

7.2.2) The moisture content history of the experimental cob wall

The drying process of the experimental wall, like that of the cylinders of test series 4 and 5, is dependent upon: temperature; the vapour pressure gradient between the interior and exterior of the material; and surface area. However, unlike the environment in which the cylinders dried, the temperature and vapour pressure of the environment around the experimental wall were not constant. Occasionally the moisture content of the experimental wall would be increased by changes in the environment around it.

The liquid moisture content of the wall can be increased by any of the following mechanisms acting individually or in combination:

i) water vapour within the wall may be caused to condense by a drop in temperature;

ii) liquid water may enter the wall in the form of rain impinging on the surface; and/ or

iii) liquid water may be drawn into the wall through the plinth by capillary action from the ground below it.

Unlike mechanisms (ii) and (iii) which can only occur across particular boundaries between the wall and the environment, condensation of water vapour can occur anywhere throughout the volume of the wall. However, the probability of the presence of water vapour is not uniform throughout the volume of the wall but is dependent upon position and immediate drying history.

Position has influence as this affects the degree of tortuosity of paths for the movement of water vapour: the deeper into the wall a particular position the *more tortuous the 'moisture transport* path' between it and the surface of the wall. Therefore the probability of the presence of water vapour in the wall decreases with increasing distance form the surface of the wall. The increasing tortuosity of the moisture transport paths create an 'insulating' effect for the interior of the wall. This prevents the moisture content of the interior of the wall from changing rapidly as a result of changes in the moisture content of the environment. The immediate drying history will affect the magnitude and direction of the force driving the diffusion of water vapour within the wall: the vapour pressure gradient.

Figure 6.35 illustrates the average moisture content of the second and third lifts of the experimental wall at similar elapsed times from their construction. An average of these values is shown in figure 6.34. The average moisture content of the probe positions in the second and third lifts at these similar elapsed times is shown in figure 6.36. Analysis of this data shows the following results.

i) There is a significant effect of time on the average moisture content of the two lifts: that is the lifts are drying ($F(10, 150)= 206.8$; $p< 0.000$).

ii) There is an interaction between the average moisture content of each lift and time: that is the drying progress of the two lifts differed in a statistically significant manner ($F(10, 280)= 2.19$; $p< 0.0183$).

iii) Although there is a significant effect of time on the average moisture content of vertically aligned probes in the second and third lifts, there is no interaction between these probe positions and time: that is all probe positions in the lifts dried at a statistically uniform rate ($F(140, 150)= 0.95$; $p< 0.6251$).

The most likely factors to cause result (ii) are differences of: the environment surrounding each lift as it dried; or in the material porosity of the the two lifts. It has already been shown that the drying process is related to the porosity of the material: increasing material porosity increases the volume and decreases the tortuosity of potential vapour transport paths. The degree of porosity will be determined by the production process and composition of the material. The drying data from test series 4 and 5 show that large differences in the composition of the samples have no significant effect upon the drying progress of the material. Given that the material composition of the wall varies less than that of the test series 4 and 5 samples and that the construction process was similar for both lifts it is more likely that differences in the environment affected the drying process then differences in the material porosity of the lifts.

The average moisture contents of the probe positions in the second and third lifts for the entire initial drying process are shown in figure 6.37. The greatest value is for probe position number 5. It is proposed that this is because this position had the lowest vapour pressure gradient between it and the immediate environment around it as a result of the tortuosity of the moisture transport paths form the centre of each lift. However, there is no statistically significant difference between any of the values shown in figure 6.37.

After a period of approximately 600 hours (25 days) from construction the rate of drying of the second lift decreased markedly: the rate of drying of the third lift appears to exhibit a similar marked decrease at approximately the same elapsed time from construction (figure 6.38). At this time the moisture content of the wall is considered to be in equilibrium with the environment. From this time the fluctuation of moisture content of the wall was due to changes in the environment.

When under the influence of the environment the greatest observed average moisture content of the wall was approximately 14% gravimetric moisture content and occurred in measurement period 2, the readings for which were taken from 11/2/95 to 15/2/95 during the winter season. The least observed moisture content of the wall was approximately 11.5% gravimetric moisture content and occurred in measurement period 4 (from 26/7/95 to 4/8/95) during the summer season. The variation with time of average measured moisture content of the experimental wall are illustrated in figure 6.39. The exposure of the wall to this range of moisture content had no visually apparent deleterious effect upon it.

The analysis of the moisture contents measured in time periods 2, 3, 4 and 5 as one data set shows that there is a statistically significant effect of time on the average moisture content of the wall (F(18, 432)= 34.41; p< 0.000) (figure 6.34). This demonstrates that the wall dries from the greatest moisture content, measured during the winter, to the least measured during the summer. Analysis of the moisture contents measured in time periods 2 and 3; and 4 and 5 as two separate data sets shows that the statistically significant effect of time upon the moisture content of the wall is due solely to the readings of time periods 4 and 5 (F(9, 162)= 4.58; p< 0.0000). That is in time periods 2 and 3 the changes in the environment were either of insufficient magnitude or duration to cause the moisture content of the wall to change significantly, but in time periods 4 and 5 the moisture content of the wall was decreasing in response to an overall difference in moisture content between the wall and its environment.

Analysis of time periods 2, 3, 4 and 5 as one data set show that the rate of change of moisture content was independent of lift but dependent upon probe position (F(36, 432)= 1.10; p< 0.3156) and
(F(144, 324)= 2.29; p< 0.000). However, analysis of the moisture contents measured in time periods 2 and 3; and 4 and 5 as two separate data sets show no such statistically significant difference in the rate of change of moisture contents for different probe positions. Therefore, the statistically significant difference in the rate of change of moisture content must be caused by changes occurring between time periods 3 and 4. In order to investigate

which probe positions were responsible for this effect two average moisture contents were calculated for each probe position: one for time periods 2 and 3; and one for time periods 4 and 5. The numerical difference between each pair of averages was investigated for statistical significance using analysis of variance. This analysis found significant differences in the decrease of these average moisture content between probe positions 1 and 3 compared with positions 4, 7, 8, 9 and 11 (figure 6.44).

Between time periods 3 and 4 the protection of the wall was improved, as described in chapter 4, after it was observed that the original covering was allowing the entry of water into the wall above probe positions 1, 2 and 3. It is likely that the significant drop of the average moisture content of probe positions 1 and 3 between time periods 3 and 4 is a result of the improvement of the protective covering of the wall.

The average moisture content of vertically aligned probe positions for time periods 2- 5 is illustrated in figure 6.43 (b). There is no statistically significant difference between any pairs of these values.

There is a statistically significant difference between the average of the moisture content of probe positions in the first lift compared with the average of those in the second and third lifts during time periods 2, 3, 4 and 5 ($F(2,24)= 11.16$; $p< 0.0004$), see figure 6.40. From figure 6.40 this difference appears large. However, figure 6.43 (a) shows that the total average moisture content of some probe positions of the first lift are very similar to those of the other lifts. It is possible that the difference in measured moisture content between the first lift and the other lifts is due to the different design of probe installed in the first lift compared to that of probes installed in the other lifts.

The only difference between the designs which could affect the readings of the TDR are the material used to maintain electrical continuity between the probe members and the conductors of the cable. The first design used silver solder to maintain electrical continuity, the second metal electrical connectors set in plastic. In order for the TDR reading to be affected by this difference the speed of the test signal transmitted along the probe by the TDR would have to be different for each probe design. This is considered unlikely.

If the differences in measured moisture contents are due to actual differences in the moisture content of the wall then this illustrates the ability of cob to maintain moisture gradients within it. It is not clear whether the difference in moisture content between the top and bottom of the wall is due to an improvement in the drying processes of the first lift caused by the light weight concrete blocks that it is built on; or mechanisms inhibiting the drying of the top of the wall. Examples of such mechanisms may be the protective covering reducing air circulation around the top of the wall; or wetting of the top of the wall by condensation of water vapour entering between the top of the wall and the protective covering.

The results of the monitoring of the moisture content of the experimental wall are summarised by the following statements.

i) Regions of the wall which are adequately protected from the ingress of precipitation dry at a statistically uniform rate.

ii) There is greater variation in the average moisture contents of vertically aligned probe positions than for average moisture contents of probes in the same lifts. The variation of average moisture contents of vertically aligned probe positions cannot be attributed to their location in the wall. The variation of average moisture contents of each lift can be attributed to their location in the wall.

Monitoring of the experimental wall has shown instantaneous variation in moisture content as well as seasonal variation in moisture content. The greatest observed instantaneous variation in the moisture content of the wall was between probe positions 1 and 7 on 14/2/95. On this date probe position 1 was at a moisture content of approximately 17% gravimetric moisture content and position 7 at approximately 10% (figure 6.42). The maximum and minimum values for total average moisture content are approximately 14% gravimetric moisture content measured on the 12/2/95 and 11.25% measured on the 4/8/95 (figure 6.39). Using the predictive equations developed previously the effect of these range of moisture contents on the properties of the test series 4 and 5 mixes can be calculated. Table 7.5, below, illustrates the percentage decrease in rigidity, yield stress and failure stress of the mixes of test series 4 and 5 across these ranges of moisture content.

seasonal variation from 14 to 11.25% moisture content

mix type	high	medium	low
compression modulus	8	11	14
yield stress	5	9	13
failure stress	4	7	10

instantaneous variation of 17 and 10% moisture content

mix type	high	medium	low
compression modulus	19	25	30
yield stress	13	20	30
failure stress	9	16	22

table 7.5

Predicted percentage drop in properties of test series 4 and 5 mixes due to variation of moisture content observed in the experimental wall

From table 7.5 it is apparent that the compression modulus undergoes the greatest percentage decrease for each moisture content range. The consequence of this is that failure of cob and cob matrix material as a result of increased moisture content is most likely to occur due to the deterioration of the compression modulus of the material. If the compression modulus is not uniform throughout a cob wall, for example because a region of the wall is relatively wet, then strain magnification within the wall will be increased possibly initiating failure else where in the wall.

From the use of TDR in monitoring of the distribution of moisture throughout the experimental wall the following observations have become apparent.

i) Practical experience of the appearance of cob and soil whose moisture contents are later determined suggests that the TDR measurements exaggerated the moisture content of the wall.

ii) The collection of TDR readings 'by eye' reduces the amount of useful information obtained from the experimental wall as described in chapter 5. However, computer controlled systems now exist which are capable of automatically recording data from probes and switching automatically between them (Holden et al. 1995; Heimovaara & de Water 1991 & 1993).

iii) The configuration of the experimental wall is not representative of the walls in many buildings, that is: environmental conditions are similar all around it, it is unrendered, and has untypical geometry. However, the wall is available for further study and the effects of imposing an environmental gradient on it, for example constructing a protective 'room' onto one side of the wall, or rendering or partially rendering it, can still be investigated. Further work on the experimental wall should also include verification of the calibration of the TDR probes see, (i) above, and examination of any impact of the different probe designs installed upon the recorded measurements.

iv) The wetting and drying process of soil is subject to hysteresis: pores within earthen materials, “do not always empty [of water] again during drying in the same order as they were filled.” (Jury et al. 1991, pg. 65). Therefore whether the wall was drying or wetting at the time of measurement will affect the moisture content readings obtained. The magnitude of this effect on the measurements recorded from the experimental wall is not known.

v) During the initial drying process the relative humidity and rainfall were measured at every reading of the wall. No consistent relationship could be established between this information and the distribution of moisture within the wall. This is likely to be due to the highly variable nature of relative humidity and the impact of effects other than rainfall upon the moisture content of the wall.

Despite these disadvantages the study has shown that TDR is an effective method of real time monitoring of the moisture content of earth walling.

7.3) Statistical analysis of data and experimental design

There have been two areas of experimentation in this project: the study of the relationship between the compression properties of samples of cob and cob matrix material and their moisture content and composition; and the study of the distribution of moisture in an experimental wall exposed to the natural environment.

The monitoring of the experimental wall was conducted such that the effect of probe position and time on moisture content could be evaluated: that is probe position and time are controlled whilst the dependent variable, moisture content, is measured. Each moisture measurement used in the analysis of the data from the experimental wall is an average value of several readings. Assuming that the experimental error is normally distributed about the true value of moisture content, this averaging reduces the affect of experimental error from the results.

The measurements taken from the experimental wall were analysed using a two way analysis of variance. This method highlights differences in the distribution of moisture content in the wall by calculating whether there is a statistically significant effect on moisture content of either time or probe position individually; or the combined effect of time and probe position. This method will also detect differences in the interactions between dependent and controlled variables.

In order to investigate the progressive effect of increasing moisture content on the compression behaviour of cob and cob matrix materials the compression properties of these materials was determined over a range of moisture contents. The analysis of this data by multiple regression provides equations predicting the compression properties, at any moisture content in the test range, of the three mixes. This analysis applies a uniform interaction between all mix types and moisture content, that is: the form of the relationship of the change in properties with moisture content is the same for each mix type. Initially this was considered to be true, so this limitation of multiple regression analysis did not affect the experimental design. However, from the data collected from test series 4 and 5 it appears that the interaction between mix type and moisture content is not uniform: the compression properties of the low mix appear to have a different relationship to variations in moisture content than either the high or medium mixes. Using regression analysis there is no method of testing whether this difference is statistically significant. Furthermore, the relationship between the scatter of measured properties due to failure of the samples by different mechanisms can not be examined statistically using regression analysis. However, unless a large number of samples were tested, experiments on the compression properties of cob and cob matrix material designed for analysis of variance would not provide the detailed information about the relationship between the measured properties and moisture content of the material given by experiments designed for regression analysis.

From the above discussion it can be seen that the two important aspects of the properties of cob that can be investigated are: the relationship between the properties of individual mixes and moisture content; and the effect of different compositions of mixes upon their properties at different moisture contents. These two approaches can not be efficiently combined in a single experimental design. Information about the deterioration of the properties of a particular earth mix will be essential for a thorough evaluation of the structural condition of individual buildings. Descriptions of the dependence of the properties of earth mixes upon their composition is applicable to the definition of codes of practice for construction in earth. The approach of further research into the properties of cob will be determined by the particular aspect to be investigated.

The most efficient method for gathering data about the effect of composition upon the properties of earth mixes is to test 'artificial' earth mixes so that differences in composition can be controlled, reducing the number of variables affecting the test results. Test series 4 and 5 addressed the effects of varying the proportions of binder and aggregate fractions of the same quality: because the 'raw materials' of these mixes all came from the same soil the angularity, degree of cohesion, surface roughness and density of each particle size range was nominally constant for all the mixes tested. For example, this test methodology could also determine the effect upon the properties of cob and cob matrix material of:

i) different binder fractions by testing samples consisting of a particular aggregate type at a particular volume fraction, but including different proportions or type of clays in the binder fraction; or

ii) strain magnification caused by the distribution of the volume fraction of aggregate by testing samples of a fixed aggregate volume fraction distributed as either a small number of large aggregate particles, or a large number of small aggregate particles.

These types of experiments not only provide data about the effect of the composition of the materials upon their properties, but also information about the mechanisms which determine the properties of cob and cob matrix material. Once identified further tests can be developed, if necessary, to investigate the parameters controlling these mechanisms in isolation of a 'recognisable' earth mixes. This knowledge can then be applied to the wide variety of naturally occurring soils.

The geotechnical approach of characterisation and classification of naturally occurring soils, described in chapter 2, does not provide information on failure mechanisms and the qualities of the raw materials controlling the failure mechanisms as efficiently as the test methodology outlined above. Therefore, the testing of 'artificial' earth mixes, and not of the geotechnical approach, will most effectively increase knowledge of the performance of earth as a building material.

Chapter 8: Conclusions and Further work

8.1) Conclusions

This project has established the following facts.

- The need for materials' behaviour research into earth as a building material, in particular, the need to consider the characterisation of the internal structure of earth building materials and not solely that of their raw ingredients.
- That the properties of earth building materials are repeatable and the result of mechanisms which may be systematically investigated. This observation, coupled with the further work which needs to be undertaken to fully understand the behaviour of earth building materials, should cause owners and building professionals to re- evaluate the current low status of earth building materials.
- The fact that there is useful information in other disciplines which is relevant to the materials behaviour of earth as a building material. Much of this information has been collected together in this document.

This project has identified:

- and proved the method of TDR monitoring as a viable technique for the real- time monitoring of the moisture content of earth building materials;
- and proved a novel methodology to investigate the behaviour of earth building materials- that of accumulating knowledge by testing mixes designed to alter specific properties of the material;
- failure mechanisms of compacted earth under unconfined compressive loading- consideration of these failure mechanisms has not been found elsewhere in the literature;
- relationships between particular material properties of compacted earth under unconfined compressive loading and explained them in terms of material composition and the properties of the material constituents.

8.2) Further work

Figure 8.1 illustrates the three related areas of materials investigation which must be explored to increase knowledge of the structural properties of earth building materials. Specific areas for further work are listed below.

- Areas of further work involving the experimental wall has been suggested (chapter 7, section 7.2.2).
- A methodology for the investigation into the effect of the qualities of the raw materials of earthen mixes has been described (chapter 7, section 7.3).
- Information from relevant literature describes how the degree of cohesion of particles of clay mineral can be influenced by controlling the type and concentration of ions within suspensions of the materials (chapter 3, section 3.3.2). Useful further work would establish whether such techniques were applicable to the use of earth as a construction material.
- The role of the void content of cob matrix material in the development of compressive properties has been highlighted (chapter 3, section 3.5.2) . Useful further work would investigate the relationship between the void content of earthen building materials and their compositions, and technique of production. The technique of mercury infusion can be used to determine porosity and pore size distribution of samples of earth building material.

Elements for investigation into the structural properties of earth building materials

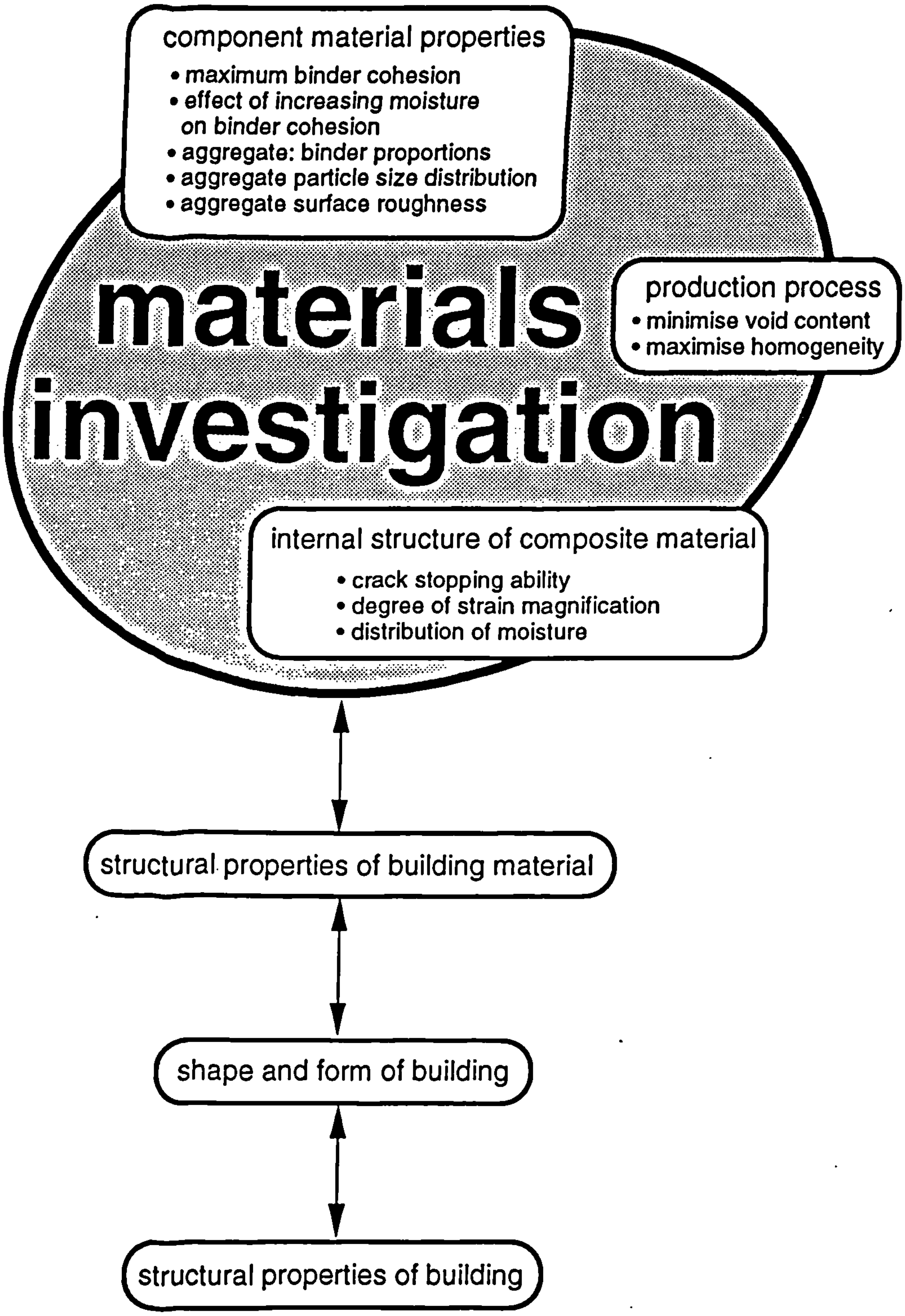


figure 8.1

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Appendix A: references and bibliography

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Appendix B: contact addresses

Regional groups

Devon Earth Building Association
50 Blacklay Road
Exeter
Devon
EX4 6TB

East Anglian Regional Telluric Houses Association
Dirk Bouwens
Paperhouse
West Harling
Norwhich
Norfolk
NR16 2SF

East Midlands Earth Structures Society
John Hurd
3 Magdalen Close
North Lane
Swaby Nr. Alford
Lincolnshire
LN13 OEB

Other useful addresses

Centre for Earthen Architecture
Linda Watson
University of Plymouth
School of Architecture
The Hoe Centre
Notte Street
Plymouth
Devon
PL4 2AR

ICOMOS UK Earth Structures Sub Committee
Linda Watson (secretary)
University of Plymouth
School of Architecture
The Hoe Centre
Notte Street
Plymouth
Devon
PL4 2AR

Ray Harrison
11 Briton Road
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Kent
ME13 8QH

Peter Messenger
Carlisle City Council
Dpt. of the Environment and Development
Civic Centre
Rickergate
Carlisle
CA3 8QG

Bruce Walker/ Chris McGregor
Historic Scotland
Longmore House
Salisbury Road
Edinburgh
EH9 1SH

Gorden Pearson
Yew Tree Cottage
Ramsey Road
Kings Sanbourme
Stedlidge
Hants
SO20 6PR

Appendix C: variable glossary

<425	weight of particles passing a 425µm sieve presented as a percentage of total dry specimen weight (%)
<75	weight of particles passing a 75µm sieve presented as a percentage of total dry specimen weight (%)
2drymod	describes a particular form of 'abnormal' stress/ strain response during a compressive test, see chapter 5
both	describes a particular form of 'abnormal' stress/ strain response during a compressive test, see chapter 5
bulk.dens	bulk density: the volume divided by the weight of the specimen at test (kg/ m^3)
compmod	the maximum gradient of the test stress/ strain graph (Pa or MPa)
drop	describes a particular form of 'abnormal' stress/ strain response during a compressive test, see chapter 5
dry.wht	dry weight: calculated mass of an oven dry specimen
dry.den	dry density: the volume divided by the oven dry weight of the specimen (kg/ m^3)
elapsed time	the amount of time a sample from test series 4 or 5 has been drying in the humidity oven
ELRstrain	the compression of a test specimen at the end of the linear stress/ strain responce presented as a ratio of initial test specimen height (dimensionless)
ELRstress	the stress at the yield point of a specimen (Pa)
fs	the failure stress of a specimen (Pa or MPa)
final.wht	the weight of a specimen at test (grms)
id	identifying code for an individual test specimen. Test series 4 and 5 are identified by H, M or L indicating their binder content: H- 'high', approximately 62% binder content; M- 'medium', approximately 44% binder content; and L- 'low', approximately 22% binder content. This is followed by a number indicating the sequence of testing within each mix type. Test series 1 and 2 are identified by two numbers separated by a semi-colon. The second number indicates the series to which the specimen belongs, the first indicates the sequence of testing of that series.
mcm	the moisture content at manufacture relative to total dry weight of a specimen (%)
mctbin	the moisture content at test relative to total dry weight of binder content of a specimen (%)
mcttw	the moisture content at test relative to total dry weight of a specimen (%) (gravimetric moisture content at test)
mixhigh?	describes specimens of test series 4 and 5 with a binder content of approximately 62%
mixlow?	describes specimens of test series 4 and 5 with a binder content of approximately 22%

none	describes 'normal' stress/ strain response see chapter 5
O/I	identifies if the drying process of a sample was suspended: 1=yes, 0=no
ovencode	identified specimens which dried together. There are 7 groups numbered from 3 to 9.
strfail	strain to failure: the compression of a test specimen at failure presented as a ratio of the initial test specimen height (dimensionless)
straw	the weight of straw content relative to total dry weight of the specimen (%)
ts	describes the test series to which the test specimens belongs: 1, 2, 4, or 5
volume	the volume of a specimen at test (m^3)

Appendix D: Fisher's transformations

The technique of Fisher's transformation is used to compare the difference in correlation of the following sets of variables. The results of these comparisons are shown in this appendix.

i) Effect of ovencode and O/I variables.

fs	with	mcttw, ovencode, O/I
and		
fs	with	mct
ELRstress	with	mcttw, ovencode, O/I
and		
ELRstress	with	mct
compmod	with	mcttw, ovencode, O/I
and		
compmod	with	mct
strfail	with	mcttw, ovencode, O/I
and		
strfail	with	mct

ii) Effect of none variable.

fs	with	mcttw, mixhigh?, mixlow?, none
and		
fs	with	mcttw, mixhigh?, mixlow?
ELRstress	with	mcttw, mixhigh?, mixlow?, none
and		
ELRstress	with	mcttw, mixhigh?, mixlow?
compmod	with	mcttw, mixhigh?, mixlow?, none
and		
compmod	with	mcttw, mixhigh?, mixlow?
strfail	with	mcttw, mixhigh?, mixlow?, none
and		
strfail	with	mcttw, mixhigh?, mixlow?

iii) Effect of variables describing 'mix type' with mcttw variable.

log(fs)	with	mcttw, mixhigh?, mixlow?
and		
fs	with	mcttw
log(ELRstress)	with	mcttw, mixhigh?, mixlow?
and		
log(ELRstress)	with	mcttw
log(compmod)	with	mcttw, mixhigh?, mixlow?
and		
log(compmod)	with	mcttw
strfail	with	mcttw, mixhigh?, mixlow?
and		
strfail	with	mcttw

iv) Effect of variables describing 'mix type' with mctbin variable.

log(fs)	with	mctbin, mixhigh?, mixlow?
and		
log(fs)	with	mctbin
log(ELRstress)	with	mctbin, mixhigh?, mixlow?
and		
log(ELRstress)	with	mctbin
log(compmod)	with	mctbin, mixhigh?, mixlow?
and		
log(compmod)	with	mctbin
strfail	with	mctbin, mixhigh?, mixlow?
and		
strfail	with	mctbin

v) Effect of variable describing mix type on the drying process.

log(mctw)	with	log(time), highmix?, lowmix?
and		
log(mctw)	with	log(time)

vi) Effect of moisture content variables.

strfail- ELRstrain	with	mcttw
and		
strfail- ELRstrain	with	mctbin

i) Effect of ovencode and O/I variables.

fs	mcttw	ocode3?	ocode4?	ocode5?	ocode6?	ocode7?	ocode8?	O/I
-280414.859	119396.76	-3E+05	-3E+05	-4E+05	-7E+05	-6E+05	-21844	1665831
180990.557	233423.82	249131	262739	254961	264356	246128	30774	235782
0.50087041	401817.75	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
4.13938674	33	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
5.3467E+12	5.328E+12	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
t	0.511502	1.1714	1.2468	1.4142	2.5581	2.4607	0.7098	7.06513
N	42							
df	33							

fs	mcttw
-77995.5396	1608193.2
24936.4085	135327.79
0.19651275	463061.77
9.78299259	40
2.0977E+12	8.577E+12

t of r= 3.1278
[t 0.25(40)= 2.021]

	with indic	without indic
r	0.707722	0.4433
r'	0.8826051	0.4763
N	42	42

z obt= 1.7940733

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

i) Effect of ovencode and O/I variables.

ELRstress	mcttw	ocode3?	ocode4?	ocode5?	ocode6?	ocode7?	ocode8?	O/I
-216106.623	126020.38	-3E+05	-83055	-3E+05	-4E+05	-5E+05	-35491	1332749
166231.074	214388.5	228815	241313	234169	242798	226057	28265	216554
0.47130644	369050.18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
3.67725124	33	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
4.0067E+12	4.495E+12	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
t	0.5878132	1.1079	0.3442	1.1048	1.838	2.0055	1.2557	6.15434
N	42							
df	33							

ELRstress	mcttw
-77249.0006	1313763.7
21613.4474	117294.36
0.24205555	401355.36
12.7743159	40
2.0578E+12	6.443E+12

t of r= 3.5741

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.6865176	0.492
r'	0.841339	0.5387
N	42	42

z obt= 1.3364867

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

i) Effect of ovencode and O/I variables.

compmod	mcttw	ocode3?	ocode4?	ocode5?	ocode6?	ocode7?	ocode8?	O/I
-19944518.6	-25249784	-7E+07	-8E+07	-6E+07	-8E+07	-7E+07	-1E+07	2.1E+08
25980627.6	33507259	4E+07	4E+07	4E+07	4E+07	4E+07	4E+06	3.4E+07
0.46390682	57679680	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
3.56955789	33	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
9.5006E+16	1.098E+17	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
t	0.7535616	2.0971	2.2255	1.6814	2.2197	1.9086	2.3778	6.30292
N	42							
df	33							

compmod	mcttw
-12761566.1	167396398
3282670.08	17814774
0.27421971	60958218
15.1130973	40
5.6159E+16	1.486E+17

t of r= 3.8876
[t 0.25(40)= 2.021]

	with indic	without indic
r	0.6811071	0.5237
r'	0.8311762	0.5814
N	42	42

z obt= 1.1031176

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

i) Effect of ovencode and O/I variables.

strfail	mcttw	ocode3?	ocode4?	ocode5?	ocode6?	ocode7?	ocode8?	O/I
-0.00320616	0.0031207	0.0036	0.0065	0.004	0.0004	-0.004	0.0017	0.01292
0.00240719	0.0031046	0.0033	0.0035	0.0034	0.0035	0.0033	0.0004	0.00314
0.44937091	0.0053442	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
3.36643127	33	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
0.00076918	0.0009425	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

t	1.005201	1.0777	1.8527	1.1849	0.1266	1.3581	4.132	4.11966
N	42							
df	33							

strfail	mcttw
0.00107272	0.0168084
0.00030875	0.0016756
0.23182312	0.0057334
12.0713406	40
0.00039681	0.0013149

t of r= 3.4744
[t 0.25(40)= 2.021]

	with indic	without indic
r	0.6703513	0.4815
r'	0.8113809	0.5249
N	42	42

z obt= 1.2650243

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

ii) Effect of none variable.

fs	mcttw	mixhigh?	mixlow?	none
232504.316	-424306.98	398408.737	-101687.632	2E+06
98077.3664	114222.71	114826.34	16832.6248	1E+05
0.67747183	305043.93	#N/A	#N/A	#N/A
19.4296658	37	#N/A	#N/A	#N/A
7.2319E+12	3.443E+12	#N/A	#N/A	#N/A

t	3.7147338	3.4696633	6.04110371	13.68
N	42			
df	37			

fs	mcttw	mixhigh?	mixlow?
-426565.351	424955.91	-95184.6539	1.69E+06
120962.711	121026.5	17588.1844	1.14E+05
0.62848376	323055.05	#N/A	#N/A
21.42785	38	#N/A	#N/A
6.7089E+12	3.966E+12	#N/A	#N/A

t of r= 8.22598899
[t 0.25(40)= 2.021]

	with indic	without indic
r	0.8230868	0.79276968
r'	1.1663135	1.07884308
N	42	42

z obt= 0.3862589

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

Appendix: Fisher's transformations

ii) Effect of none variable.

ELRstress	mcttw	mixhigh?	mixlow?	none
189986.992	-420460.19	310786.388	-97769.5741	1E+06
82751.5854	96374.026	96883.3279	14202.3225	97850
0.71168927	257377.11	#N/A	#N/A	#N/A
22.8334395	37	#N/A	#N/A	#N/A
6.0502E+12	2.451E+12	#N/A	#N/A	#N/A
t	4.3627957	3.20784179	6.88405533	13.58
N	42			
df	37			

ELRstress	mcttw	mixhigh?	mixlow?
-422305.578	332478.96	-92455.7748	1.41E+06
101642.301	101695.9	14778.9639	9.60E+04
0.67061648	271456.04	#N/A	#N/A
25.7890115	38	#N/A	#N/A
5.7011E+12	2.8E+12	#N/A	#N/A

t of r= 9.02435502

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.8436168	0.81891177
r'	1.2335875	1.15350464
N	42	42

z obt= 0.3536364

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

ii) Effect of none variable.

compmod	mcttw	mixhigh?	mixlow?	none
18527108	-29007573	24486540	-14405112.7	2E+08
18725598.8	21808178	21923426.9	3213799.38	2E+07
0.38716861	58241065	#N/A	#N/A	#N/A
5.84387431	37	#N/A	#N/A	#N/A
7.929E+16	1.255E+17	#N/A	#N/A	#N/A

t	1.3301236	1.11691207	4.48226881	7.467
N	42			
df	37			

compmod	mcttw	mixhigh?	mixlow?
-29187531.3	26601951	-13886922.9	1.73E+08
21801368.3	21812865	3169956.13	2.06E+07
0.37095487	58224903	#N/A	#N/A
7.46967347	38	#N/A	#N/A
7.597E+16	1.288E+17	#N/A	#N/A

t of r= 4.85679344

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.6222287	0.60906065
r'	0.7286337	0.7074267
N	42	42

z obt= 0.0936475

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

ii) Effect of none variable.

strfail	mcttw	mixhigh?	mixlow?	none
-0.00269579	-0.0049478	-0.00045198	0.001066	0.02
0.00171635	0.0019989	0.00200945	0.00029457	0.002
0.38400598	0.0053382	#N/A	#N/A	#N/A
5.76637943	37	#N/A	#N/A	#N/A
0.0006573	0.0010544	#N/A	#N/A	#N/A

t	2.4752763	0.22492646	3.61884051	9.911
N	42			
df	37			

strfail	mcttw	mixhigh?	mixlow?
-0.00492162	-0.0007598	0.0009906	1.89E-02
0.00203704	0.0020381	0.00029619	1.92E-03
0.34293494	0.0054403	#N/A	#N/A
6.6109778	38	#N/A	#N/A
0.00058699	0.0011247	#N/A	#N/A

t of r= 4.56911063

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.6196822	0.58560647
r'	0.7244889	0.67095308
N	42	42

z obt= 0.2364079

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

iii) Effect of variables describing 'mix type' with mcttw variable.

log(fs)	mcttw	mixhigh?	mixlow?
-0.15679984	0.1438159	-0.03388527	6.22234176
0.03943579	0.0394566	0.00573403	0.03724658
0.66640633	0.1053211	#N/A	#N/A
25.3036783	38	#N/A	#N/A
0.84204628	0.4215166	#N/A	#N/A

t	3.6449161	5.90950259	167.05808
N	42		
df	38		

log(fs)	mcttw
-0.02782108	6.1903743
0.00850037	0.0461308
0.21123278	0.1578494
10.7120465	40
0.26690589	0.9966569

t of r= 3.27292629

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.8163371	0.45960067
r'	1.1457377	0.4968049
N	42	42

z obt= 2.8656097

z obt > z 0.025 (=+/- 1.96) therefore there is a significant difference

iii) Effect of variables describing 'mix type' with mcttw variable.

log(ELRstress)	mcttw	mixhigh?	mixlow?
-0.218940075	0.1493686	-0.04603855	6.16581421
0.044179581	0.0442029	0.00642379	0.04172703
0.724222031	0.1179904	#N/A	#N/A
33.26400248	38	#N/A	#N/A
1.389277471	0.5290258	#N/A	#N/A

t	3.3791593	7.16688751	147.765472
N	42		
df	38		

log(ELRstress)	mcttw
-0.038626789	6.1101208
0.010088295	0.0547483
0.268206937	0.1873367
14.66026125	40
0.514502238	1.403801

t of r= 3.82887206

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.8510124	0.51788699
r'	1.2598123	0.57344798
N	42	42

z obt= 3.0309028

z obt > z 0.025 (=+/- 1.96) therefore there is a significant difference

iii) Effect of variables describing 'mix type' with mcttw variable.

log(compmod)	mcttw	mixhigh?	mixlow?
-0.0980276	0.1474392	-0.0568825	8.2100462
0.0663464	0.0663814	0.00964688	0.0626633
0.524951	0.1771913	#N/A	#N/A
13.997248	38	#N/A	#N/A
1.3184049	1.193077	#N/A	#N/A

t	2.2210918	5.89646572	131.018404
N	42		
df	38		

log(compmod)	mcttw
-0.0519107	8.2024264
0.0107103	0.058124
0.3699937	0.1988875
23.491431	40
0.9292325	1.5822494

	with indic	without indic
r	0.724535	0.60827109
r'	0.9171261	0.70617249
N	42	42

z obt= 0.9315459

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

iii) Effect of variables describing 'mix type' with mcttw variable.

strfail	mcttw	mixhigh?	mixlow?
-0.0049216	-0.0007598	0.0009906	0.01894538
0.002037	0.0020381	0.00029619	0.00192395
0.3429349	0.0054403	#N/A	#N/A
6.6109778	38	#N/A	#N/A
0.000587	0.0011247	#N/A	#N/A

t	0.3727875	3.34449775	9.84710903
N	42		
df	38		

strfail	mcttw
0.0010727	0.0168084
0.0003087	0.0016756
0.2318231	0.0057334
12.071341	40
0.0003968	0.0013149

t of r= 3.47438349

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.5856065	0.48148013
r'	0.6709531	0.52490931
N	42	42

z obt= 0.6449118

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

iii) Effect of variables describing 'mix type' with mcttw variable.

log(fs)	mctbin	mixhigh?	mixlow?
-0.050503374	0.1015304	-0.01096185	6.18112111
0.04552596	0.0422801	0.00215634	0.03603959
0.618962631	0.1125616	#N/A	#N/A
20.57591716	38	#N/A	#N/A
0.78209818	0.4814647	#N/A	#N/A

t	2.4013758	5.08355525	171.509192
N	42		
df	38		

log(fs)	mctbin
-0.013641549	6.2298589
0.002093901	0.0320556
0.514821496	0.1237996
42.44388341	40
0.650509312	0.6130535

t of r= 6.51489704

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.7867418	0.71751062
r'	1.0628226	0.90249513
N	42	42

z obt= 0.7079871

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

iii) Effect of variables describing 'mix type' with mcttw variable.

log(ELRstress)	mctbin	mixhigh?	mixlow?
-0.069105593	0.0904956	-0.01556066	6.11677648
0.050153522	0.0465777	0.00237552	0.03970289
0.695398671	0.1240032	#N/A	#N/A
28.91774368	38	#N/A	#N/A
1.333985527	0.5843177	#N/A	#N/A

t	1.9428935	6.55042343	154.063741
N	42		
df	38		

log(ELRstress)	mctbin
-0.018510121	6.1596572
0.002270167	0.0347541
0.624348973	0.1342211
66.48180661	40
1.197690661	0.7206126

t of r= 8.15363763

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.8339057	0.79015756
r'	1.2008237	1.07185098
N	42	42

z obt= 0.569528

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

iii) Effect of variables describing 'mix type' with mcttw variable.

log(compmod)	mctbin	mixhigh?	mixlow?
0.090214	0.0738814	-0.01960975	8.15346687
0.0729687	0.0677663	0.00345616	0.057764
0.5075193	0.180413	#N/A	#N/A
13.053461	38	#N/A	#N/A
1.2746255	1.2368564	#N/A	#N/A

t	1.0902384	5.67385446	141.151347
N	42		
df	38		

log(compmod)	mctbin
-0.0186031	8.1918831
0.0030512	0.0467105
0.4816903	0.1803972
37.173943	40
1.2097566	1.3017253

t of r= 6.09704381

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.7124039	0.69403915
r'	0.8920482	0.85570692
N	42	42

z obt= 0.1604786

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

iii) Effect of variables describing 'mix type' with mcttw variable.

strfail	mctbin	mixhigh?	mixlow?
-0.0082893	0.0005447	0.00035253	0.01981554
0.0021929	0.0020366	0.00010387	0.00173598
0.3473627	0.0054219	#N/A	#N/A
6.7417651	38	#N/A	#N/A
0.0005946	0.0011171	#N/A	#N/A

t	0.2674636	3.39401835	11.4146116
N	42		
df	38		

strfail	mctbin
0.0001514	0.0198907
0.000108	0.0016537
0.0468316	0.0063865
1.9653035	40
8.016E-05	0.0016315

t of r= 1.40189284
[t 0.25(40)= 2.021]

	with indic	without indic
r	0.5893748	0.21640617
r'	0.6767076	0.21988261
N	42	42

z obt= 2.0172846

z obt > z 0.025 (=+/- 1.96) therefore there is a significant differe

v) Effect of variable describing mix type on the drying process.

log(mctw)	log(time)	highmixyes?	lowmixyes?
-0.12300116	0.14866226	-0.5835668	1.3842448
0.02583012	0.02300424	0.0182417	0.027019
0.82381006	0.14870497	#N/A	#N/A
350.676975	225	#N/A	#N/A
23.2637365	4.97546279	#N/A	#N/A

t	6.46238463	31.990813	51.232227
N	196		
df	225		

log(mctw)	log(time)
-0.55602255	1.38240022
0.02309165	0.02901861
0.72402447	0.1833488
579.795643	221
19.4908648	7.42930924

t of r= 23.694537

[t 0.25(100)=1.984]

	with indic	without indic
r	0.90763983	0.8508963
r'	1.51396312	1.2593915
N	196	196

z obt= 0.67094088

zobt < z0.25(=+/- 1.96) there is no significant difference

iii) Effect of variables describing 'mix type' with mcttw variable.

strfail - ELRstress	mcttw
0.000970169	0.0035363
0.000171831	0.0009325
0.443501256	0.0031909
31.87796991	40
0.000324567	0.0004073

t	3.7921819
N	42
df	40

strfail - ELRstress	mctbin
0.000231663	0.0051596
6.23873E-05	0.0009551
0.256348464	0.0036886
13.78863361	40
0.000187603	0.0005442

t of r= 3.71330494

[t 0.25(40)= 2.021]

	with indic	without indic
r	0.6659589	0.50630866
r'	0.8034461	0.55775342
N	42	42

z obt= 1.0849493

z obt < z 0.025 (=+/- 1.96) therefore there is no significant difference

Appendix E: probability of form abnormalities in stress/ strain graphs of test series 4 and 5.

To test if the observed frequency of the stress/ strain abnormalities of test series 4 and 5 are fairly distributed across the three mix types a null hypothesis is created stating that there is no significant difference between the observed and the expected frequency of the occurrence of the different graphical forms. This hypothesis is tested by comparing the Chi square statistic calculated for the sample with a critical Chi square value obtained from tables.

Observed frequency of graphical forms:

mix type	graphical form				
	none	both	drop	2mod	TOTAL
high	9	4	0	0	13
medium	9	2	3	2	16
low	7	5	0	1	13
TOTAL	25	11	3	3	42

Calculation of expected frequency of graphical forms if the null hypothesis is true:

mix type	graphical form				
	none	both	drop	2mod	TOTAL
high	7.74	3.40	0.93	0.93	13
medium	9.52	4.19	1.14	1.14	16
low	7.74	3.40	0.93	0.93	13
TOTAL	25	11	3	3	42

Calculation of Chi square statistic:

mix type	graphical form	observed frequency(O)	expected frequency(E)	(O - E)^2/ E
high	none	9	7.74	0.21
	both	4	3.40	0.11
	drop	0	0.93	0.93
	2mod	0	0.93	0.93
medium	none	9	9.52	0.03
	both	2	4.19	1.14
	drop	3	1.14	3.03
	2mod	2	1.14	0.65
low	none	7	7.74	0.07
	both	5	3.40	0.75
	drop	0	0.93	0.93
	2mod	1	0.93	0.01
			Total	**8.79**

That is: Chi square statistic for sample = sum (O - E)^2/ E = 8.79.

Number of degrees of freedom = (number of rows -1) x (number of columns -1)
= 2 x 3 = 6

From tables critical value of Chi square for 6 degrees of freedom at 0.05 significance level (two tailed) is 12.6.

As 8.79 < 12.6 accept null hypothesis: there is no significant bias in the distribution of graphical forms across the mix types.

Appendix: probability of form abnormalities in stress/ strain graphs of test series 4 and 5

Appendix F: ANOVA tables

ANOVA tables: test series 4 and 5

variance of distribution of all test moisture contents

source of variation	df	sum of squares	mean square	F value	p value
mctbin	2	770.7518	385.3759	5.515707*	0.007772*
error	39	2724.884	69.86882		

variance of distribution of test moisture contents < 18% mctbin

source of variation	df	sum of squares	mean square	F value	p value
mctbin	2	48.0452	24.0226	1.278979	0.293557
error	29	544.6966	18.78264		

ANOVA tables: experimental wall

Initial drying progress: time period 1

source of variation	df	sum of squares	mean square	F value	p value
probe	14	2.130338	0.152167	1.2142	0.355985
error	15	1.879845	0.125323		
time	10	3.50001	0.350001	206.0814*	0.000000*
probe* time	140	0.2254	0.00161	0.948	0.625138
error	150	0.2547	0.001698		

source of variation	df	sum of squares	mean square	F value	p value
lift	1	0.139298	0.139298	1.0076	0.324072
error	28	3.870888	0.138246		
time	10	3.50001	0.350001	220.102*	0.000000*
lift* time	10	0.0349	0.00349	2.1948*	0.018290*
error	280	0.4452	0.00159		

environmental progress: time periods 2- 5

source of variation	df	sum of squares	mean square	F value	p value
probe	8	909.5768	113.6971	1.21282	0.346
error	18	1687.424	93.74577		
time	18	565.0416	31.3912	47.71039*	0.000000*
probe* time	144	217.224	1.5085	2.29274*	0.000000*
error	324	213.1758	0.65795		

source of variation	df	sum of squares	mean square	F value	p value
lift	2	1251.203	625.6014	11.15653*	0.000375*
error	24	1345.798	56.0749		
time	18	565.0416	31.3912	34.40831*	0.000000*
lift*time	36	36.2844	1.0079	1.10473	0.315572
error	432	394.1179	0.91231		

environmental progress: 'winter period' (time periods 2-)

source of variation	df	sum of squares	mean square	F value	p value
probe	8	757.3407	94.66759	1.97495	0.109888
error	18	862.8151	47.93417		
time	8	8.11944	1.01493	1.608803	0.127105
probe*time	64	45.42016	0.70969	1.124965	0.279582
error	144	90.84384	0.63086		

environmental progress: 'summer period' (time periods - 5)

source of variation	df	sum of squares	mean square	F value	p value
probe	8	287.3831	35.92289	0.748993	0.649558
error	18	863.3077	47.96154		
time	9	21.26142	2.36238	4.575950*	0.000022*
probe*time	72	36.65808	0.50914	0.986215	0.517292
error	162	83.63412	0.51626		

environmental progress: decrease in average values between time periods 3 and 4

source of variation	df	sum of squares	mean square	F value	p value
probe	8	28.5311	3.566387	7.857580*	0.000151*
error	18	8.169822	0.453879		

Tukey HSD test. Main effect: lift

lift	1st	2nd	3rd
	10.4403	13.72262	13.78301
1st		0.001400*	0.001184*
2nd	0.001400*		0.997014
3rd	0.001184*	0.997014	

Tukey HSD test. Main effect: lift

probe	3.690932	2.879434	3.601353	1.111105	2.229781	1.185666	0.990619	1.338845	1.391053
	1	2	3	4	5	7	8	9	11
1		0.852806	1	0.004556*	0.230714	0.005997*	0.002946*	0.010591*	0.012854*
2	0.852806		0.914868	0.087037	0.950772	0.111698	0.057392	0.182007	0.212989
3	1	0.914868		0.006339*	0.296811	0.00836*	0.004070*	0.014771*	0.017917*
4	0.004556*	0.087037	0.006339*		0.54165	1	1	0.999961	0.999818
5	0.230714	0.950772	0.296811	0.54165		0.623282	0.41588	0.783029	0.830296
7	0.005997*	0.111698	0.00836*	1	0.623282		0.999988	0.999998	0.999982
8	0.002946*	0.057392	0.004070*	1	0.41588	0.999988		0.999109	0.997606
9	0.010591*	0.182007	0.014771*	0.999961	0.783029	0.999998	0.999109		1
11	0.012854*	0.212989	0.017917*	0.999818	0.830296	0.999982	0.997606	1	

Appendix G: experimental wall data, time period 1

	period 1 29/7/93	period 1 30/7/93	period 1 2/8/93	period 1 4/8/936	period 1 5/8/93	period 1 6/8/93	period 1 11/8/93	period 1 12/8/93	period 1 13/8/93	period 1 17/8/93	period 1 18/8/93
2nd lift											
1	1.33	1.30	1.32	1.28	1.28	1.24	1.18	1.16	1.14	1.12	1.12
2	1.29	1.26	1.24	1.20	1.18	1.18	1.10	1.10	1.08	1.06	1.06
3	1.06	0.94	0.86	0.94	0.86	0.84	0.80	0.80	0.80	0.76	0.78
4	1.35	1.28	1.26	1.24	1.20	1.20	1.14	1.12	1.10	1.08	1.16
5	1.38	1.38	1.38	1.36	1.30	1.32	1.22	1.20	1.18	1.18	1.16
6	1.25	1.12	1.14	1.00	0.98	0.96	0.94	0.92	0.88	0.84	0.86
7	1.28	1.20	1.16	1.14	1.10	1.10	1.02	1.00	0.98	0.96	0.98
8	1.36	1.30	1.30	1.24	1.18	1.18	1.10	1.08	1.06	0.96	1.04
9	1.31	1.20	1.18	1.16	1.08	1.08	1.06	1.04	1.02	1.02	1.00
10	1.28	1.18	1.16	1.14	1.12	1.10	1.02	1.00	0.98	0.96	0.98
11	1.32	1.28	1.24	1.22	1.18	1.18	1.08	1.06	1.06	1.00	1.00
12	1.36	1.34	1.30	1.26	1.22	1.24	1.15	1.14	1.12	1.08	1.06
13	1.30	1.28	1.24	1.20	1.18	1.16	1.08	1.06	1.02	0.98	0.96
14	1.25	1.20	1.16	1.12	1.10	1.10	1.01	1.00	1.00	0.96	0.96
15	1.26	1.20	1.18	1.14	1.10	1.10	0.98	0.98	0.96	0.90	0.90
3rd lift											
1	1.12	1.10	1.04	1.04	1.04	1.00	0.92	0.92	0.92	0.92	0.88
2	1.30	1.26	1.24	1.18	1.16	1.14	1.02	1.02	0.92	0.94	0.98
3	1.28	1.26	1.08	0.90	1.02	0.88	0.92	0.88	0.86	0.82	0.84
4	1.34	1.32	1.26	1.22	1.20	1.06	1.10	1.10	1.06	1.02	1.02
5	1.30	1.32	1.28	1.24	1.24	1.20	1.16	1.12	1.08	1.08	1.06
6	1.36	1.36	1.30	1.26	1.24	1.22	1.16	1.10	1.10	1.10	1.04
7	1.24	0.96	0.84	0.94	0.98	0.86	0.82	0.80	0.76	0.68	0.70
8	0.82	0.86	0.90	0.98	1.00	0.94	0.74	0.72	0.68	0.68	0.68
9	1.44	1.44	1.36	1.30	1.28	1.26	1.18	1.14	1.14	1.12	1.12
10	1.18	1.16	1.10	1.04	1.04	1.02	0.98	0.96	0.96	0.94	0.94
11	1.24	1.26	1.20	1.16	1.14	1.10	1.00	1.02	1.02	0.96	0.96
12	1.36	1.32	1.26	1.20	1.18	1.14	1.02	0.88	0.92	1.02	0.88
13	1.24	1.24	1.16	1.10	1.08	1.08	1.00	1.00	0.98	0.98	0.96
14	1.38	1.36	1.28	1.20	1.18	1.16	1.06	1.02	1.04	1.02	1.02
15	1.32	1.28	1.22	1.16	1.14	1.14	1.08	1.02	1.02	1.00	1.00
average lift moisture content											
2nd	1.29	1.23	1.21	1.18	1.14	1.13	1.06	1.04	1.03	0.99	1.00
3rd	1.26	1.23	1.17	1.13	1.13	1.08	1.01	0.98	0.96	0.95	0.94
varience of average lift moisture content											
2nd	5.44E-03	1.03E-02	1.33E-02	1.05E-02	1.16E-02	1.28E-02	1.02E-02	9.50E-03	9.20E-03	1.08E-02	1.04E-02
3rd	2.01E-02	2.26E-02	2.09E-02	1.39E-02	8.52E-03	1.35E-02	1.44E-02	1.37E-02	1.49E-02	1.67E-02	1.45E-02
overall averages											
2nd	1.12										
3rd	1.08										
probe position averages											
1	1.23	1.20	1.18	1.16	1.16	1.12	1.05	1.04	1.03	1.02	1.00
2	1.30	1.26	1.24	1.19	1.17	1.16	1.06	1.06	1.00	1.00	1.02
3	1.17	1.10	0.97	0.92	0.94	0.86	0.86	0.84	0.83	0.79	0.81
4	1.35	1.30	1.26	1.23	1.20	1.13	1.12	1.11	1.08	1.05	1.09
5	1.34	1.35	1.33	1.30	1.27	1.26	1.19	1.16	1.13	1.13	1.11
6	1.31	1.24	1.22	1.13	1.11	1.09	1.05	1.01	0.99	0.97	0.95
7	1.26	1.08	1.00	1.04	1.04	0.98	0.92	0.90	0.87	0.82	0.84
8	1.09	1.08	1.10	1.11	1.09	1.06	0.92	0.90	0.87	0.82	0.86
9	1.38	1.32	1.27	1.23	1.18	1.17	1.12	1.09	1.08	1.07	1.06
10	1.23	1.17	1.13	1.09	1.08	1.06	1.00	0.98	0.97	0.95	0.96
11	1.28	1.27	1.22	1.19	1.16	1.14	1.04	1.04	1.04	0.98	0.98
12	1.36	1.33	1.28	1.23	1.20	1.19	1.09	1.01	1.02	1.05	0.97
13	1.27	1.26	1.20	1.15	1.13	1.12	1.04	1.03	1.00	0.98	0.96
14	1.32	1.28	1.22	1.16	1.14	1.13	1.04	1.01	1.02	0.99	0.99
15	1.29	1.24	1.20	1.15	1.12	1.12	1.03	1.00	0.99	0.95	0.95

overall probe position averages		overall probe position variances	
1	1.11	1	6.03E-03
2	1.13	2	1.07E-02
3	0.92	3	1.35E-02
4	1.17	4	8.78E-03
5	1.23	5	7.70E-03
6	1.10	6	1.26E-02
7	0.98	7	1.48E-02
8	0.99	8	1.21E-02
9	1.18	9	1.06E-02
10	1.06	10	7.93E-03
11	1.12	11	1.12E-02
12	1.16	12	1.70E-02
13	1.10	13	1.10E-02
14	1.12	14	1.26E-02
15	1.09	15	1.28E-02

Note: these values are TDR readings in meters.

Appendix H: experimental wall data, time period 2- 5

	period 2 12/2/95	period 2 13/2/95	period 2 14/2/95	period 2 15/2/95	period 3 18/3/95	period 3 19/3/95	period 3 20/3/95	period 3 21/3/95	period 3 22/3/95	period 4 28/7/95	period 4 29/7/95	period 4 30/7/95	period 4 31/7/95
1st lift													
1	14.46	14.90	15.53	15.92	14.74	14.74	15.14	14.87	14.87	9.70	11.42	10.40	11.42
2	13.89	14.07	13.31	14.04	13.60	13.60	13.75	14.60	13.89	10.40	10.91	11.42	11.42
3	15.53	14.90	13.31	14.87	12.70	13.31	12.85	12.54	13.31	8.97	9.70	10.05	10.40
4	6.48	8.83	6.68	6.88	5.87	6.28	8.79	8.42	9.70	8.23	5.46	7.08	8.23
5	12.70	12.88	12.70	12.23	13.60	12.07	13.15	12.54	12.70	10.74	11.42	10.40	10.40
7	10.74	8.83	7.85	8.79	10.74	7.47	10.23	10.23	10.91	7.08	9.34	7.47	8.97
8	12.07	10.95	9.34	8.42	10.74	10.74	10.23	11.91	16.04	9.70	9.70	9.70	11.42
9	10.40	8.08	8.61	8.04	10.40	10.40	10.57	10.91	11.58	7.85	8.97	7.85	10.05
11	10.40	10.26	9.34	10.23	10.40	10.40	10.23	10.57	9.88	7.85	8.61	8.23	8.23
2nd lift													
1	16.94	17.32	17.21	16.76	16.64	16.04	16.28	16.76	16.04	14.04	14.74	13.89	14.32
2	16.94	15.92	16.52	16.28	16.87	17.21	16.76	16.52	16.76	16.16	12.38	13.31	13.75
3	15.99	16.41	16.04	16.04	15.92	15.27	15.53	15.53	15.01	13.15	12.07	12.70	13.45
4	13.54	13.75	13.31	13.89	14.60	14.46	13.60	13.89	13.89	11.58	13.60	12.38	13.15
5	13.84	12.54	12.70	12.38	13.15	14.46	13.00	15.01	13.31	10.91	12.70	11.91	13.45
7	13.54	13.15	12.70	12.70	12.85	12.70	12.70	13.00	12.70	11.25	11.42	11.74	11.91
8	14.95	14.87	14.74	14.46	14.87	15.53	14.46	14.74	15.01	13.75	14.18	15.53	14.60
9	14.68	14.32	14.46	13.89	14.04	14.18	14.18	14.46	14.46	13.15	13.89	14.18	13.45
11	14.12	13.75	13.89	13.60	14.60	14.46	15.01	14.18	14.18	13.45	13.31	12.38	13.45
3rd lift													
1	17.39	17.54	17.43	17.64	15.66	15.79	16.04	15.79	16.04	11.91	12.70	12.70	13.45
2	18.22	16.87	18.26	18.06	17.32	17.85	17.21	17.21	17.43	14.32	15.79	14.74	14.87
3	17.39	17.32	17.43	18.06	16.16	17.21	17.21	17.21	17.43	13.75	15.27	14.46	14.04
4	14.41	14.32	13.89	14.18	14.60	14.46	14.18	14.18	13.89	11.25	12.07	12.70	11.58
5	15.48	14.32	13.31	14.46	13.75	14.18	14.74	13.89	14.18	11.58	12.38	11.74	11.91
7	11.35	9.16	10.05	9.70	10.57	9.70	10.05	9.34	9.70	9.88	9.70	10.05	10.23
8	14.95	11.58	13.31	15.01	14.32	14.74	15.01	14.18	13.89	13.45	14.18	13.60	14.04
9	16.48	16.41	17.21	18.26	18.73	17.64	17.64	16.52	16.76	15.66	15.27	16.04	15.66
11	13.25	13.15	13.31	13.31	13.15	13.31	13.00	13.00	12.38	12.54	11.74	11.42	13.15
average lift moisture content													
1st	11.85	11.52	10.74	11.05	11.42	11.00	11.66	11.84	12.54	8.95	9.50	9.18	10.06
2nd	14.95	14.67	14.62	14.45	14.84	14.92	14.61	14.90	14.59	13.05	13.14	13.11	13.51
3rd	15.43	14.52	14.91	15.41	14.92	14.99	15.01	14.59	14.63	12.70	13.23	13.05	13.21
varience of average lift moisture content													
1st	6.62	6.60	8.14	9.75	6.21	6.97	3.97	3.84	4.32	1.43	2.98	2.12	1.51
2nd	1.66	2.25	2.45	2.21	1.79	1.46	1.77	1.32	1.45	2.37	1.04	1.36	0.51
3rd	4.36	7.27	6.84	7.42	5.13	5.85	5.23	5.54	5.87	2.79	3.65	3.08	2.61
overall lift average moisture content					overall lift varience								
1st	10.44				1st	1.22							
2nd	13.72				2nd	0.99							
3rd	13.78				3rd	1.31							
probe position averages													
1	16.26	16.59	16.73	16.77	15.68	15.52	15.82	15.81	15.65	11.88	12.95	12.33	13.06
2	16.35	15.62	16.03	16.13	15.93	16.22	15.91	16.11	16.03	13.63	13.03	13.15	13.35
3	16.30	16.21	15.59	16.32	14.92	15.26	15.20	15.10	15.25	11.96	12.35	12.40	12.63
4	11.48	12.30	11.29	11.65	11.69	11.73	12.19	12.16	12.49	10.35	10.38	10.72	10.99
5	14.00	13.25	12.90	13.02	13.50	13.57	13.63	13.81	13.39	11.08	12.16	11.35	11.92
7	11.88	10.38	10.20	10.39	11.39	9.95	10.99	10.86	11.10	9.40	10.15	9.75	10.37
8	13.99	12.47	12.46	12.63	13.31	13.67	13.23	13.61	14.98	12.30	12.69	12.94	13.35
9	13.85	12.94	13.43	13.40	14.39	14.08	14.13	13.97	14.27	12.22	12.71	12.69	13.06
11	12.59	12.39	12.18	12.38	12.72	12.72	12.75	12.59	12.15	11.28	11.22	10.68	11.61
overall position averages			overall position variances				1st lift	2nd lift	3rd lift				
1	14.15		1	3.63		1	13.01	15.16	14.27				
2	14.52		2	2.13		2	12.46	15.05	16.06				
3	13.68		3	3.54		3	11.51	13.89	15.63				
4	11.30		4	0.50		4	7.75	13.11	13.05				
5	12.28		5	1.46		5	11.61	12.50	12.73				
7	10.17		7	0.62		7	8.84	12.05	9.62				
8	12.85		8	0.68		8	10.40	14.47	13.69				
9	13.12		9	0.60		9	9.25	13.78	16.34				
11	11.76		11	0.56		11	9.14	13.48	12.67				

Note: these values are converted from TDR readings in meters into gravimetric moisture contents using the experimental calibration equation.

	period 4 1/8/95	period 4 2/8/95	period 4 3/8/95	period 4 4/8/95	period 5 7/8/95	period 5 8/8/95
1st lift						
1	12.38	11.74	11.42	11.08	11.08	11.42
2	12.07	11.74	11.42	11.08	11.08	10.40
3	10.05	8.61	8.97	8.97	10.40	9.34
4	8.61	5.87	10.05	9.70	8.23	7.85
5	10.74	10.74	10.74	9.70	10.40	10.74
7	8.61	8.61	7.85	6.28	9.34	8.61
8	8.61	8.97	11.08	10.74	8.97	8.23
9	8.97	8.97	8.23	8.61	8.97	8.23
11	7.47	8.97	7.85	8.23	8.61	7.85
2nd lift						
1	14.18	13.60	12.85	13.00	13.31	14.18
2	14.18	13.31	13.15	13.31	13.31	13.31
3	13.31	11.74	11.58	11.42	11.74	11.08
4	12.38	12.38	12.54	12.07	12.38	11.74
5	11.08	10.74	11.58	10.74	13.31	10.74
7	11.42	11.08	10.91	11.08	11.08	11.08
8	13.31	14.46	14.04	13.89	14.18	13.31
9	13.31	13.31	12.85	13.00	12.70	13.31
11	12.38	12.70	12.54	12.70	12.38	13.00
3rd lift						
1	12.07	11.74	12.23	10.05	13.31	11.74
2	14.46	14.74	14.60	14.46	14.74	13.89
3	15.53	14.46	14.04	12.70	13.31	13.89
4	13.00	11.42	11.58	12.38	12.07	11.74
5	12.07	10.05	10.91	10.05	11.08	11.74
7	8.97	8.97	8.42	8.97	9.34	8.61
8	13.60	13.60	12.85	12.70	12.07	13.00
9	15.01	15.01	14.32	15.53	15.27	16.99
11	13.00	13.31	12.23	12.07	12.38	11.08
average lift moisture content						
1st	9.72	9.36	9.73	9.38	9.68	9.19
2nd	12.84	12.59	12.45	12.36	12.71	12.42
3rd	13.08	12.59	12.35	12.10	12.62	12.52
varience of average lift moisture content						
1st	2.57	3.00	2.06	2.17	1.04	1.63
2nd	1.09	1.33	0.80	1.05	0.78	1.40
3rd	3.43	4.12	3.35	4.04	2.92	4.80
probe position averages						
1	12.88	12.36	12.16	11.38	12.56	12.45
2	13.57	13.26	13.06	12.95	13.04	12.53
3	12.96	11.60	11.53	11.03	11.82	11.44
4	11.33	9.89	11.39	11.38	10.89	10.45
5	11.30	10.51	11.08	10.16	11.60	11.08
7	9.66	9.55	9.06	8.78	9.92	9.43
8	11.84	12.35	12.66	12.44	11.74	11.51
9	12.43	12.43	11.80	12.38	12.31	12.84
11	10.95	11.66	10.87	11.00	11.12	10.65

Appendix: experimental wall data, time periods 2- 5

Appendix I: test series 4 and 5 drying data

id	sample information			date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
H03	mcm	24.62		10/5/94	10:22	182.94	0.00	39.71	0.00	24.62	
	oven	3		10/5/94	12:01	178.00	1.65	34.28	2.70	21.25	2.99
	dry mass	146.8		10/5/94	14:44	170.40	4.37	25.93	6.86	16.08	2.80
	start time	10/5/94	10:22	10/5/94	15:30	168.20	5.13	23.51	8.06	14.58	2.87
	mct	9.14		10/5/94	16:22	165.90	6.00	20.99	9.32	13.01	2.65
	O/I	1		11/5/94	10:39	162.10	6.00	16.81	11.39	10.42	
				11/5/94	11:12	160.80	6.55	15.38	12.10	9.54	2.36
				11/5/94	11:23	160.40	6.73	14.94	12.32	9.26	2.18
H04	mcm	24.62		10/5/94	10:28	186.87	0.00	39.71	0.00	24.62	
	oven	3		10/5/94	12:01	182.90	1.55	35.44	2.12	21.97	2.56
	dry mass	149.95		10/5/94	14:44	176.50	4.27	28.56	5.55	17.71	2.36
	start time	10/5/94	10:28	10/5/94	15:30	174.80	5.03	26.73	6.46	16.57	2.22
	mct	9.19		10/5/94	16:22	172.70	5.90	24.47	7.58	15.17	2.42
	O/I	1		11/5/94	10:39	168.70	5.90	20.17	9.72	12.50	
				11/5/94	11:12	167.30	6.45	18.66	10.47	11.57	2.55
				11/5/94	12:11	164.70	7.43	15.87	11.86	9.84	2.64
				11/5/94	12:23	164.20	7.63	15.33	12.13	9.50	2.50
				11/5/94	12:30	163.90	7.75	15.01	12.29	9.30	2.57

id	sample information	date&time	mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
H05 mcm	24.09	16/5/94 9:57	181.16			0.00		
oven	5	16/5/94 11:30	176.70	1.55	33.93	2.46	21.04	
dry mass	145.99	16/5/94 15:05	168.40	5.13	24.76	7.04	15.35	2.32
start time	16/5/94 9:57	16/5/94 15:57	166.40	6.00	22.55	8.15	13.98	2.31
mct	5.91	16/5/94 17:02	164.20	7.08	20.12	9.36	12.47	2.03
O/I	1	17/5/94 9:11	163.80	7.08	19.68	9.58	12.20	
		17/5/94 11:07	159.60	9.02	15.04	11.90	9.32	2.17
		17/5/94 11:56	158.00	9.83	13.27	12.78	8.23	1.96
		17/5/94 12:22	157.30	10.27	12.50	13.17	7.75	1.62
		17/5/94 12:51	156.60	10.75	11.72	13.56	7.27	1.45
		17/5/94 13:34	155.60	11.47	10.62	14.11	6.58	1.40
		17/5/94 14:22	154.80	12.27	9.73	14.55	6.03	1.00
H06 mcm	24.09	16/5/94 9:57	183.33			0.00		
oven	5	16/5/94 11:30	179.20	1.55	34.35	2.25	21.29	
dry mass	147.74	16/5/94 15:05	171.10	5.13	25.50	6.67	15.81	2.26
start time	16/5/94 9:57	16/5/94 15:57	169.40	6.00	23.65	7.60	14.66	1.96
mct	5.63	16/5/94 17:02	167.10	7.08	21.14	8.85	13.10	2.12
O/I	1	17/5/94 9:11	166.90	7.08	20.92	8.96	12.97	
		17/5/94 11:07	162.40	9.02	16.00	11.42	9.92	2.33
		17/5/94 11:56	160.80	9.83	14.26	12.29	8.84	1.96
		17/5/94 12:22	159.90	10.27	13.28	12.78	8.23	2.08
		17/5/94 12:51	159.00	10.75	12.29	13.27	7.62	1.86
		17/5/94 13:34	157.90	11.47	11.09	13.87	6.88	1.53
		17/5/94 14:22	156.80	12.27	9.89	14.47	6.13	1.38
		17/5/94 15:03	156.20	12.95	9.24	14.80	5.73	0.88

Appendix: test series 4 and 5 drying data

id		sample information		date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
H07	mcm	27.12		3/10/94	12:25						
	oven	6		3/10/94	15:31	174.00	3.10	33.36		20.68	
	dry mass	144.18		4/10/94	10:04	151.00	21.65	7.63		4.73	1.24
	start time	3/10/94	12:25								
	mct	4.97									
	O/I	0									
H08	mcm	27.12		3/10/94	12:25						
	oven	6		3/10/94	15:31	168.00	3.10	32.87		20.38	
	dry mass	139.56		4/10/94	10:04	146.00	21.65	7.44		4.61	1.19
	start time	3/10/94	12:25								
	mct	4.33									
	O/I	0									
H09	mcm	22.63		5/10/94	10:34						
	oven	7		5/10/94	14:27	174.00	3.88	26.57	5.02	16.47	
	dry mass	149.39		6/10/94	10:12	153.08	23.63	3.98	16.44	2.47	1.06
	start time	5/10/94	10:34	6/10/94	10:43	152.99	24.15	3.89	16.49	2.41	0.17
	mct	2.07		6/10/94	14:58	152.38	28.40	3.23	16.82	2.00	0.14
	O/I	0									
H10	mcm	23.7		5/10/94	10:34						
	oven	7		5/10/94	14:27	169.18	3.88	28.55	4.85	17.70	
	dry mass	143.74		6/10/94	10:12	148.10	23.63	4.89	16.71	3.03	1.07
	start time	5/10/94	10:34	6/10/94	10:43	148.00	24.15	4.78	16.76	2.96	0.19
	mct	3.03									
	O/I	0									

Appendix: test series 4 and 5 drying data

id		sample information		date&time	mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
H11	mcm	26.66		7/10/94 16:19						
	oven	8		10/10/94 9:42	145.56	65.38	5.33	18.44	3.31	
	dry mass	140.9		10/10/94 14:57	145.50	70.63	5.27	18.47	3.26	0.01
	start time	7/10/94	16:19	11/10/94 9:42	145.41	89.38	5.16	18.52	3.20	0.00
	mct	2.94		11/10/94 12:42	145.38	92.38	5.13	18.54	3.18	0.01
	O/I	0		11/10/94 16:12	145.36	95.88	5.11	18.55	3.17	0.01
				12/10/94 10:16	145.17	113.95	4.89	18.66	3.03	0.01
				12/10/94 12:05	145.16	115.77	4.88	18.66	3.02	0.01
				12/10/94 16:43	145.15	120.40	4.87	18.67	3.02	0.00
				13/10/94 9:41	145.00	137.37	4.69	18.75	2.91	0.01
				13/10/94 13:07	144.99	140.80	4.68	18.76	2.90	0.00
				13/10/94 14:46	144.99	142.45	4.68	18.76	2.90	0.00
				14/10/94 11:09	144.90	162.83	4.58	18.81	2.84	0.00
				14/10/94 14:54	144.90	166.58	4.58	18.81	2.84	0.00
H12	mcm	26.66		7/10/94 16:19						
	oven	8		10/10/94 9:42	139.80	65.38	4.56	18.82	2.82	
	dry mass	135.96		10/10/94 14:57	139.75	70.63	4.50	18.85	2.79	0.01
	start time	7/10/94	16:19	11/10/94 9:42	139.67	89.38	4.40	18.89	2.73	0.00
	mct	2.48		11/10/94 12:42	139.64	92.38	4.37	18.91	2.71	0.01
	O/I	0		11/10/94 16:12	139.62	95.88	4.34	18.92	2.69	0.01
				12/10/94 10:16	139.44	113.95	4.13	19.03	2.56	0.01
				12/10/94 12:05	139.44	115.77	4.13	19.03	2.56	0.00
				12/10/94 16:43	139.41	120.40	4.09	19.05	2.54	0.01
				13/10/94 9:41	139.28	137.37	3.94	19.12	2.44	0.01
				13/10/94 13:07	139.26	140.80	3.91	19.13	2.43	0.01
				13/10/94 14:46	139.26	142.45	3.91	19.13	2.43	0.00
				14/10/94 11:09	139.17	162.83	3.81	19.18	2.36	0.00

Appendix: test series 4 and 5 drying data

id		sample information		date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
H13	mcm	24.53		18/10/94	10:34	183.10	0.00	39.57	0.00	24.53	
	oven	8		19/10/94	9:41	152.35	23.12	5.84	16.79	3.62	1.33
	dry mass	147.03		19/10/94	12:13	151.99	25.65	5.44	16.99	3.37	0.14
	start time	18/10/94	10:34	19/10/94	13:15	151.87	26.68	5.31	17.05	3.29	0.12
	mct	3.2									
	O/I	0									
H14	mcm	24.53		18/10/94	10:34	183.63	0.00	39.56		24.53	
	oven	8		19/10/94	9:41	152.83	23.12	5.87	16.90	3.64	1.33
	dry mass	147.46		19/10/94	12:13	152.40	25.65	5.40	17.14	3.35	0.17
	start time	18/10/94	10:34	19/10/94	13:15	152.26	26.68	5.25	17.21	3.26	0.14
	mct	3.34									
	O/I	0									
H16	mcm	25		24/10/94	10:32	179.56	0.00	39.87	0.23	24.72	
	oven	9		24/10/94	11:20	177.74	0.80	37.83	1.24	23.46	2.28
	dry mass	143.97		24/10/94	12:11	175.88	1.65	35.75	2.29	22.16	2.19
	start time	24/10/94	10:32	24/10/94	16:40	166.46	6.13	25.20	7.56	15.62	2.10
	mct	10.76		24/10/94	16:49	166.16	6.28	24.86	7.73	15.41	2.00
	O/I	1		25/10/94	9:39	166.11	6.28	24.80	7.76	15.38	
				25/10/94	10:37	163.93	7.25	22.36	8.98	13.86	2.26
				25/10/94	11:14	162.81	7.87	21.11	9.61	13.09	1.82
				25/10/94	12:57	159.49	9.58	17.39	11.46	10.78	1.93
L04	mcm	16.32		10/5/94	9:58	211.41	0.00	74.18	0.00	16.32	
	oven	3		10/5/94	11:51	206.70	1.88	62.40	2.23	13.73	2.50
	dry mass	181.75		10/5/94	14:44	200.50	4.77	46.89	5.16	10.32	2.15
	start time	10/5/94	9:58	10/5/94	15:08	199.60	5.17	44.64	5.59	9.82	2.25
	mct	9.1		10/5/94	15:29	198.90	5.52	42.89	5.92	9.44	2.00
	O/I	0		10/5/94	15:36	198.50	5.63	41.89	6.11	9.22	3.43

Appendix: test series 4 and 5 drying data

id		sample information		date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
L05	mcm	16.63		10/5/94	16:54	207.63	0.00	75.60	0.00	16.63	
	oven	3		11/5/94	9:25	181.90	16.52	9.91	12.39	2.18	1.56
	dry mass	178.02									
	start time	10/5/94	16:54								
	mct	2.13									
	O/I	0									
L06	mcm	16.63		10/5/94	16:58	206.34				13.53	
	oven	3									
	dry mass	181.75									
	start time										
	mct	2.28									
	O/I	0									
L07	mcm	16.04		12/5/94	9:50	207.90	0.00	72.30	0.12	15.91	
	oven	4		12/5/94	15:24	192.70	5.57	33.78	7.42	7.43	2.73
	dry mass	179.37		12/5/94	16:16	190.70	6.43	28.71	8.38	6.32	2.31
	start time	12/5/94	9:50	13/5/94	9:42	190.70	6.43	28.71	8.38	6.32	
	mct	5.65		13/5/94	9:55	190.00	6.65	26.94	8.72	5.93	3.23
	O/I	1		13/5/94	10:01	189.80	6.75	26.43	8.81	5.81	2.00
L08	mcm	16.04		12/5/94	9:50	209.50	0.00	72.68	0.04	15.99	
	oven	4		12/5/94	15:24	194.10	5.57	33.92	7.39	7.46	2.77
	dry mass	180.62		12/5/94	16:16	192.30	6.43	29.39	8.25	6.47	2.08
	start time	12/5/94	9:50	13/5/94	9:42	192.10	6.43	28.89	8.35	6.36	
	mct	5.73		13/5/94	9:55	191.40	6.65	27.13	8.68	5.97	3.23
	O/I	1		13/5/94	10:01	191.20	6.75	26.63	8.77	5.86	2.00

Appendix: test series 4 and 5 drying data

id	sample information		date&time	mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
L09 mcm	16.61		16/5/94 9:57						
oven	5		16/5/94 11:30	207.30	1.55	65.36	1.91	14.38	
dry mass	181.24		16/5/94 15:05	202.60	1.55	53.57	4.14	11.79	
start time	16/5/94	9:57	16/5/94 15:57	200.60	2.42	48.55	5.08	10.68	2.31
mct	7.73		16/5/94 17:02	198.10	3.50	42.28	6.27	9.30	2.31
O/I	1*2		17/5/94 9:11	197.80	5.05	41.53	6.41	9.14	
			17/5/94 10:06	195.50	5.97	35.76	7.50	7.87	2.51
L10 mcm	17.88		5/10/94 15:42						
oven	7		6/10/94 10:11	179.85	18.48	14.63	12.44	3.22	
dry mass	174.24		6/10/94 10:45	179.70	19.05	14.24	12.51	3.13	0.26
start time	5/10/94	15:42	6/10/94 11:35	179.48	19.88	13.67	12.62	3.01	0.26
mct	2.6		6/10/94 14:57	178.83	23.25	11.97	12.93	2.63	0.19
O/I	0		6/10/94 16:00	178.65	24.30	11.50	13.02	2.53	0.17
L11 mcm	17.88		5/10/94 15:42						
oven	7		6/10/94 10:11	180.97	18.48	15.43	12.29	3.39	
dry mass	175.03		6/10/94 10:45	180.79	19.05	14.96	12.38	3.29	0.32
start time	5/10/94	15:42	6/10/94 11:35	180.57	19.88	14.39	12.48	3.17	0.26
mct	3.21								
O/I	0								

Appendix: test series 4 and 5 drying data

id	sample information			date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
L12	mcm	18.11		7/10/94	12:48	205.10	0.00	71.18	2.07	15.66	
	oven	8		7/10/94	15:29	200.16	2.68	58.52	4.43	12.87	1.84
	dry mass	177.33		7/10/94	16:13	198.74	3.42	54.88	5.11	12.07	1.94
	start time	7/10/94	12:48	7/10/94	16:32	198.10	3.73	53.24	5.42	11.71	2.02
	mct	4.2		10/10/94	9:43	197.77	3.73	52.39	5.57	11.53	
	O/I	1		10/10/94	14:53	189.20	8.90	30.43	9.67	6.69	1.66
				10/10/94	15:56	188.00	9.95	27.35	10.24	6.02	1.14
				10/10/94	16:26	187.51	10.45	26.09	10.47	5.74	0.98
				11/10/94	9:41	187.43	14.18	25.89	10.51	5.70	
				11/10/94	12:40	185.29	17.17	20.40	11.53	4.49	0.72
				11/10/94	14:32	184.61	19.03	18.66	11.86	4.11	0.36
L13	mcm	18.11		7/10/94	12:48	203.40	0.00	70.97	2.11	15.61	
	oven	8		7/10/94	15:29	197.72	2.68	56.30	4.85	12.39	2.12
	dry mass	175.93		7/10/94	16:13	196.21	3.42	52.40	5.57	11.53	2.06
	start time	7/10/94	12:48	7/10/94	16:32	195.59	3.73	50.79	5.87	11.17	1.96
	mct	5.42		10/10/94	9:43	195.38	3.73	50.25	5.97	11.06	
	O/I	1		10/10/94	14:53	186.90	8.90	28.34	10.05	6.24	1.64
				10/10/94	15:56	185.82	9.95	25.55	10.57	5.62	1.03
				10/10/94	16:26	185.42	10.45	24.52	10.77	5.39	0.80
L14	mcm	16.12		12/10/94	10:14						
	oven	8		12/10/94	12:03	204.43	1.82	61.12	2.30	13.45	
	dry mass	180.2		12/10/94	16:17	194.96	6.05	37.23	6.83	8.19	2.24
	start time	12/10/94	10:14	12/10/94	16:41	194.12	6.45	35.11	7.23	7.72	2.10
	mct	3.8		12/10/94	16:53	193.74	6.65	34.15	7.41	7.51	1.90
	O/I	1		13/10/94	9:39	193.71	6.65	34.08	7.43	7.50	
				13/10/94	13:09	188.31	10.15	20.46	10.01	4.50	1.54
				13/10/94	14:47	187.17	11.78	17.58	10.55	3.87	0.70
				13/10/94	15:20	186.87	12.33	16.82	10.69	3.70	0.55

Appendix: test series 4 and 5 drying data

id		sample information		date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
L15	mcm	15.86		18/10/94	9:58		0.00				
	oven	8		19/10/94	9:41	181.12	23.72	1.56	13.39	0.34	
	dry mass	180.5		19/10/94	10:43	181.00	24.75	1.26	13.45	0.28	0.12
	start time	18/10/94	9:58								
	mct	0.38									
	O/I	0									
L16	mcm	16.12		19/10/94	16:06	210.83	0.00	70.96	0.44	15.61	
	oven	9		19/10/94	16:57	208.70	0.85	65.65	1.44	14.44	2.51
	dry mass	182.36		20/10/94	14:57	185.50	22.85	7.83	12.40	1.72	1.05
	start time	19/10/94	16:06	24/10/94	12:19	183.73	116.22	3.41	13.24	0.75	0.02
	mct	0.85		24/10/94	13:12	183.74	117.10	3.44	13.23	0.76	-0.01
	O/I	0									
M01	mcm	21.63		12/5/94	10:02	194.62	0.00	49.16	0.00	21.63	
	oven	4		12/5/94	15:24	181.80	5.37	30.95	6.59	13.62	2.39
	dry mass	160.01		12/5/94	16:14	179.80	6.20	28.11	7.61	12.37	2.40
	start time	12/5/94	10:02	13/5/94	9:42	179.70	6.20	27.97	7.67	12.31	
	mct	8.27		13/5/94	11:28	175.10	7.97	21.43	10.03	9.43	2.60
	O/I	1		13/5/94	12:13	173.40	8.72	19.02	10.90	8.37	2.27
M02	mcm	21.63		12/5/94	10:07	195.53	0.00	49.16	0.00	21.63	2.54
	oven	4		12/5/94	15:24	182.40	5.28	30.59	6.72	13.46	2.49
	dry mass	160.76		12/5/94	16:14	180.30	6.12	27.62	7.79	12.15	2.52
	start time	12/5/94	10:07	13/5/94	9:42	180.10	6.12	27.34	7.89	12.03	
	mct	8.92		13/5/94	11:28	175.40	7.88	20.70	10.30	9.11	2.66
	O/I	1									

Appendix: test series 4 and 5 drying data

id	sample information		date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
M03 mcm	19.35		16/5/94	11:30	201.79	0.00		0.00		
oven	5		16/5/94	15:05	192.60	3.58	31.63	4.55	13.92	2.56
dry mass	169.07		16/5/94	15:57	190.70	4.45	29.08	5.49	12.79	2.19
start time	16/5/94	11:30	16/5/94	17:02	188.30	5.53	25.85	6.68	11.37	2.22
mct	2.53		17/5/94	9:11	173.50	21.68	5.96	14.02	2.62	0.92
O/I	0									
M04 mcm	19.35		16/5/94	11:30		0.00				
oven	5		16/5/94	15:05	193.00	3.58	31.02	4.78	13.65	
dry mass	169.82		16/5/94	15:57	190.90	4.45	28.21	5.81	12.41	2.42
start time	16/5/94	11:30	16/5/94	17:02	188.30	5.53	24.73	7.10	10.88	2.40
mct	2.9		17/5/94	9:11	174.80	21.68	6.66	13.76	2.93	0.84
O/I	0									
M05 mcm	19.35		16/5/94	11:30						
oven	5		16/5/94	15:05	191.50	3.58	31.59	4.57	13.90	
dry mass	168.13		16/5/94	15:57	189.50	4.45	28.89	5.56	12.71	2.31
start time	16/5/94	11:30	16/5/94	17:02	187.20	5.53	25.78	6.71	11.34	2.12
mct	6.29		17/5/94	9:11	186.90	5.53	25.37	6.86	11.16	
O/I	1		17/5/94	11:07	182.20	7.47	19.02	9.20	8.37	2.43
			17/5/94	11:56	180.50	8.28	16.72	10.05	7.36	2.08
			17/5/94	12:22	179.70	8.72	15.64	10.45	6.88	1.85
			17/5/94	12:51	178.90	9.20	14.56	10.85	6.41	1.66
M06 mcm	23.69		3/10/94	15:29		0.00				
oven	6		4/10/94	10:05	157.00	18.60	10.26	15.50	4.51	
dry mass	150.22		4/10/94	11:48	157.00	20.32	10.26	15.50	4.51	0.00
start time	3/10/94	15:29								
mct	4.51									
O/I	0									

Appendix: test series 4 and 5 drying data

id	sample information			date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
M07	mcm	23.69		3/10/94	15:29						
	oven	6		4/10/94	10:05	157.00	18.60			4.40	
	dry mass	150.39		4/10/94	15:50	156.00	24.35			3.73	0.17
	start time	3/10/94	15:29								
	mct	3.64									
	O/I	0									
M08	mcm	20.58		5/10/94	10:55	193.98	0.00		0.00		
	oven	7		5/10/94	14:28	185.07	3.55	34.19	4.59	15.04	2.51
	dry mass	160.87		6/10/94	10:07	165.73	23.20	6.87	14.56	3.02	0.98
	start time	5/10/94	10:55	6/10/94	11:37	165.47	24.70	6.50	14.70	2.86	0.17
	mct	2.88		6/10/94	12:23	165.37	25.47	6.36	14.75	2.80	0.13
	O/I	0									
M09	mcm	20.58		5/10/94	10:55						
	oven	7		5/10/94	14:28	183.51	3.55	34.23	4.58	15.06	
	dry mass	159.49		6/10/94	10:07	164.31	23.20	6.87	14.56	3.02	0.98
	start time	5/10/94	10:55	6/10/94	11:37	164.04	24.70	6.48	14.70	2.85	0.18
	mct	1.86		6/10/94	12:23	163.93	25.47	6.33	14.76	2.78	0.14
	O/I	0		6/10/94	15:58	163.48	29.05	5.69	14.99	2.50	0.13
				7/10/94	10:00	162.35	47.08	4.08	15.58	1.79	0.06
				7/10/94	11:09	162.31	48.23	4.02	15.60	1.77	0.03
				7/10/94	11:13	162.30	48.30	4.00	15.61	1.76	0.15

Appendix: test series 4 and 5 drying data

id		sample information		date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
M10	mcm	20.6		10/10/94	15:40		0.00				
	oven	8		11/10/94	9:43	167.14	18.05	10.60	13.21	4.67	
	dry mass	159.69		11/10/94	12:41	166.49	21.02	9.68	13.55	4.26	0.22
	start time	10/10/94	15:40	11/10/94	14:34	166.16	22.90	9.21	13.72	4.05	0.18
	mct	2.35		11/10/94	16:13	165.90	24.55	8.84	13.86	3.89	0.16
	O/I	0		12/10/94	10:15	164.29	42.58	6.55	14.69	2.88	0.09
				12/10/94	12:04	164.22	44.40	6.45	14.73	2.84	0.04
				12/10/94	16:42	164.05	49.03	6.21	14.82	2.73	0.04
				13/10/94	9:40	163.59	66.00	5.55	15.06	2.44	0.03
				13/10/94	13:08	163.54	69.47	5.48	15.08	2.41	0.01
				13/10/94	14:45	163.53	71.08	5.47	15.09	2.40	0.01
				14/10/94	11:08	163.34	91.47	5.19	15.19	2.29	0.01
				14/10/94	14:55	163.34	95.25	5.19	15.19	2.29	0.00
				19/10/94	9:43	163.28	210.05	5.11	15.22	2.25	0.00
M11	mcm	20.6		10/10/94	15:40		0.00				
	oven	8		11/10/94	9:43	170.44	18.05	10.53	13.24	4.64	
	dry mass	162.89		11/10/94	12:41	169.76	21.02	9.59	13.58	4.22	0.23
	start time	10/10/94	15:40	11/10/94	14:34	169.42	22.90	9.11	13.76	4.01	0.18
	mct	2.92		11/10/94	16:13	169.16	24.55	8.75	13.89	3.85	0.16
	O/I	0		12/10/94	10:15	167.50	42.58	6.43	14.73	2.83	0.09
				12/10/94	11:04	167.47	43.40	6.39	14.75	2.81	0.04
M14	mcm	20.21		17/10/94	15:29		0.00				
	oven	8		18/10/94	10:01	165.38	18.53	6.27	14.52	2.76	
	dry mass	160.94		18/10/94	10:56	165.22	19.45	6.04	14.60	2.66	0.17
	start time	17/10/94	15:29	19/10/94	9:38	165.22	42.15	6.04	14.60	2.66	0.00
	mct	2.27		19/10/94	12:13	164.46	44.73	4.97	14.99	2.19	0.29
	O/I	1									

Appendix: test series 4 and 5 drying data

id		sample information		date&time		mass	elapsed time	mc%bin	mc%mcm	mc/ tw	Δmass/ Δtime
M14	mcm	19.65		19/10/94	16:05	195.08	0.00	43.68	0.36	19.22	
	oven	9		19/10/94	16:57	192.44	0.87	40.02	1.71	17.61	3.05
	dry mass	163.63		20/10/94	14:58	167.85	22.88	5.86	14.27	2.58	1.12
	start time	19/10/94	16:05	21/10/94	16:19	166.15	48.23	3.50	15.14	1.54	0.07
	mct	1.33		24/10/94	11:02	165.66	114.95	2.82	15.39	1.24	0.01
	O/I	0		24/10/94	11:34	165.65	115.48	2.81	15.39	1.23	0.02
M15	mcm	19.65		19/10/94	16:05	193.63	0.00	43.86	0.30	19.30	
	oven	9		19/10/94	16:57	190.93	0.87	40.07	1.69	17.63	3.12
	dry mass	162.31		20/10/94	14:58	167.02	22.88	6.60	14.00	2.90	1.09
	start time	19/10/94	16:05	21/10/94	16:19	165.39	48.23	4.31	14.84	1.90	0.06
	mct	1.7		24/10/94	11:02	164.92	114.95	3.65	15.08	1.61	0.01
	O/I	0		24/10/94	12:18	164.92	116.22	3.65	15.08	1.61	0.00
M16	mcm	18.95		25/10/94	10:36	197.29	0.00	42.47	0.22	18.68	
	oven	9		25/10/94	11:13	195.67	0.62	40.25	1.04	17.71	2.63
	dry mass	166.23		25/10/94	12:56	190.94	2.33	33.78	3.43	14.86	2.76
	start time	25/10/94	10:36	25/10/94	15:05	185.17	4.48	25.90	6.35	11.39	2.68
	mct	9.51		25/10/94	16:10	182.06	5.57	21.64	7.93	9.52	2.87
	O/I	0									
M17	mcm	18.95		25/10/94	10:36	196.01	0.00	42.60	0.17	18.74	
	oven	9		25/10/94	11:13	194.41	0.62	40.40	0.99	17.77	2.59
	dry mass	165.07		25/10/94	12:56	189.86	2.33	34.13	3.31	15.02	2.65
	start time	25/10/94	10:36	25/10/94	15:05	184.40	4.48	26.61	6.09	11.71	2.54
	mct	11.63									
	O/I	0									

Appendix: test series 4 and 5 drying data

Appendix J: test series 1 and 2 compression and compostion data

id	ELRstres MPa	mcttw %	fs MPa	compmod MPa	mctbin %	strfail	straw %	final.wht grms	<425 %	<75 %
2A;1	0.25	/	0.30	23.50	/	3.72E-02	2.50	2931	63	41
2B;1	0.19	/	0.66	25.10	/	3.63E-02	2.50	/	63	41
3;1	0.25	/	0.43	26.00	/	2.86E-02	2.80	5750	69	43
4;1	0.40	2.31	0.60	59.10	5.50	1.79E-02	1.80	6180	62	42
6;1	0.33	2.89	0.45	39.40	7.61	1.76E-02	2.00	/	58	38
7A;1	0.41	2.35	0.48	17.30	6.35	4.88E-02	1.00	/	40	37
7B;1	0.16	2.35	0.31	12.30	6.35	4.40E-02	1.00	3141	40	37
8;1	0.31	2.27	0.63	65.20	6.14	2.05E-02	1.10	2679	61	37
1;2	/	6.25	0.42	31.50	13.89	1.64E-02	0.90	7893	55	45
2;2	0.25	12.05	0.31	13.30	27.39	4.31E-02	0.70	7887	54	44
3;2	0.28	6.90	0.40	29.60	15.00	1.64E-02	0.70	8005	56	46
4;2	0.39	6.24	0.46	31.50	/	2.34E-02	/	8289	/	/
5;2	0.24	5.48	0.40	70.30	12.18	2.01E-02	0.70	8262	56	45
6;2	0.27	5.33	0.46	67.10	12.69	1.47E-02	0.80	8495	52	42
7;2	0.13	14.63	0.24	10.10	31.80	5.43E-02	1.20	10767	55	46
8;2	0.17	14.35	0.25	10.50	/	4.02E-02	/	10118	/	/
9;2	0.17	10.73	0.29	19.00	23.33	3.04E-02	1.50	9524	57	46

Note: sample numbers 2 and 7 of test series 1 were cut in half before testing, each half is labelled A or B.

Appendix: test series 1 and 2 compression and composition data

Appendix K: calculations of particle surface areas and volumes of test series 4 and 5

This page calculates average surface areas of the aggregate used in ts4

sieve appa	assumed dia /mm	volume /m^3	surface area/ m^2	part mass /kg	s s a /m^2/kg	size ratio
5						
2	4.59	5.05E-08	6.61E-05	1.35E-04	4.90E-01	0.40
1.18	1.79	2.99E-09	1.00E-05	8.11E-06	1.24E+00	0.59
0.6	1.06	6.25E-10	3.54E-06	1.69E-06	2.09E+00	0.51
0.425	0.54	8.32E-11	9.21E-07	2.19E-07	4.21E+00	0.71
0.3	0.38	2.95E-11	4.62E-07	7.91E-08	5.84E+00	0.71
0.212	0.27	1.04E-11	2.30E-07	2.77E-08	8.30E+00	0.71
0.15	0.19	3.67E-12	1.15E-07	9.79E-09	1.17E+01	0.71
0.063	0.14	1.35E-12	5.89E-08	3.63E-09	1.63E+01	0.42
0.016	0.06	1.14E-13	1.14E-08	3.07E-10	3.70E+01	0.25
0.002	0.02	2.06E-15	7.83E-10	5.55E-12	1.41E+02	0.13

High mix

average sample dry weight (kg) = 1.52E-01

sieve appa	%passing	%held	surface area/ m^2	volume
5	100.00			
2	89.54	1.05E+01	7.81E-03	5.97E-06
1.18	83.57	5.97E+00	1.13E-02	3.36E-06
0.6	78.91	4.66E+00	1.48E-02	2.62E-06
0.425	76.64	2.27E+00	1.46E-02	1.31E-06
0.3	74.45	2.19E+00	1.95E-02	1.24E-06
0.212	72.62	1.83E+00	2.31E-02	1.04E-06
0.15	69.64	2.98E+00	5.33E-02	1.70E-06
0.063	62.30	7.34E+00	1.82E-01	4.15E-06
0.016	49.84	1.25E+01	7.02E-01	7.04E-06
0.002	15.58	3.43E+01	7.36E+00	1.94E-05

Low mix

average sample dry weight (kg) = 1.86E-01

sieve appa	%passing	%held	surface area/ m^2	volume
5	100.00			
2	79.36	2.06E+01	1.88E-02	1.44E-05
1.18	68.78	1.06E+01	2.44E-02	7.26E-06
0.6	58.99	9.79E+00	3.80E-02	6.72E-06
0.425	55.11	3.88E+00	3.04E-02	2.74E-06
0.3	51.33	3.78E+00	4.11E-02	2.62E-06
0.212	47.82	3.51E+00	5.42E-02	2.45E-06
0.15	41.95	5.87E+00	1.28E-01	4.09E-06
0.063	29.24	1.27E+01	3.84E-01	8.77E-06
0.016	23.39	5.85E+00	4.03E-01	4.04E-06
0.002	7.31	1.61E+01	4.22E+00	1.11E-05

Medium mix

average sample dry weight (kg) = 1.69E-01

sieve appa	%passing	%held	surface area/ m^2	volume
5	100.00			
2	86.02	1.40E+01	1.16E-02	8.86E-06
1.18	78.65	7.37E+00	1.54E-02	4.60E-06
0.6	70.93	7.72E+00	2.73E-02	4.82E-06
0.425	67.50	3.43E+00	2.45E-02	2.21E-06
0.3	64.84	2.66E+00	2.63E-02	1.68E-06
0.212	62.70	2.14E+00	3.01E-02	1.36E-06
0.15	57.92	4.78E+00	9.51E-02	3.03E-06
0.063	48.54	9.38E+00	2.58E-01	5.89E-06
0.016	38.83	9.71E+00	6.08E-01	6.10E-06
0.002	12.14	2.67E+01	6.37E+00	1.68E-05

Appendix: particle surface and volume calculations

	High	Medium	Low
void volume fraction	0.39	0.35	0.30
aggregate volume/ aggregate surface area	6.56E-05	6.65E-05	6.82E-05
total volume	4.78E-05	5.53E-05	6.42E-05
total aggregate surface area	0.33	0.49	0.72
total particle surface area	8.39	7.47	5.34
total aggregate volume	2.14E-05	3.25E-05	4.9E-05
total binder volume	2.64E-05	2.29E-05	1.51E-05
binder volume/ aggregate surface area	8.10E-05	4.68E-05	2.10E-05
binder volume/ aggregate volume	1.234028	0.704329	0.308582
binder surface area/ aggregate surface area	24.72225	14.2968	6.423316
total particle volume/ total particle surface area	5.7E-06	7.41E-06	1.2E-05
aggregate volume fraction	0.27	0.38	0.54
binder volume fraction	0.34	0.27	0.17

Appendix: particle surface and volume calculations

Appendix L: test series 4 and 5 compression data

id	ts	mcm	ovencode	O/I	mcttw %	mctbin %	final.wht grms	dry.weight grms	bulk.dens kg/ m^3	dry.den kg/ m^3	volume m^3	ELRstress Pa	ELRstrain
H03	4	24.62	3	1	9.14	14.74	160.21	146.80	2028	1858	7.90E-05	8.40E+05	1.33E-02
H04	4	24.62	3	1	9.19	14.82	163.73	149.95	1997	1829	8.20E-05	7.40E+05	1.00E-02
H05	4	24.09	5	1	5.91	9.53	154.62	145.99	1985	1874	7.79E-05	9.60E+05	2.10E-02
H06	4	24.09	5	1	5.63	9.08	156.06	147.74	1927	1824	8.10E-05	8.80E+05	1.38E-02
H07	5	27.12	6	0	4.97	8.01	151.34	144.18	1876	1787	8.07E-05	1.00E+06	2.23E-02
H08	5	27.12	6	0	4.33	6.98	145.60	139.56	1886	1808	7.72E-05	1.54E+06	1.50E-02
H09	5	22.63	7	0	2.07	3.34	152.49	149.39	1891	1853	8.06E-05	1.36E+06	1.65E-02
H10	5	23.70	7	0	3.03	4.89	148.10	143.74	1924	1867	7.70E-05	1.24E+06	1.45E-02
H11	5	26.66	8	0	2.94	4.74	145.05	140.90	1902	1847	7.63E-05	2.06E+06	1.60E-02
H12	5	26.66	8	0	2.48	3.99	139.33	135.96	1929	1883	7.22E-05	2.20E+06	1.73E-02
H13	5	24.53	8	0	3.20	5.16	151.74	147.03	1954	1894	7.76E-05	1.36E+06	1.75E-02
H14	5	24.53	8	0	3.34	5.39	152.39	147.46	1985	1921	7.68E-05	1.46E+06	8.50E-03
H16	5	25.00	9	1	10.76	17.36	174.99	143.97	2246	1848	7.79E-05	8.40E+05	1.18E-02

Appendix: test series 4 and 5 compression data

id	compmod Pa	fs Pa	strfail	strfail-ELRstrain	drop	2drymo	both	none
H03	6.40E+07	1.04E+06	2.16E-02	8.32E-03	0	0	0	1
H04	6.81E+07	1.09E+06	2.36E-02	1.36E-02	0	0	0	1
H05	9.41E+07	1.10E+06	2.45E-02	3.50E-03	0	0	1	0
H06	1.17E+08	1.25E+06	2.12E-02	7.42E-03	0	0	1	0
H07	9.82E+07	1.27E+06	3.54E-02	1.32E-02	0	0	1	0
H08	1.03E+08	1.65E+06	1.76E-02	2.57E-03	0	0	0	1
H09	9.73E+07	1.71E+06	2.28E-02	6.27E-03	0	0	0	1
H10	1.89E+08	1.75E+06	2.48E-02	1.03E-02	0	0	0	1
H11	2.13E+08	2.47E+06	2.44E-02	8.41E-03	0	0	0	1
H12	2.67E+08	2.57E+06	2.18E-02	4.54E-03	0	0	0	1
H13	1.90E+08	1.85E+06	2.36E-02	6.14E-03	0	0	1	0
H14	8.40E+07	1.99E+06	1.55E-02	6.99E-03	0	0	0	1
H16	8.48E+07	1.37E+06	2.60E-02	1.43E-02	0	0	0	1

Appendix: test series 4 and 5 compression data

id	ts	mcm	ovencode	O/I	mcttw %	mctbin %	final.wht grms	dryweight grms	bulkdens kg/ m^3	dryden kg/ m^3	volume m^3	ELRstress Pa	ELRstrain
L04	4	16.32	3	0	9.10	41.34	198.28	181.75	2188	2006	9.06E-05	2.10E+05	4.25E-03
L05	4	16.63	3	0	2.13	9.69	181.82	178.02	2023	1981	8.99E-05	6.05E+05	1.18E-02
L06	4	16.63	3	0	2.28	10.36	180.95	176.92	2000	1955	9.05E-05	4.40E+05	4.50E-03
L07	4	16.04	4	0	5.65	25.67	189.50	179.37	2092	1980	9.06E-05	5.40E+05	7.50E-03
L08	4	16.04	4	0	5.73	26.02	190.96	180.62	2018	1909	9.46E-05	6.20E+05	2.50E-02
L09	4	16.61	5	1	7.73	35.12	195.25	181.25	2097	1947	9.31E-05	4.00E+05	1.55E-02
L10	5	17.88	7	0	2.60	11.80	178.77	174.24	1988	1937	8.99E-05	6.60E+05	9.00E-03
L11	5	17.88	7	0	3.21	14.61	180.66	175.03	1969	1908	9.18E-05	7.00E+05	7.75E-03
L12	5	18.11	8	1	4.20	19.08	184.77	177.33	2017	1936	9.16E-05	6.20E+05	9.25E-03
L13	5	18.11	8	1	5.42	24.65	185.47	175.93	2030	1926	9.14E-05	5.20E+05	1.08E-02
L14	5	16.12	8	1	3.80	17.27	187.05	180.20	2064	1989	9.06E-05	7.20E+05	1.33E-02
L15	5	15.86	8	0	0.38	1.71	181.18	180.50	1985	1978	9.13E-05	8.80E+05	1.35E-02
L16	5	16.12	9	0	0.85	3.88	183.92	182.36	2008	1991	9.16E-05	1.04E+06	5.30E-03

Appendix: test series 4 and 5 compression data

id	compmod Pa	fs Pa	strfail	strfail-ELRstrain	drop	2drymo	both	none
L04	5.00E+07	4.90E+05	1.78E-02	1.35E-02	0	0	0	1
L05	7.62E+07	7.72E+05	1.68E-02	5.04E-03	0	0	1	0
L06	9.70E+07	6.57E+05	1.00E-02	5.54E-03	0	0	0	1
L07	7.27E+07	7.39E+05	1.34E-02	5.90E-03	0	0	1	0
L08	2.94E+07	7.96E+05	2.98E-02	4.76E-03	0	0	1	0
L09	3.52E+07	6.88E+05	2.74E-02	1.19E-02	0	0	1	0
L10	6.86E+07	9.20E+05	1.72E-02	8.15E-03	0	0	0	1
L11	8.91E+07	9.87E+05	1.43E-02	6.57E-03	0	0	0	1
L12	1.03E+08	8.92E+05	1.56E-02	6.35E-03	0	0	0	1
L13	6.43E+07	8.65E+05	2.17E-02	1.09E-02	0	0	0	1
L14	7.38E+07	1.01E+06	2.32E-02	9.96E-03	0	0	0	1
L15	1.37E+08	1.19E+06	1.86E-02	5.08E-03	0	1	0	0
L16	2.41E+08	1.35E+06	9.19E-03	3.89E-03	0	0	1	0

Appendix: test series 4 and 5 compression data

id	ts	mcm	ovencode	O/I	mcttw %	mctbin %	final.wht grms	dryweight grms	bulkdens kg/ m^3	dryden kg/ m^3	volume m^3	ELRstress Pa	ELRstrain
M01	4	21.63	4	1	8.27	18.79	173.24	160.01	2028	1873	8.54E-05	2.80E+05	5.75E-03
M02	4	21.63	4	1	8.92	20.28	175.10	160.76	2041	1873	8.58E-05	6.60E+05	2.65E-02
M03	4	19.35	5	0	2.53	5.75	173.35	169.07	2022	1972	8.57E-05	9.40E+05	1.45E-02
M04	4	19.35	5	0	2.90	6.60	174.75	169.82	1983	1927	8.81E-05	7.40E+05	2.25E-02
M05	4	19.35	5	1	6.29	14.29	178.70	168.13	2037	1916	8.77E-05	5.60E+05	8.50E-03
M06	5	23.69	6	0	4.51	10.24	156.99	150.22	1904	1822	8.25E-05	8.20E+05	2.25E-02
M07	5	23.69	6	0	3.64	8.26	155.86	150.39	2025	1954	7.70E-05	1.02E+06	2.53E-02
M08	5	20.58	7	0	2.88	6.54	165.50	160.87	1940	1885	8.53E-05	8.40E+05	8.50E-03
M09	5	20.58	7	0	1.86	4.22	162.45	159.49	1890	1855	8.60E-05	1.12E+06	1.35E-02
M10	5	20.60	8	0	2.35	5.35	163.45	159.69	1946	1902	8.40E-05	1.64E+06	1.15E-02
M11	5	20.60	8	0	2.92	6.64	167.65	162.89	1952	1896	8.59E-05	1.48E+06	1.63E-02
M14	5	20.21	8	1	2.27	5.16	164.60	160.94	1975	1931	8.33E-05	1.06E+06	1.33E-02
M14[	5	19.65	9	0	1.33	3.03	165.81	163.63	1953	1927	8.49E-05	1.76E+06	1.32E-02
M15	5	19.65	9	0	1.70	3.87	165.08	162.32	1924	1892	8.58E-05	1.45E+06	1.13E-02
M16	5	18.95	9	0	9.51	21.62	182.04	166.23	2114	1930	8.61E-05	7.80E+05	1.28E-02
M17	5	18.95	9	0	11.63	26.44	184.27	165.07	2146	1922	8.59E-05	6.40E+05	1.70E-02

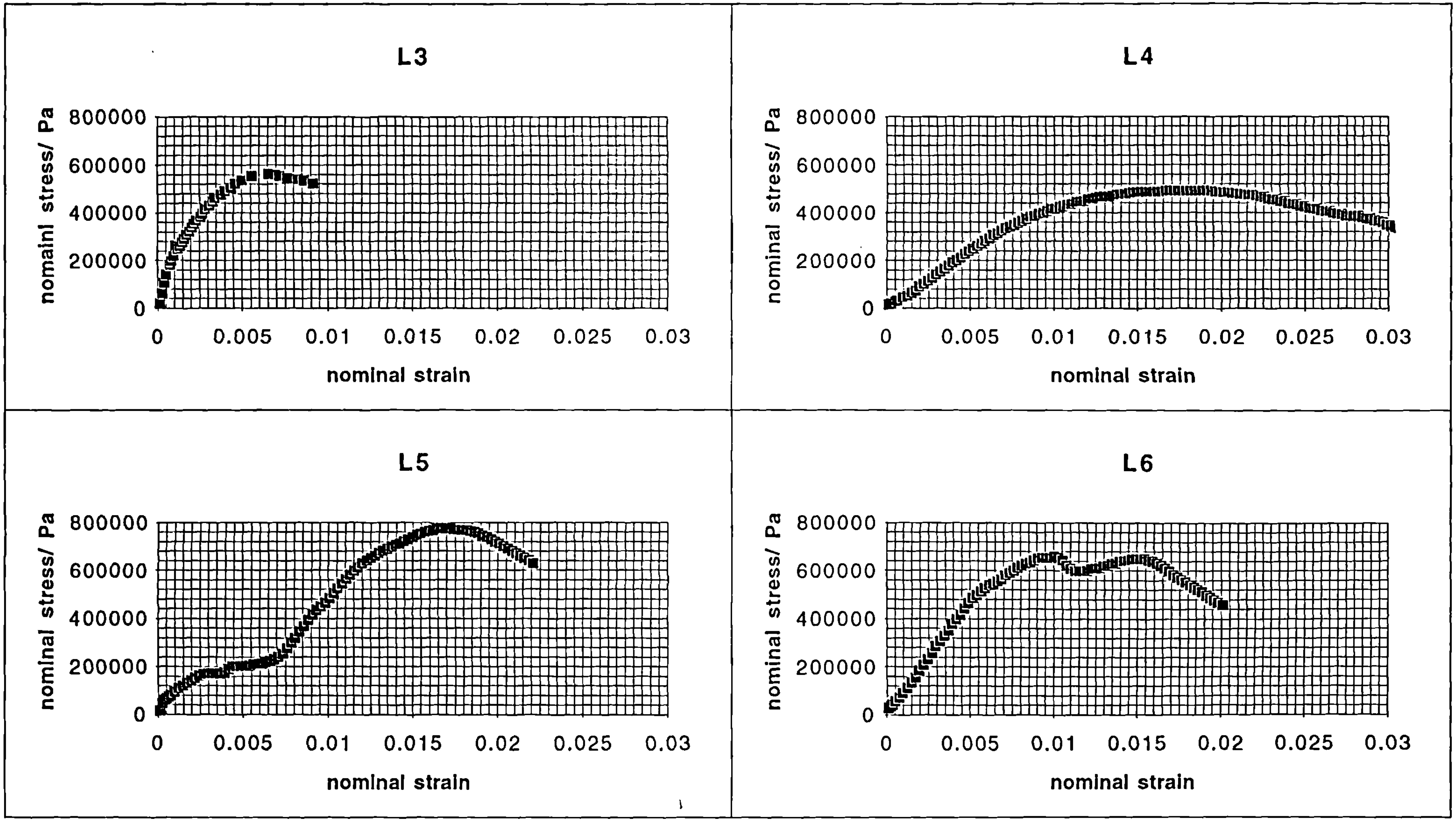
Appendix: test series 4 and 5 compression data

id	compmod Pa	fs Pa	strfail	strfail-ELRstrain	drop	2drymo	both	none
M01	4.42E+07	4.68E+05	1.77E-02	1.19E-02	0	0	0	1
M02	3.02E+07	7.71E+05	3.45E-02	8.00E-03	0	0	0	1
M03	1.27E+08	1.26E+06	1.94E-02	4.90E-03	1	0	0	0
M04	6.43E+07	9.00E+05	2.89E-02	6.36E-03	1	0	0	0
M05	6.79E+07	8.40E+05	1.98E-02	1.13E-02	1	0	0	0
M06	7.41E+07	9.76E+05	2.74E-02	4.87E-03	0	0	1	0
M07	5.93E+07	1.08E+06	2.67E-02	1.43E-03	0	1	0	0
M08	1.40E+08	1.29E+06	1.81E-02	9.64E-03	0	0	1	0
M09	8.12E+07	1.25E+06	2.83E-02	1.48E-02	0	0	0	1
M10	2.76E+08	1.98E+06	1.49E-02	3.44E-03	0	0	0	1
M11	1.33E+08	1.79E+06	2.26E-02	6.33E-03	0	1	0	0
M14	9.80E+07	1.20E+06	1.80E-02	4.78E-03	0	0	0	1
M14[	8.93E+07	1.98E+06	1.59E-02	2.68E-03	0	0	0	1
M15	3.45E+08	2.06E+06	1.79E-02	6.65E-03	0	0	0	1
M16	7.37E+07	1.22E+06	2.66E-02	1.39E-02	0	0	0	1
M17	5.00E+07	9.45E+05	3.92E-02	2.22E-02	0	0	0	1

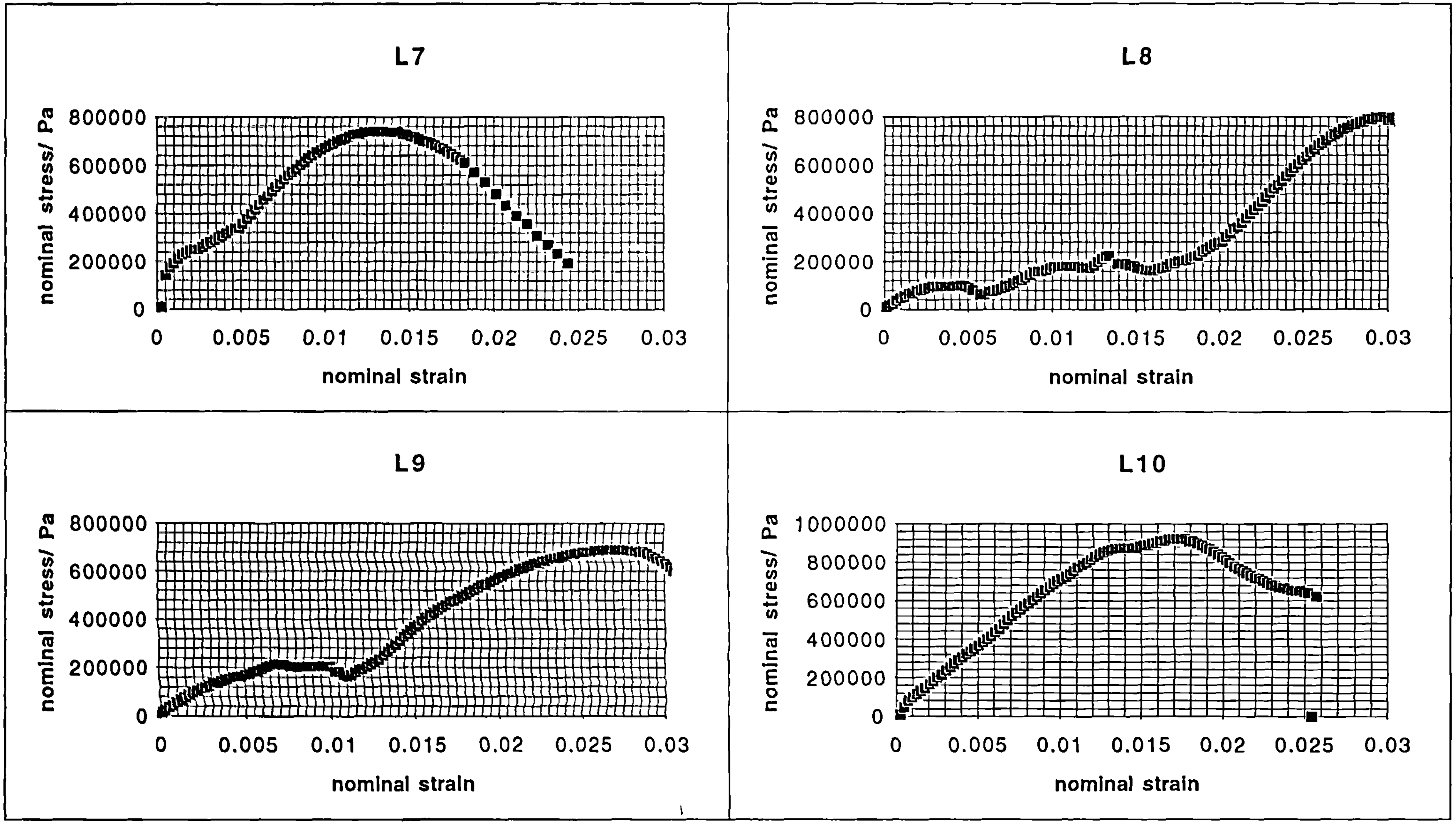
Appendix: test series 4 and 5 compression data

Appendix M: test series 4 and 5 stress/ strain graphs

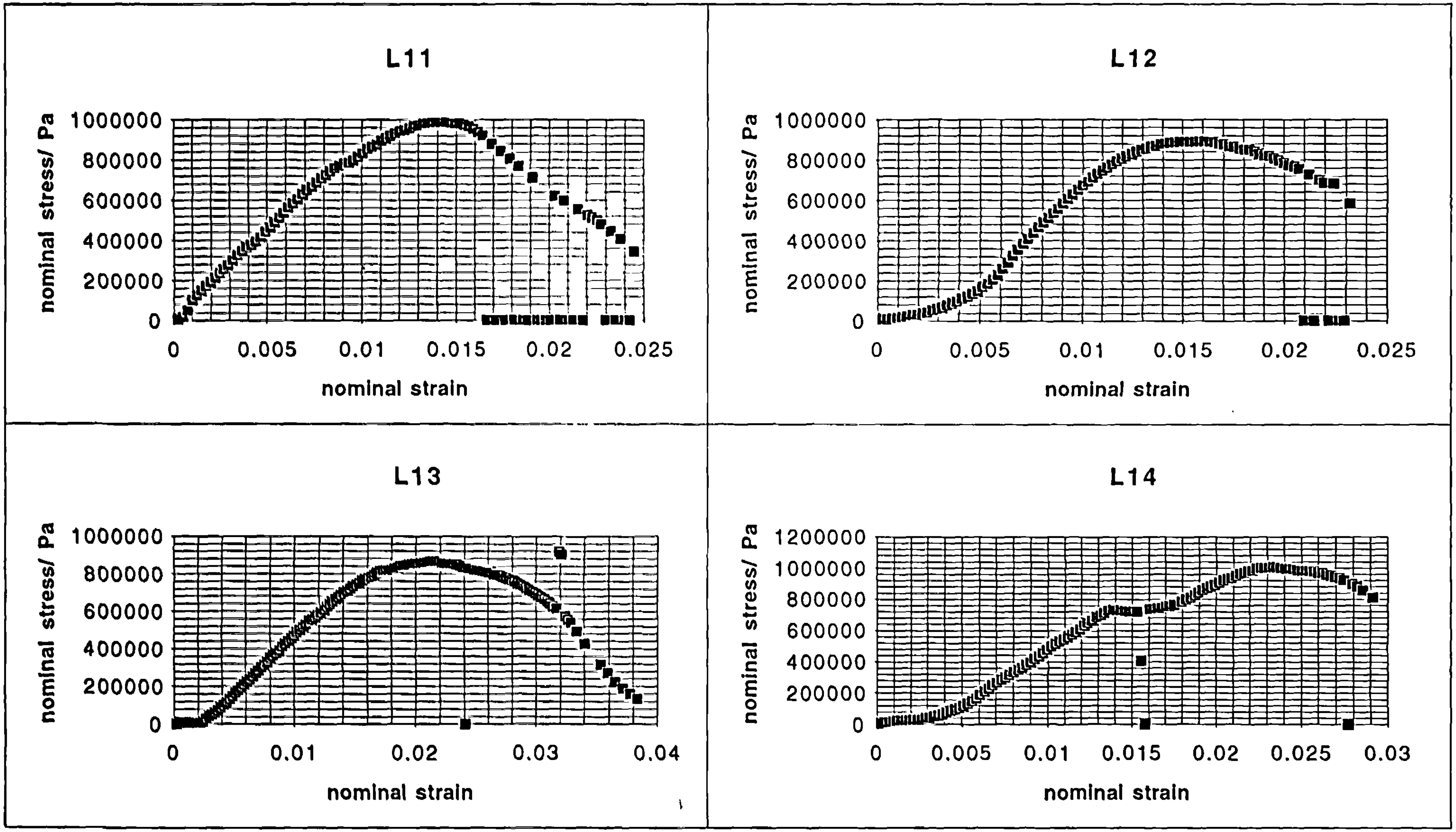
This appendix contains the stress/ strain graphs drawn by computer from values recorded during the compression tests of series 4 and 5. Each graph plots nominal stress in Pascals on the y axis against nominal strain on the x axis. The particular sample, whose compression test the graph illustrates, is printed above each graph.



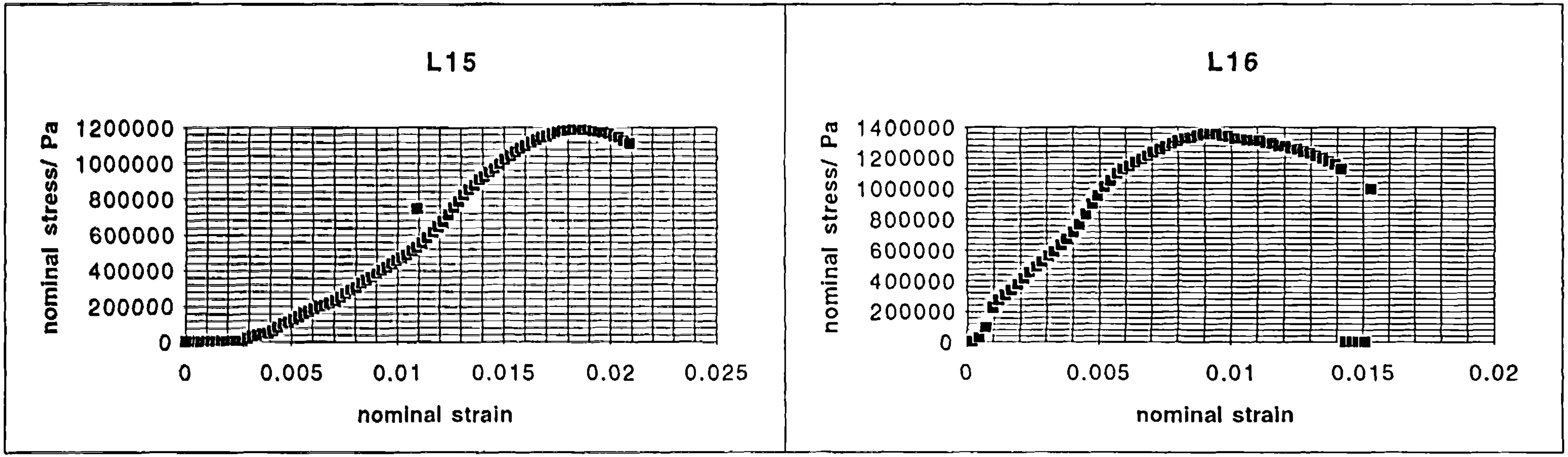
Appendix: test series 4 and 5 stress/ strain graphs



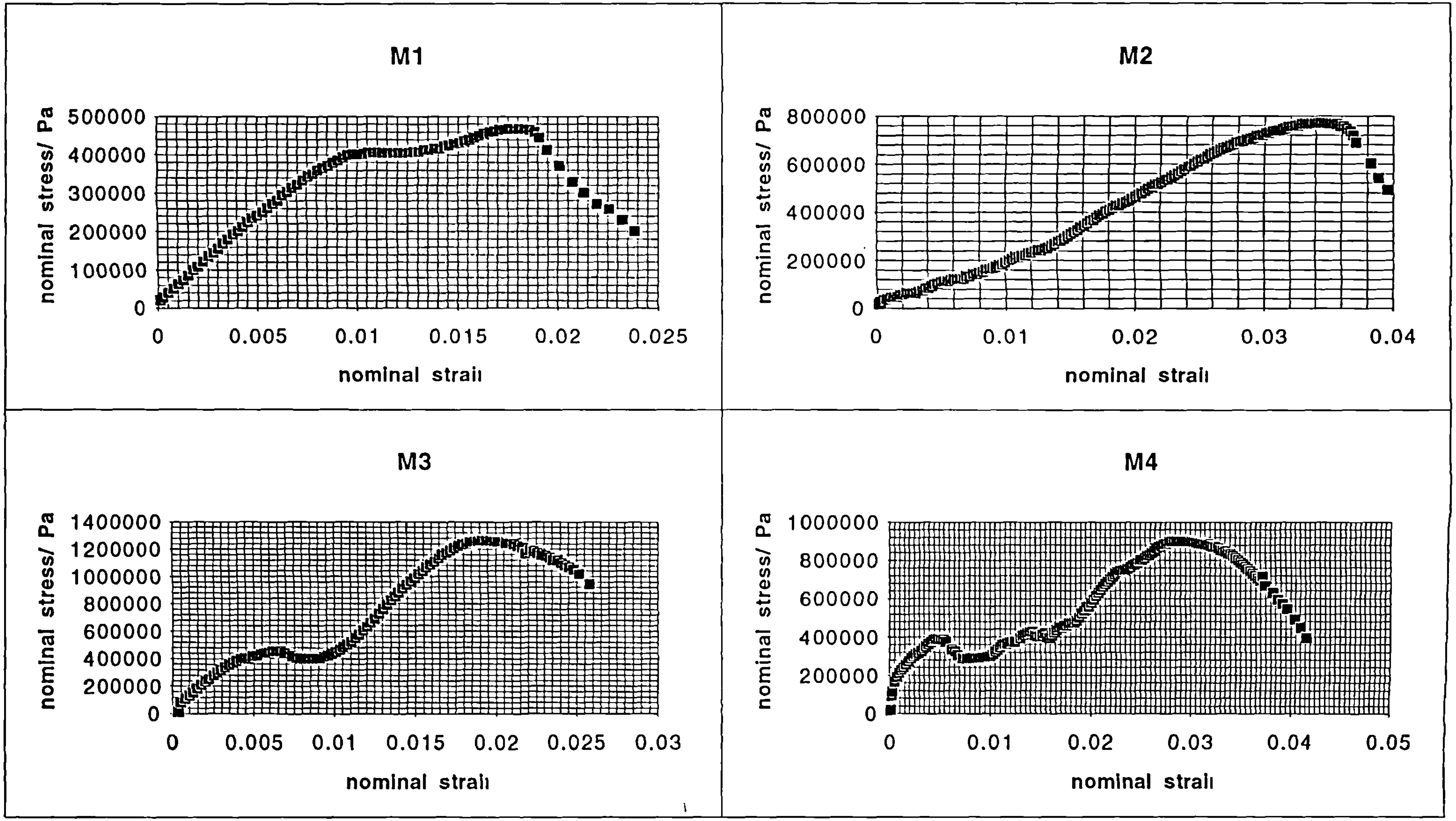
Appendix: test series 4 and 5 stress/ strain graphs



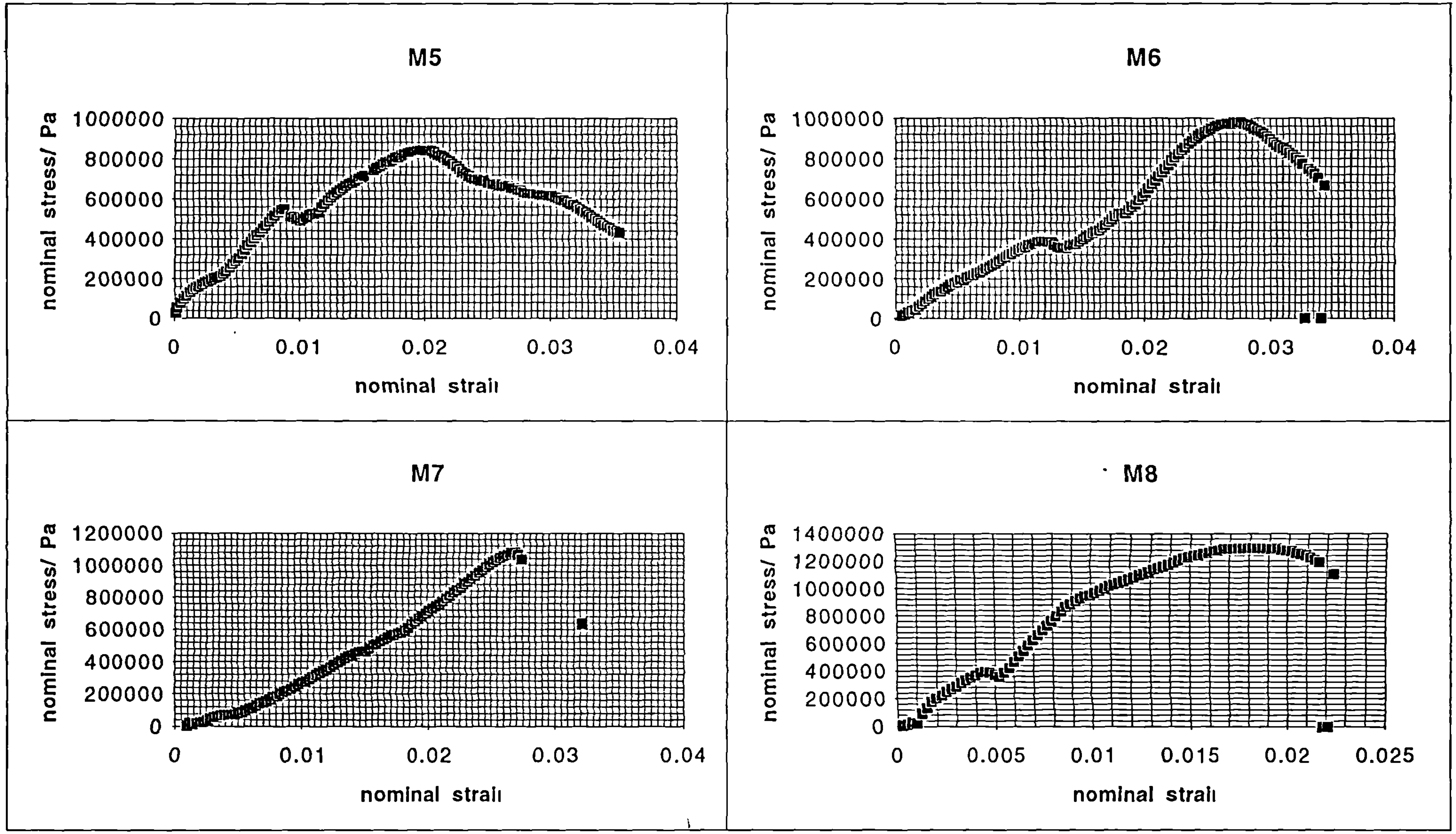
Appendix: test series 4 and 5 stress/ strain graphs



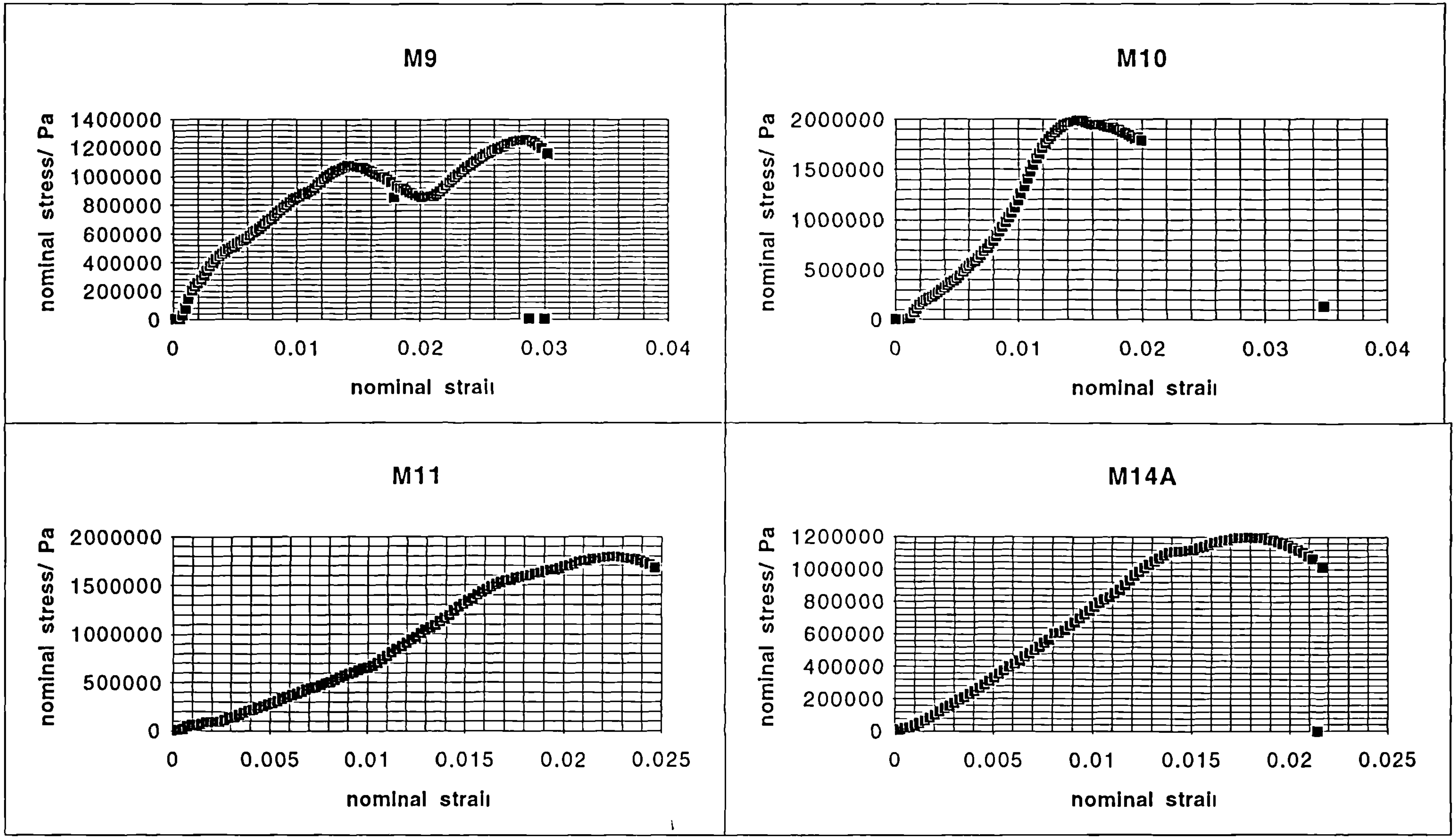
Appendix: test series 4 and 5 stress/ strain graphs



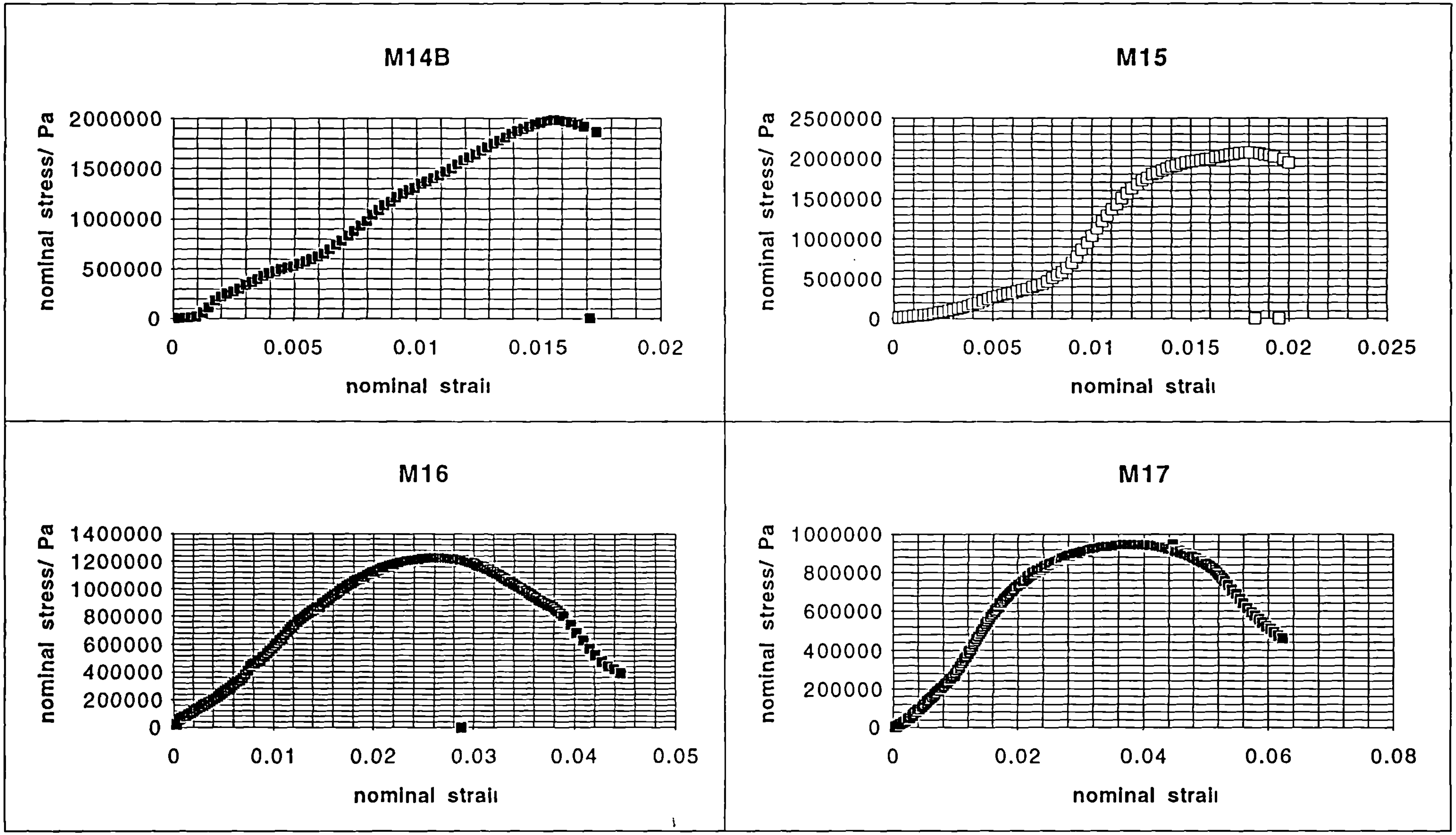
Appendix: test series 4 and 5 stress/ strain graphs



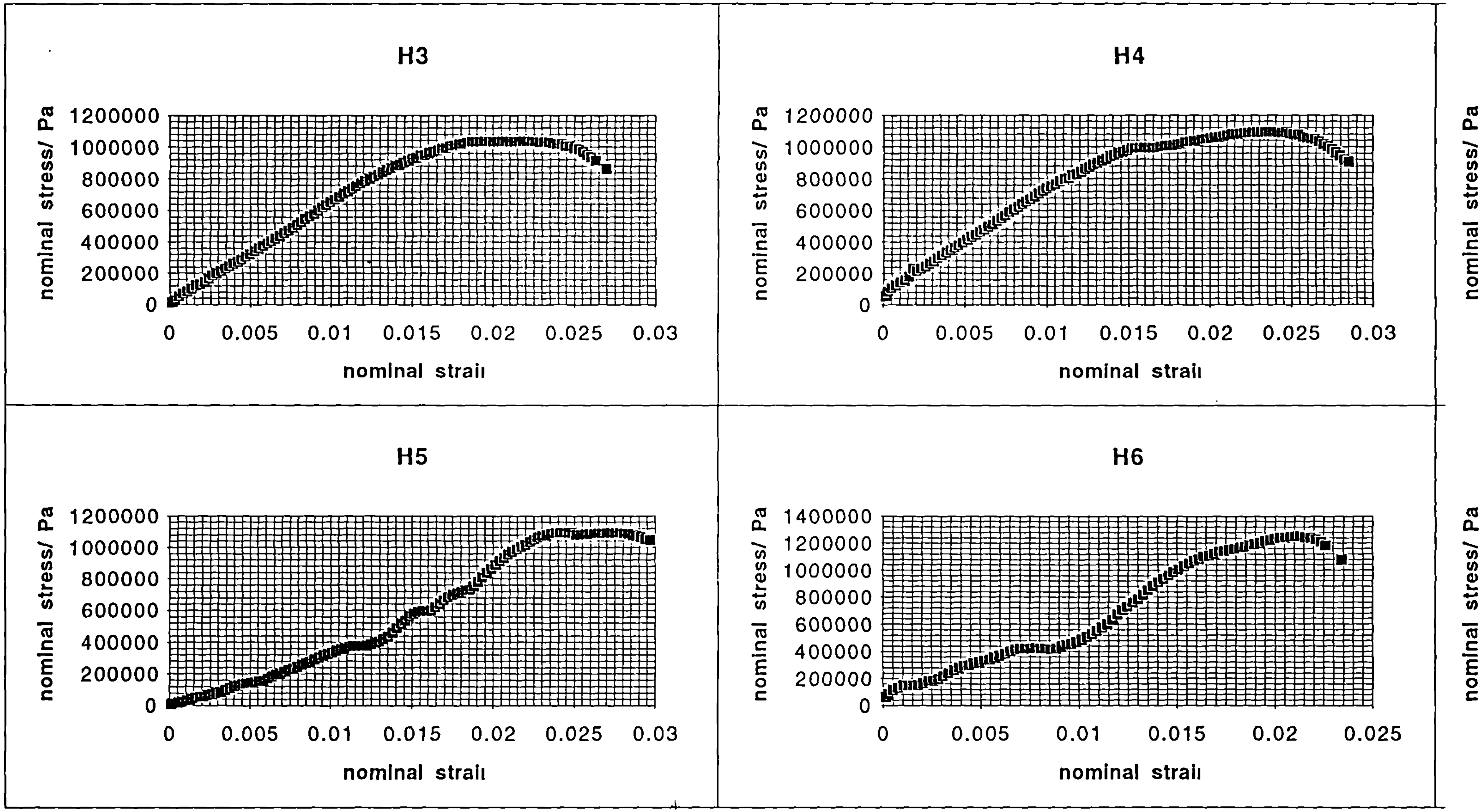
Appendix: test series 4 and 5 stress/ strain graphs



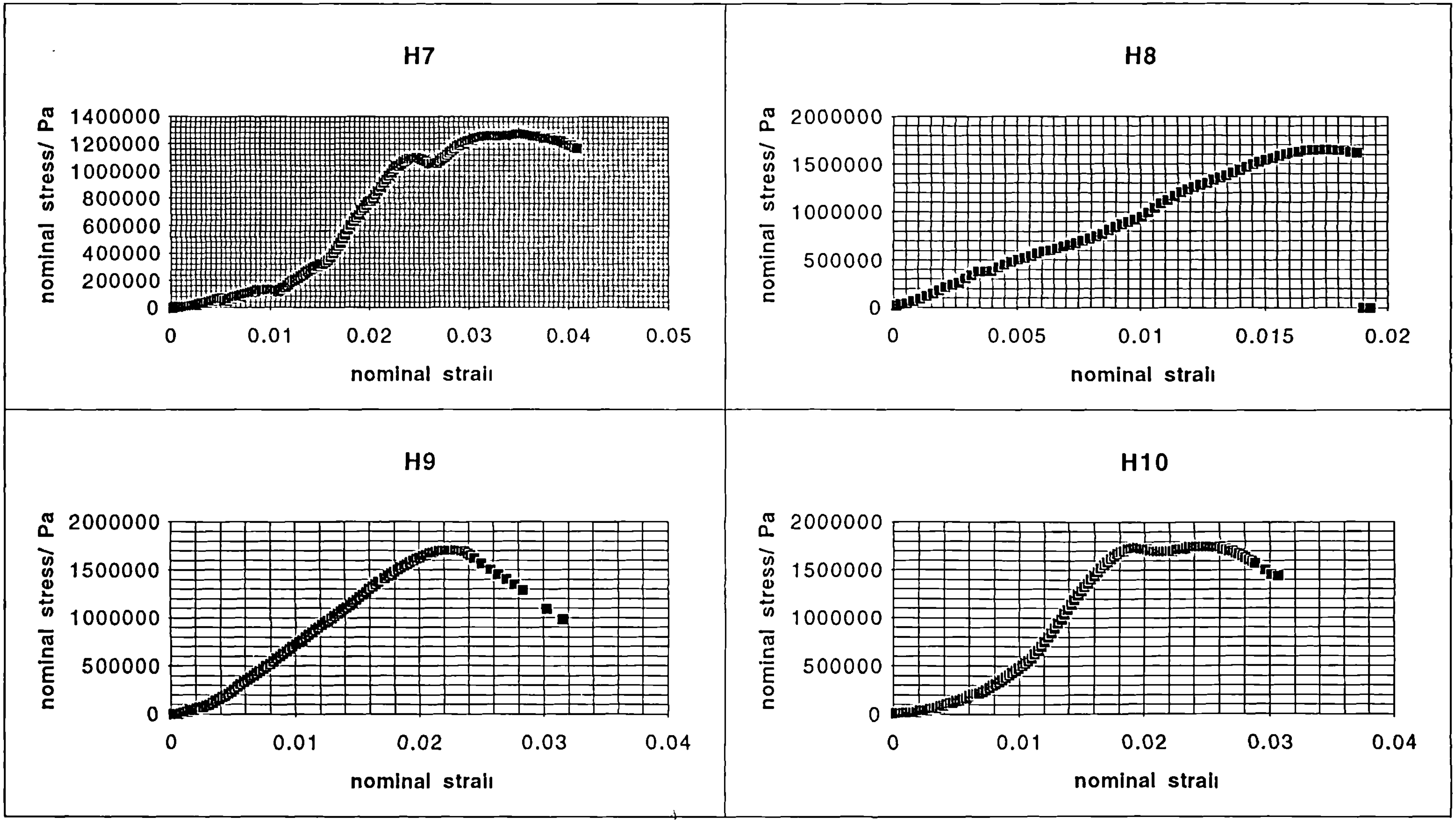
Appendix: test series 4 and 5 stress/ strain graphs



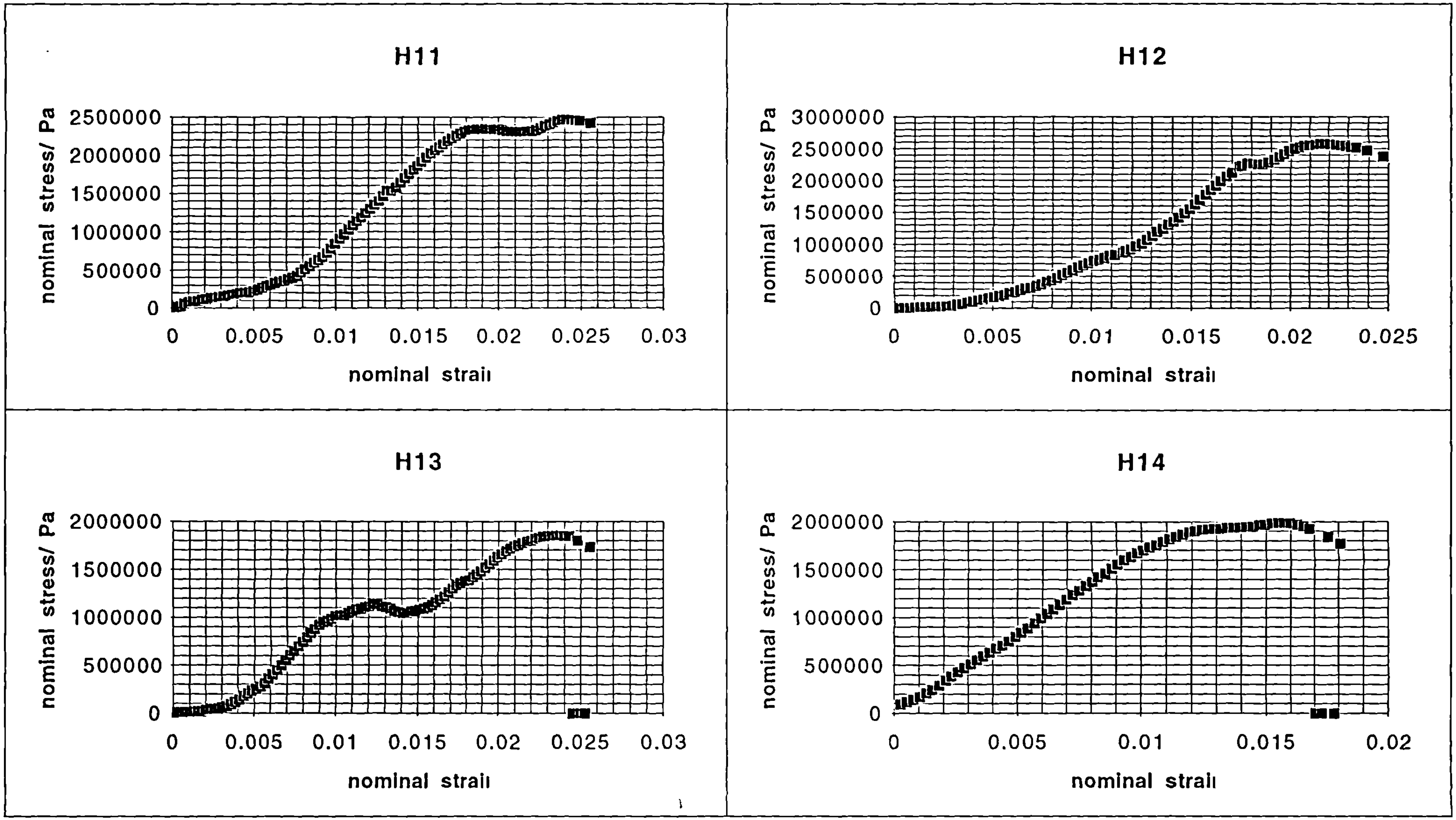
Appendix: test series 4 and 5 stress/ strain graphs



Appendix: test series 4 and 5 stress/ strain graphs



Appendix: test series 4 and 5 stress/ strain graphs



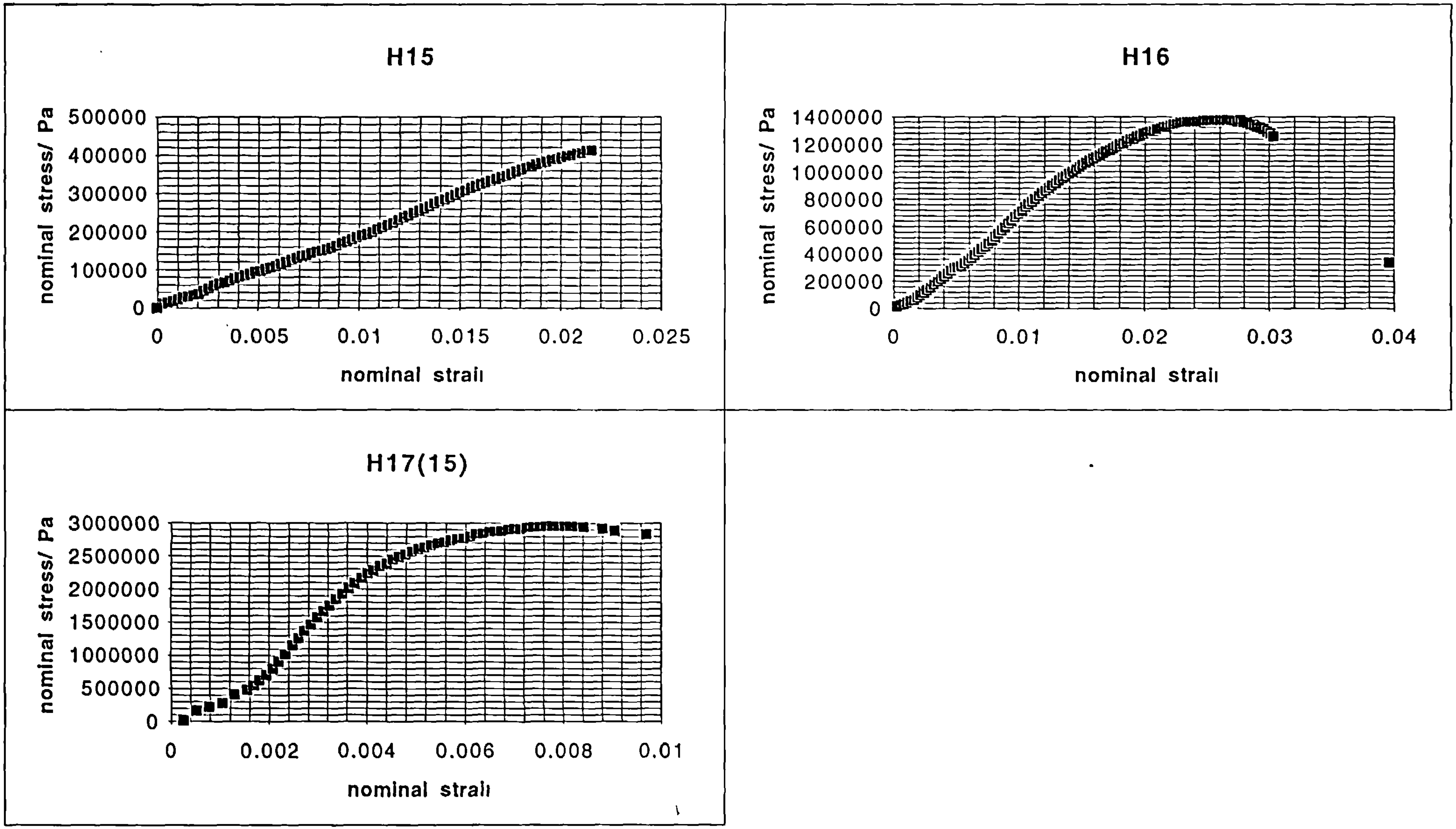
H11

H12

H13

H14

Appendix: test series 4 and 5 stress/ strain graphs



Appendix: test series 4 and 5 stress/ strain graphs