2004

SPECIFICATION DEVELOPMENT FOR THE USE OF DEVON COB IN EARTHEN CONSTRUCTION

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http://hdl.handle.net/10026.1/1291

http://dx.doi.org/10.24382/4255
University of Plymouth

SPECIFICATION DEVELOPMENT FOR THE USE OF DEVON COB IN EARTHEN CONSTRUCTION.

By

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A thesis submitted to the University of Plymouth
In partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

School of Earth, Ocean and Environmental Sciences
Faculty of Science

July 2004

Specification Development for the Use of Devon Cob in Earthen Construction

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ABSTRACT

The traditional earthen building practice of cob construction has been historically linked to Devon for many centuries. However no standards or specifications exist to facilitate a technical appraisal of the material. This thesis sets out to develop an appropriate test methodology for the classification and compressive strength determination of Devon cob.

The absence of appropriate standards for cob construction is shown as a function of neglect for Devon cob as a potential construction material. National and international events that have re-kindled interest in earth as a building material are discussed, with particular reference to cob construction. A rationale is presented to justify the selection of the soils used in the experimental program. The utilisation of 'soil surveys' to inform selection of suitable cob building is found to be hindered by a lack of modernisation in terms of data presentation. A definitive test methodology is presented and used in the determination of unconfined compressive strength for cobs formed from the selected soils. While the addition of straw is shown to influence the strength of soils, its influence is clearly matrix specific. The pressure membrane test is presented as a suitable means of classifying cob fabrics at a microstructure level. These findings offer new insights into Devon cob.

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Acknowledgements

I would like to thank staff at the School of Civil and Structural Engineering for my initial employment on this project and for the provision of laboratory and office facilities. Particular mention should be given to Bob Saxton, for his enthusiastic encouragement and John Hutchinson for his technical assistant within the laboratory, and the dissemination of his expert advice on child-rearing! Furthermore I would like to thank Francoise Ozanne for her much valued friendship and her generous assistance with translations.

I gratefully acknowledge the considerable help of Dr. Rex Harries for the collection of the soil samples. I would like to thank the technical staff of the Department of geographical sciences, namely Richard Hartley, Pat Bloomfield and Ann Kelly for their generous assistance when required. Ann is warmly thanked for fixing of the cob samples for sectioning, via crystic resin techniques which my pregnancy prevented me from doing. Many thanks are also extended to Mike Asthon for his painstaking work with the thin sectioning and mounting of the cob samples.

For those who freely gave of their time and expertise I extend much gratitude, especially to Dr. Andrew Williams, Dr. Ian Dennis and Dr. Roy Moate and his staff of the Electron Microscopy Centre at the University of Plymouth.

To fellow earthen building researchers who were equally generous with their expertise I give many thanks - this is particularly extended to Larry Keefe, Maggie Ford and Steve Goodhew.

I am greatly indebted to Dr. Jim Griffiths for rescuing me from Ph.D supervision -limbo and agreeing to act as Director of Studies. Without his help this thesis may never have been completed. He has been a constant source of optimism and positive encouragement. I thank him for this and his considerable patience. I also extend thanks to Dr. Martin Stokes, my second supervisor, for his helpful and motivational comments on my drafts.

To my self-appointed third supervisor, my husband, Dr. Kenneth Coventry, I thank you for the late night cups of tea, your financial, domestic and secretarial support, not to mention your assistance with proof-reading and compilation. I am especially grateful to you for your reluctant and yet disciplined attendance at Saturday-morning ballet-classes. The production of this work is as much a reflection of your commitment as it is mine. You have given of your time freely, unconditionally and with much personal sacrifice, for these reasons and because I'll never cut a disc, I dedicate this work to you.

This thesis is also dedicated to the memory of my parents; Gareth James and Winifred Evans, with much love.

Finally, I dedicate this thesis to Charlotte (1), and especially Jessica who has more understanding of a "Ph.D" than is proper for a four year old! I look forward to more "Mummy days"!

September2003

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.

This study was partly financed with the aid of a studentship from the Faculty of Technology, University of Plymouth.

Signed:...M. A. Coventry.....

Date:...22/7/04.........

Chapter 1. Introduction

1.1 Overview

Construction utilising materials such as bamboo, straw, natural stone and earth may seem to the majority of people to lie in the domain of the historic and vernacular. However, to some of the future constructors of our built environment these materials will offer obvious alternatives to the more conventional options posed by fired clay bricks, concrete and steel as their potential is explored through the tertiary education system (Little and Morton, 2001; Walker, 2002).

Earthen construction is a generic description for one natural building technology encompassing many differing methods, as discussed in Section 1.2. This thesis is particularly concerned with one earthen construction material, namely Devon cob. Implementing natural building technologies within mainstream construction, using materials like Devon cob, can only be achieved by establishing standards and specification in order to allay concerns of proposers, procurers and financiers regarding suitability and performance (Little and Morton, 2001). Section 1.3 details the specific aims and objectives of this study in relation to this need. Section 1.4 concludes this chapter by chartering the pathway of this thesis to realising these aims and objectives.

1.2 Defining earthen building methods

Houben and Guillard (1994) provide the most comprehensive commentary on the variety of earthen construction methods that have been adopted worldwide. From the twelve earthen construction techniques identified, the five most relevant methods are briefly outlined below in order to facilitate definition when referred to in subsequent chapters. A more extensive commentary is presented for the material central to this thesis, Devon cob.

1.2.1 Adobe

This technique involves the formation of individual earth bricks from malleable mud (Houben and Guillard, 1994). The bricks are then air-dried and ultimately utilised as masonry, bonded by a mortar constituted from the same material as the brick itself (May, 1984).

1.2.2 Rammed earth

Often referred to by its French synonym, Pise, rammed earth is a monolithic method of earthen construction that utilises formwork to confine the selected earth while it is compacted inside the formwork in a series of layers. By moving the formwork upward, further layers may be compacted, one on top of the last, promoting the rapid progression of wall formation (Keable, 1996).

1.2.3 Wattle and daub

This construction technique utilises a load-bearing vertical framework of posts, between which branches or twigs interlace to produce a woven lattice. A wet clayey soil is then applied in such a manner as to ensure the mix squeezes through and between the lattice, packing itself into gaps and adhering to the lattice weave. The addition of fibres (animal, vegetable or plant) may be used to improve matrix binding during this phase of construction as the wet soil layers are applied, allowed to dry and further applications are built-up onto the framework (Norton, 1986).

1.2.4. Compressed earth block

Compressed earth block construction is a form of stabilised earth masonry. A wet mixture of stabilised soil is compacted in a machine mould. Once the blocks are formed, a period of curing occurs, the duration of which is determined by the method of stabilisation. The construction of compressed earth block masonry is akin to that of conventional brick masonry practice with cement mortars or cement-soil mortars being equally appropriate for wall construction (Walker et al, 2000).

1.2.5 Cob construction

Cob construction (or mud walling) is a monolithic building technique utilising earth mixed with straw and water. This matrix is stacked in layers with each layer compacted prior to the formation of the next and thus the process continues until a wall of the desired height is achieved.

However, on referring to traditional 'Devon cob' a very particular process of cob construction is suggested which identifies soil selection, formation strata, labour, resources and process. It is a tradition which has spanned between the fourteenth and nineteenth centuries (Beacham ibid. Keefe, 1998) and has been predominantly used within the county of Devon, in areas where the limited availability of suitable building stone forced the use of alternative building materials. Consequently half of the United Kingdom's earthen buildings are believed to found in Devon (Gillilan, 1995).

The formation strata for Devon cob is traditionally a stone plinth (or pinning) of approximately 600mm in height and 350mm in depth. Once the plinth was built, preparation of the cob mix began adjacent to the selected site (Egeland, 1988). Thus soil selection for Devon cob was defined by the landscape of Devon and more specifically the citing of the new structure. Operating in a gang of four men, sub-soil was removed from the ground and the larger stones were picked out. The earth would be placed in a heap and regularly turned-over by two men with picks or trodden by horses or cattle (Williams-Ellis & Eastwick-Field, 1947; McCann, 1983). Another man would be regularly adding water as the material was worked, while the fourth member of the gang was responsible for the addition of straw. Williams-Ellis and Eastwick-Field (1947), Brown (1979) and Egeland (1988) all testify to the use of barley straw. Egeland (1988) also believes this straw to have been 'chopped' straw prior to its addition to the cob mix, a view unsupported by Wright

(1991). Furthermore the Historic Buildings Trust (1992) suggest that either wheat or barley straw may have been used.

On preparation of the cob matrix, building can begin. An eloquent account of cob construction activity is given by the Reverend Coperinger Hill (McCann, 1983*),* *" one man gets upon the pinning with a small three-tined fork; his partner throws up to him small lumps of clay, the size of a double fist, which he adroitly catches on the fork, and deposits smartly on the wall, walking backwards."* Once deposited, the cob matrix is treaded into place with any surplus material projecting from the sides, eventually pared off. Each layer (or perch) was constructed in this fashion and left, covered with straw, to dry whereupon subsequent layers could be constructed. According to Williams-Ellis and Eastwick-Field (1947), construction activity occurred between March to September to facilitate drying.

1.3 Research aims and objectives.

The primary mode of load transfer through a cob structure is in the form of compression forces through the structural walls. Practitioners (designers, engineers, and architects) utilise material capacity in order to achieve appropriate design. However, Devon cob is a wholly natural material and its inherent strength capacity is subject to far greater variations than may be appreciated. The longevity of many of the existing traditional cob buildings cannot fail to impress a generation that discusses the design-life of buildings in time scales of but a few decades, and much may be gleaned from the past in order to inform the future. Thus the initial aims of this research were focused on quantification of the compressive strength of traditional Devon cob, qualified by material definition and statistical variation, in order to inform design. In the absence of a standard test specification for cob, the formation of an appropriate test methodology became the research objective. On establishing this methodology, traditional cob building mixes would be sampled and tested utilising the defined methodology whereupon the structural and material consideration of traditional Devon cobs would facilitate cob specification in conservation and future construction.

1.4 Layout of thesis

From Chapter 1, Chapter 2 leads to a consideration of the environmental changes currently shaping the management of our built environment, that have rekindled interest in the utilisation of earth as a building material. Local and international developments are shown to be instrumental in promoting cob conservation and construction. However, the potential for new construction is only recently shown to be feasible given the changes to building regulations made in 1985. Prior to this, little interest in establishing the structural capacity of Devon cob as a load-bearing material existed. Consequently the volume of literature pertinent to this subject is shown to be notable by its absence and thus literature pertaining to other developing earthen building technologies is considered. Of the only two directly related studies pertaining to the structural capacity of cob, the stated test-methodologies are shown to lack rigour and material selection is shown to be limited.

Material selection for the purpose of this study is addressed in Chapter 3. The rationale developed through this chapter pursues traditional Devon cob matrices, matrices of differing geotechnical classification and matrices of particular interest identified in the literature. The use of the Soil Survey is adopted to aid selection of suitable earthen building material through consideration of its descriptive and quantitative classification data. Once selected, the sampled soils are re-classified within the laboratory and the results are presented. The efficacy of the Soil Survey for the sourcing of Devon cob is questioned and highlights the requirement of the Survey to modernise and facilitate the broadening of its user group.

Chapter 4 continues by outlining a test methodology for the unconfined compression testing of Devon cob. The test methodology is rigorously defined from the point of manufacture of the test samples, to test execution. The 7-blow Proctor is introduced as a means by which to obtain samples of traditional cob density. The establishment of the test methodology is then absorbed within a testing framework, designed to ascertain the short-term and long-term strength capacity of a variety of Devon cobs and the soil matrices from which they are composed, together with their inherent variability.

The results of this test-program are presented in Chapter 5 wherein the significance of straw to the strength capacity of the cob matrix is shown to be soil matrix specific. Chapter 6 discusses these results giving particular reference to the individual soil matrices tested and clarifies the role of straw within the cob matrix.

Chapter 7 concludes this work and highlights the considerable potential for future investigation.

Chapter 2. The case for cob construction: supporting conservation and sustainable development via technical and scientific understanding.

2.1 Introduction

This chapter considers the climate that is promoting the current revival of traditional earthen building techniques. Areas pertinent to this revival are the development of interest groups concerned with the conservation of vernacular building history and the calls for change in the international development of the built environment. The establishment of appropriate test methodologies via specification is shown to be vital to the success of this promotion. Therefore, national and international developments in the testing of earthen building technologies, specifically cob and earth block, are reviewed accordingly.

2.2 A revival in earthen building construction, a revival of cob.

Talk of revival in earthen building techniques has been documented in Britain, since 1919, when St. Loe Strachey (1920) wrote of the building crisis faced by Britain due to a shortage of materials coupled by considerable demand for new housing after the First World War. Weller (1922), in his introduction to a special report commissioned by the Building Research Board into cob and pise de terre, cited the virtues of this form of construction, but viewed the suitability of earthen building techniques to address a social housing problem as implausible. L'isle D'Abeau, a sixty unit social housing project, has since been built near Lyon in France during the mid-nineteen eighties (Sinha & Schumann, 1994) representing a showcase of earth building technologies.

In 1947, St. Loe Strachey's comments of 1920 re-accompanied the introduction to the re-print of "Building in Cob, Pise and Stabilised Earth", the publication in which they first appeared (Williams Ellis et al, 1947). In this post- Second World War period, Britain was to face a similar situation to that experienced post World War 1 and earthen building techniques were again discussed as a potential solution. However, opportunities to promote cob construction were to remain stifled until 1985, for two reasons: the lack of a British Standard Code of Practice applicable to cob and the nature of the Bylaws and Building Regulations imposed by Local Government since 1858, to control construction activity (Ley and Widgery, 1997). Fortunately changes to these Bylaws and Regulations in 1985, paved the way for a potential revival of cob construction.

The changes to the Building Regulations were particularly timely given the rising concerns of energy consumption attributed to the development of our built environment (Brundtland Report, 1987; CERF Report, 1996). The total energy consumed in development considers the energy used in the extraction of raw materials for product production, the energy spent in product production and all associated transportation costs. The analysis and summation of these energies defines an 'embodied energy assessment' (Narayanan and Beeby, 2001). On consideration of the cob building process presented in Section 1.2.5, the embodied energies associated with cob construction are unquestionably negligible when compared with more common forms of construction. Needless to say, the energy associated with cob building conservation is similarly low.

International efforts to conserve earthen architecture had gathered apace during the nineteen eighties (ICCROM, 1987). Interest groups in the conservation of vernacular architecture and the conservation and repair of cob buildings, in particular, had formed (Keefe and Child, 2000). During the early nineteen nineties these groups, namely the Devon Earth Building Group and Plymouth University Centre for Earthen Architecture, focused on the dissemination of good practice and appropriate repair techniques in hope of arresting the escalating demise, in the structural integrity of existing cob buildings. A retired cob building mason was also investing time disseminating the practice of cob construction to an apprentice, thus assuring the sustainability of this traditional, low-energy building technique for the future (Harrison, 1992).

Coincident to this period of local focus on cob, The United Nations Earth Summit in Rio de Janeiro, 1992, was being held. One outcome from this summit was a programme of action - Agenda 21- to support the implementation of international sustainability measures (United Nations, 1993). Agenda 21, outlined a holistic approach to creating a more sustainable future by encouraging a 'global partnership' to assume collective responsibility. Local Agenda 21 called for communities to engage at a local level in the sustainability debate and actively promote a climate of change. More specifically, the scientific and technological community was encouraged to develop codes of practice and guidelines in the pursuit of research and implementation focused towards low energy impact development while educators were asked to improve dissemination and skill transfer (United Nations, 1993).

It is much to the credit of Devon Earth Building Group and Plymouth University Centre for Earthen Architecture that their own objectives, focused towards training, dissemination and research, echoed the ideals and philosophy that underpinned international developments at that time. Fortunately work into other earthen building technologies is also progressing to this end (Walker, 1999; Mesbah et al 1999; Minke, 2000; Morel et al; 2000). This work is necessitated by a lack of standardisation in performance criteria (Houben and Guillard, 1994; Walker, 1999). Without this, loan institutions and investors are reluctant to solicit services readily extended to purchasers of developments built from contemporary building materials, due to anxieties concerning the recuperation of monies beyond the loan period. The density of historic cob construction in the South-West is testament to its viability and while new cob building work now progresses (Keefe and Child, 2000), reluctance to approve its use could be dissipated by definitive documentation on use and specification (Ley and Widgery, 1997). This documentation would not only promote sustainability for the developments to come, but would also ensure the sustainability of Devon's cultural heritage of cob buildings.

2.3 Devon Cob

Published work relating directly to cob varies from 'arts and crafts' inspired movements (Bee, 1997) which provide guidance on the construction of cob buildings, to historical guidance notes (Devon Historic Buildings Trust, 1992 & 1993). Keefe and Child (2000) have documented the events that established a research programme into earth construction within University of Plymouth, School of Architecture where particular interest has focused on cob construction. An investigation into cob's compressive strength and rigidity, as executed by Greer (1996) is discussed below. Keefe (1998) has produced a well-documented pathology of structural failure in cob walls, defining links to the geographical landscape of Devon. Harries et al (2000) have suggested a performance specification for cob which is discussed below. Goodhew (2000) has demonstrated the feasibility of measuring the thermal properties of cob in the field. Forde (2002) has established a methodology for the recording of cob buildings utilising a geographical information system. This methodology has been utilised in a case study of twelve cob buildings within a particular Devon parish, and incorporates architectural, geographical and geological data. The inclusion of technical data pertaining to the classification of the material from which these buildings were built together with the characteristic strength capacity of this material is not included due to its lack of availability. However the extension of this inventory to encompass such technical data is feasible if an appropriate test methodology were established.

Saxton (1995) provides one of the first technical papers addressing the compressive strength of cob, utilising a single soil type obtained from Teignmouth, in South Devon. A three-part investigation is detailed which considers the compression testing of fifty-four cylinders. The first part of this investigation considers the compression testing of twenty-four cylinders that were either wet or dry strength tested (i.e. either tested immediately post-manufacture or after air-drying). Fourteen cylinders were tested for compressive strength variation with moisture content via a non-standardised disc penetration test using nominal load applications, and finally a further eight cylinders were compression tested at intermediate moisture contents. Within each of the three divided test-programs, further divisions can be made between the samples in terms of their straw contents (which range between 0 to 3% by dry weight of soil) and their moisture condition at manufacture (which vary from 'slightly' dry to optimum to 'slightly' wet). Certainly any variation in moisture content at the time of compaction will be influential on the matrix density, as may be established via any undergraduate soil mechanics textbook (e.g. Cernica, 1995). However, Saxton (1995), by his own admission, fails to document the effect on matrix density upon straw inclusion into the soil. Work by Morrel et al (2000) on the inclusion of sisal fibres into a soil matrix has illustrated that at low percentages of fibre inclusion, the dry density of the resulting matrix is not sensitive to the presence of fibres. Regardless of these findings, it is apparent that higher percentages of fibre inclusion will indeed affect density values.

The results presented by Saxton (1995) are, therefore, subject to considerable scatter. This is probably due to the significant variations between test-cylinder matrixes although no indication is given of the statistical variability of independent results and this too must be considered. Increasing straw content within the soil matrix appears to indicate the ability of cob to tolerate higher failure strains on loading. Again, the statistical significance of this finding is not presented due to the lack of repetition within the test program. Walker (1997) has identified a similar lack of statistical consideration attributable to test procedures in alternative earthen building technologies. In conclusion Saxton (1995) postulates that the addition of straw into the cob soil matrix was 'probably' added to the cylinders to improve wet strength thus negating the use of shuttering.

Greer's (1996) research utilises the same single soil type adopted by Saxton in his work outlined above. However, Greer concentrates on manipulating the particle size classification within this soil to obtain artificial mixes to investigate the various roles of the binder and aggregate fractions within a soil matrix, when subject to compression testing. Compression testing is carried out utilising the unconfined, undrained method (Scott, 1980), adopting a cylindrical sample size of 36mm diameter, and 77mm length. Larger scale testing was also carried out on two sets of cob blocks. One set of eight blocks was manufactured by heritage craftsmen, the other set of nine blocks by Greer himself. However, no indication is given of the manufacture techniques employed by either Greer or the craftsmen employed. Furthermore, this work lacks clarity in its presentation of a definitive test methodology as blocks are cut and compression tested utilising three block sizes.

Nevertheless, Greer's work has been credited by Harrison (1999), with defining the potential of straw as a means of shear provision in newly dried walls. Inspection of this work will not find this conclusion borne out of the results from the testing programs presented. Despite this Greer does suggest an alternative use for straw as a cob matrix 'crack stopper' (the potential of fibres to stop cracks within a soil matrix was first suggested by Houben and Guillard, 1994), via two mechanisms:

(1) The first mechanism suggests that fibre inclusions within a soil matrix, promotes the development of the crack around the fibre as opposed to through it, see fibre 1 in Figure 2.1. Here the energy used to propagate the crack is dissipated around the fibre thus propagation becomes less likely.

(2) The second mechanism describes the potential of straw fibres to be forced into tension by a crack opening propagating through the matrix, see Figure 2.1, fibre 2. Swamy (1989) details a similar phenomenon on consideration of the resistance to crack propagation within a cement-fibre composite. Here, propagation is halted by the stress at the crack tip being distributed in part to the embedded fibre. If too much stress is applied to the fibre (as in fibre 4 of Figure 2.1) the fibre may fracture.

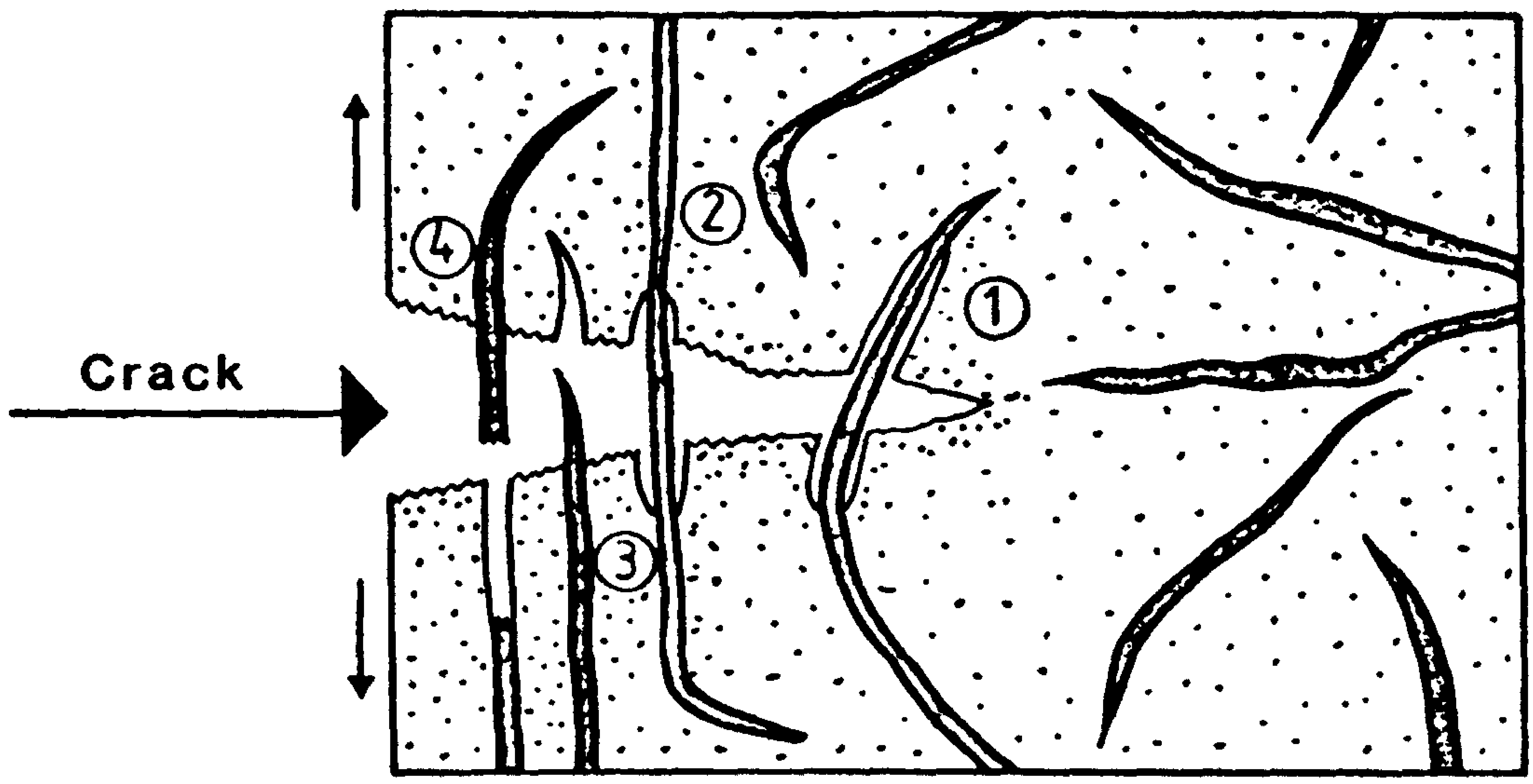


Figure 2.1. Schematic representation of crack propagation through a fibre reinforced matrix. Adapted from Swamy, (1988)

However, due to problems concerning the dimensional stability of plant fibres in the presence of water as outlined by Castro et al (1981) and Lilholt et al (2000), there is a tendency for shrinkage to occur with water loss. If straw fibres within a cob matrix exhibited similar tendencies to those of sisal, drying of the cob matrix would result in the appearance of a fine line of voids, along the length of the fibre (Ghavami, 1999). If this were to occur, the matrix could not de-bond (as per fibre 1) from the cob during loading to prevent crack propagation, as de-bonding would already have occurred upon drying (Filho, 1990). According to Swarmy (1988) a de-bonded fibre within a cement-fibre composite may fail to act in composite if pulled-out of the matrix (see fibre 3), dissipating energy in the form of friction. Thus in order to ascertain failure mechanisms it is important to clarify the behaviour of the straw within the cob matrix.

Harries et al. (2000) have published performance indicators for cob shown in Table 2.1.

Performance indicators	Performance specification
Grading	Based on recommendations by Middelton (1950), Houben (1994) and Norton (1997)
Clay content	10-25%
Moisture content	18-25%
Strength	400-1000kN/m^2
Density	-
Linear shrinkage	< 6%
Straw content	2% by weight

Table 2.1 Performance indicators for cob (adapted from Harries et al, 2000)

This specification was purported to *afford "reproducible and consistent results for a wide range of natural and modified matrices"*. However, the authors acknowledge that too few results were obtained to facilitate statistical analysis. Furthermore the method used to achieve the strength results is unspecified and thus cannot be transferred to permit the comparative analysis of other cob matrices.

2.4 International research in earthen building

Considerable research into the compressed earth block has been conducted in France since the mid- eighties (Olivier and Mesbah, 1986, and references therein). Much of this research has considered the optimisation of the mechanical characteristics of compressed blocks via cement stabilisation, and different compaction methods of block manufacture (Olivier et al., 1989). The static compaction method was shown to produce the most homogeneous cylinders and this method was adopted in subsequent studies investigating the triaxial testing of earth samples at different degrees of compaction (Olivier and Mesbah, 1995).

Field classification techniques have also been addressed (Mesbah and Olivier, 1990), and the "methylene blue test" is purported to provide a simplified procedure for the identification of clay soils (CNRS Report, 1995). This technique is explored in Chapter 3. Test methods have also been developed to obtain cylindrical laboratory test-specimens, which possess the same functional characteristics of the compressed bricks manufactured on-site (Mesbah et al, 1999).

Further work on earth block masonry has also continued in Saudi Arabia, Australia and India (Ozkan et al, 1995; Walker et al, 2000; Walker, 2002). Walker (2000) has suggested that the testing procedures of earth cylinders be akin to those adopted in BS 3921 (1974) for fired clay masonry units. Here uni-axial compressive strength is determined utilising a steadily applied load (0.1mm^2/sec to 0.7 mm^2/sec), applied to a cylinder between two thin restraining platens of ply wood and a load calculation which considers the load applied over the original cross–sectional area. This is a rational approach considering the blocks are effectively being utilised as traditional masonry units cemented together by earth to form a masonry panel, and here aspect ratios are often obtained to cross-relate cylinder strengths to block strengths. Furthermore, dry testing is deemed to be more relevant to in-service moisture conditions than wet/minimum compressive strength tests, particularly for unstabilised earthen building materials (Walker, 1997). Dry compressive strength determination is certainly more relevant to earth block construction, although unstabilised cob construction relies on the wet/minimum strength capacity of the material to support each 'lift'. Thus wet strength has a significant bearing on the process of cob construction while dry strength determination indicates the in-service capacity of the material. Unlike earth block construction, the monolithic nature of the material suggests more commonality with traditional soil mechanics than masonry design.

2.5 Conclusions

International and local developments have alerted researchers to the relevance and importance of data acquisition and technical research into earth building materials. Cob construction, the traditional form of earthen building in Devon, has no definitive specification associated with it to ensure construction standards are being met and neither is there a standardised methodology to determine strength parameters in the laboratory. Thus no reliable strength capacity values attributable to traditional cob are available. The establishment of these values could ultimately feed into an established cob building inventory to support conservation.

The limited testing that has been carried out for cob to date fails to provide a comprehensive methodology. Issues concerning sample variation in terms of matrix density and statistical significance have not been addressed. The role of the straw content within the cob matrix is not fully understood in terms of its contribution to strength immediately post placement and eventually when dried, and no published data exists to clarify this situation.

International developments in earth block have adopted masonry standards to inform testing methodologies, which, although appropriate for this form of construction, is no more applicable to cob than traditional geotechnical testing standards. International research has also concentrated upon the optimisation of material properties and thus mechanical properties, and while there is potential to develop cob technology the work contained within this thesis focuses upon prior learning from the traditional material in order to ultimately facilitate its development as a contemporary material.

Chapter 3. Material selection and soil classification

3.1 Introduction

Previous work by Greer (1996) investigating the compression testing of soils traditionally utilised to form a cob matrix, limited the scope of his investigation to the Teignmouth Breccias. While the utilisation of this soil in Devon's earth building history is not in question, it is no more distinctive for this reason than many other soils within the Devon area. Therefore it was deemed important to this study to establish a more rigorous rationale that would form a basis for the selection of the material.

This chapter explains the initial decision to base the soil selection on the pedalogical classification presented in the Soil Survey of England. It details the geological and geotechnical classifications of the selected soils, and re-assesses the appropriateness of a pedalogical classification system in the selection of soils for earthen building.

3.2 Establishing a rationale for soil selection

In Chapter 1, the historical significance of Devon's earth building history has been discussed and thus the intention to limit the selection of soils to the County of Devon alone. However, the variety of soils within the Devon area is considerable. This situation forced the development of a rationale on which to base soil selection.

One logical approach would have been to base selection on consideration of the relative densities of the distribution of cob buildings within Devon. However, this approach would require the existence of an inventory of all known cob buildings within the County. Without this evidence we are left only with Keefe's (1998) crude assessment of the distribution of cob buildings within the county. Keefe has defined the most concentrated regions in which the cob buildings of Devon may be found, by reference to the Upper Carboniferous, Permian and Triassic geological formations of Devon's geological landscape (see Figure 3.2). However recent work by Forde (2001) on the Parish of Sandford, in mid Devon, has begun to address the systematic identification and recording of these structures. The extension of this work to the whole County, will facilitate the statistical analysis of these structures, and their respective topography and physiography.

Keefe (1998) has identified the importance of environmental factors to the production of cob as a building material. In conclusion to his study of twenty cob building failures within Devon, Keefe has highlighted areas of Devon's landscape where the long-term structural integrity of a cob building could be threatened by the material used to produce it. From this point it was clear that any developing rationale which informed material selection should, in the absence of a cob-building inventory, be predominantly based on soil-type. More specifically, the author became interested in selecting soil types that overlay the geologically significant areas identified by Keefe, discussed in detail in Section 3.3.2. Significance was also attributed to the selection of soils of proven historical value to Devon's earth building history.

The discussion on Devon's traditional earth-building practices presented in Chapter 1, accepts the notion of localised material selection in the procurement of suitable cob building material. Evidence of a soil's significance to the history of earthen building was therefore accepted in the form of an existing historical cob construction about the vicinity of the sample site. Date plaques and maps were used as indicators of the period from which these buildings had stood. On-site observational assessments of the building's construction fabric (in terms of soil colour and general soil classification) bearing a resemblance to the land on which it was founded, afforded reasonable confirmation of the historical value of the soil's adoption in earthen building practices.

Selecting soils of proven historical context, afforded this investigation the opportunity to support the maintenance and continued survival of those structures still in existence while simultaneously producing information which would promote cob as a viable construction technology for the future. These aspirations conform to the accepted definition of "sustainability" as presented in Chapter 2.

Thus far the rationale informing soil selection was biased towards Devon soils utilised in traditional cob buildings and in particular those soils identified by Keefe's (1998) study of cob building failures. The final rationale was set to satisfy pertinent geotechnical issues. These issues encompassed a desire to observe possible failures that may be exhibited in a cob matrix, given soils ranging in geotechnical properties, should the selection of such a range of materials prove historically valid to cob building. Figure 3.1 illustrates the relationship between these constraints.

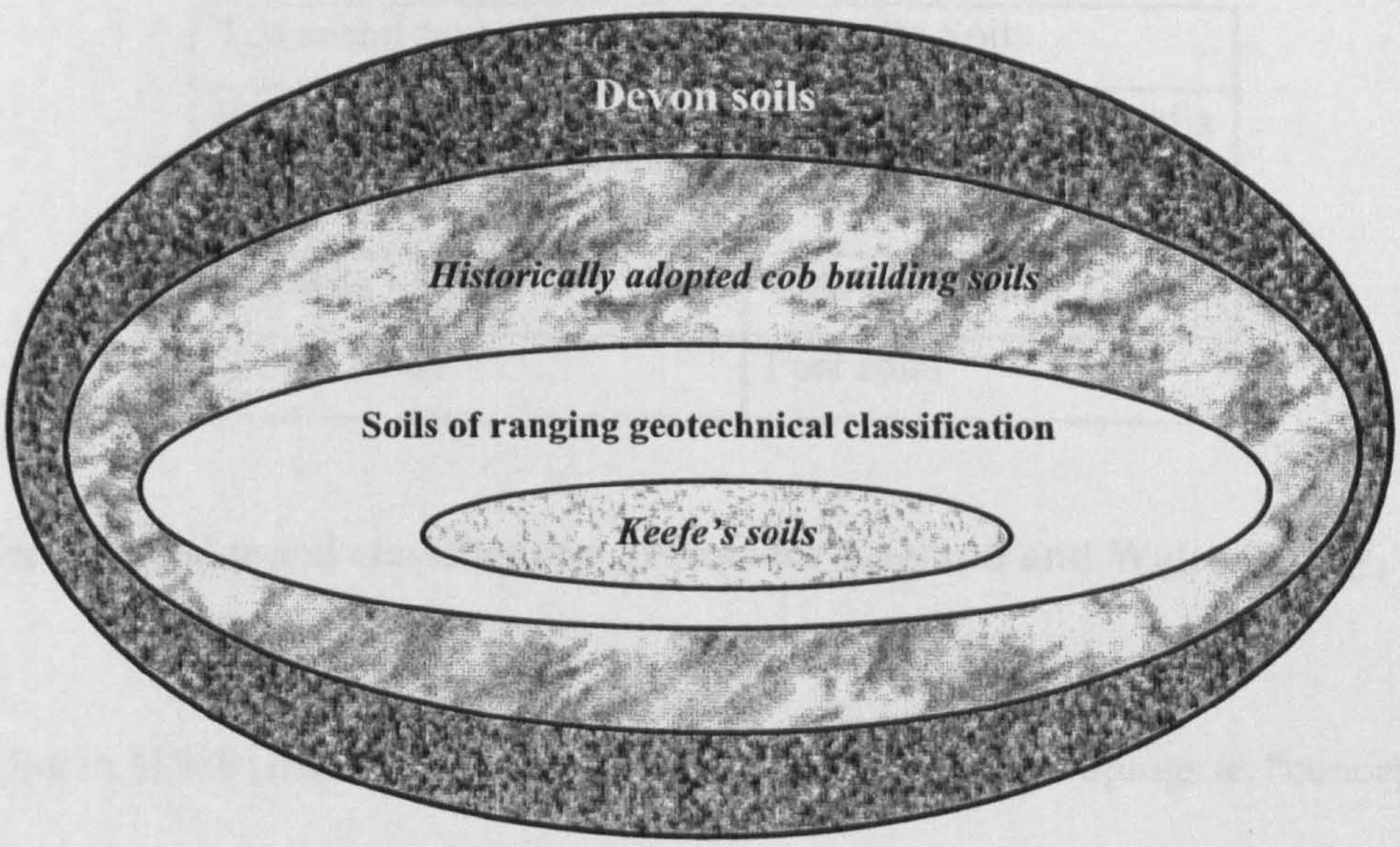


Figure 3.1. Rationale for soil selection

The validity of the soils selected to the history of cob building would, as has already been explained, be confirmed on site. The other criterion issues - geological, geographical and geotechnical factors - required careful consideration when viewed independently and when combined, if the selection process was to be properly informed. In order to accomplish this efficiently, the 'Soil Survey Memoirs of The Exeter District' (1968), was adopted to facilitate this process.

3.2.1 The system of soil mapping used by the Soil Survey of England and Wales

The Soil Survey of the Exeter District and its accompanying memoirs provided a means of identifying sites of definable soil units. Avery (1973) has given a concise explanation of the methods employed in England and Wales for the mapping of soil units. These units are otherwise known as 'Series'.

The establishment of a *soil series* derives from the rationalised breakdown of 10 major soil classification groups into a series of groups, sub-groups and eventually 'series'. Table 3.1 lists the initial classification groups from which all further divisions are borne.

Terrestrial raw soils	Podzolic Soils
Hydic raw soils	Surface-water gley soils
Lithomorphic raw soils	Groundwater gley soils
Pelosols	Man-made soils
Brown Soils	Peat soils

Table 3.1. Major soil classification groups for England and Wales (Avery, 1973)

Butler (1980) has described these major classification groupings as "conceptual divisions". However, further extension to this initial classification into groups and sub-groups offers a more elaborate and rational explanation of soil formation as divisions are diagnostically based on material composition and soil horizons. Division of the sub-groups on the basis of texture, profile contrast, origin and material mineralogy eventually leaves us with the unit of mapping, the *soil series*. For each series mapped, the Soil Survey Memoirs contain information concerning the particle size distribution, Atterberg limits and geological data of a given series. This information is all of considerable significance to a geotechnical engineer.

Current guidance, TRRL report 192 (1996), on the execution of the desktop study should give direction to geotechnical engineers who may have yet to establish the existence or utility of the soil survey. Lee and Griffiths (1987) suggested that the main use of the soil survey was confined to the identification of areas of significant agricultural value and gave an insight into the extended use to which soil surveys may be applied. Unfortunately, more recent work by Hasan (1994) indicates that the use of soil surveys would still appear to be restricted to agricultural industries. Hasan challenged the neglect of the geotechnical engineer's use of the soil survey, highlighting its beneficial contribution to the production of project planning and feasibility reports, echoing previous recommendations by Lee and Griffiths (1987). Indorante et al. (1996) suggest that if the user profile of the survey is to change, existing surveys must address the deficiencies in the qualitative nature of the material presented. M^{c}Bratney et al. (2000) herald the development of pedometry as a developing soil science which, in essence, marries pedology with developing quantitative methods in mathematics and statistics. Pedometric surveys may well provide the bridge facilitating widening of the soil survey user group but this work is still in its infancy and its application, in terms of up-dated surveys, is not yet widespread.

However, the significance of the current information held by the Soil Survey of England and Wales, to the identification of potential project-soil-selection-sites was evident. It was envisaged that by utilising the 'Soil Survey Memoirs of the Exeter District' (1971) together with the more commonly adopted geological maps to execute an effective desk study of Devon prior to sampling, the selection criteria outlined in Section 3.2 would largely be met, and suitable areas of sample selection identified.

3.3 Outcomes from the desk study

3.3.1 The geological landscape of Devon (The Upper Carboniferous and Permo Triassic Formations)

Durrance and Laming (1997) have provided the most recent account of the geology of Devon. Figure 3.2 provides a simplified illustration of their findings.

Figure 3.2 illustrates that the sedimentary rocks of the Carboniferous Period, are a significant component of the geological landscape of Devon. Together the Upper and Lower Carboniferous Periods represent the Culm Measures, so defined because there do not appear to be any major lithological changes in the boundaries of the Carboniferous Period in Devon (Thomas, 1997).

The outcrop of the Upper Carboniferous formation is sub-divided into two discrete distributions by a Permian ridge known as the Crediton Trough which runs from the west of Exeter to the north of Okehampton. North of the Crediton Trough lies the thickly deposited Bude formation of "massive sandstone beds", commonly slightly calcareous with brown weathering, non-graded and interbedded with thin sandstones, siltstones and shales as "extensive sheet features" (Thomas, 1997). Thomas attributes the thickness of this formation to "deposition in an actively subsiding basin" and proffers earthquake activity as a contributing factor to the occurrence of soft-sediment deformation.

South of the Crediton trough, lies the older rocks of the Crackington Formation comprising laterally continuous sandstone sheets interbedded with dark grey and black shale. These beds appear to have been deposited along the axis of the trough with thicker, coarser beds alternating in succession with finer grained sequences (Thomas, 1997). This formation represents the deposition of a distal turbidite suite with groove moulding eventually flute cast with coarse sediments by east/ west flowing currents (Thomas, 1997).

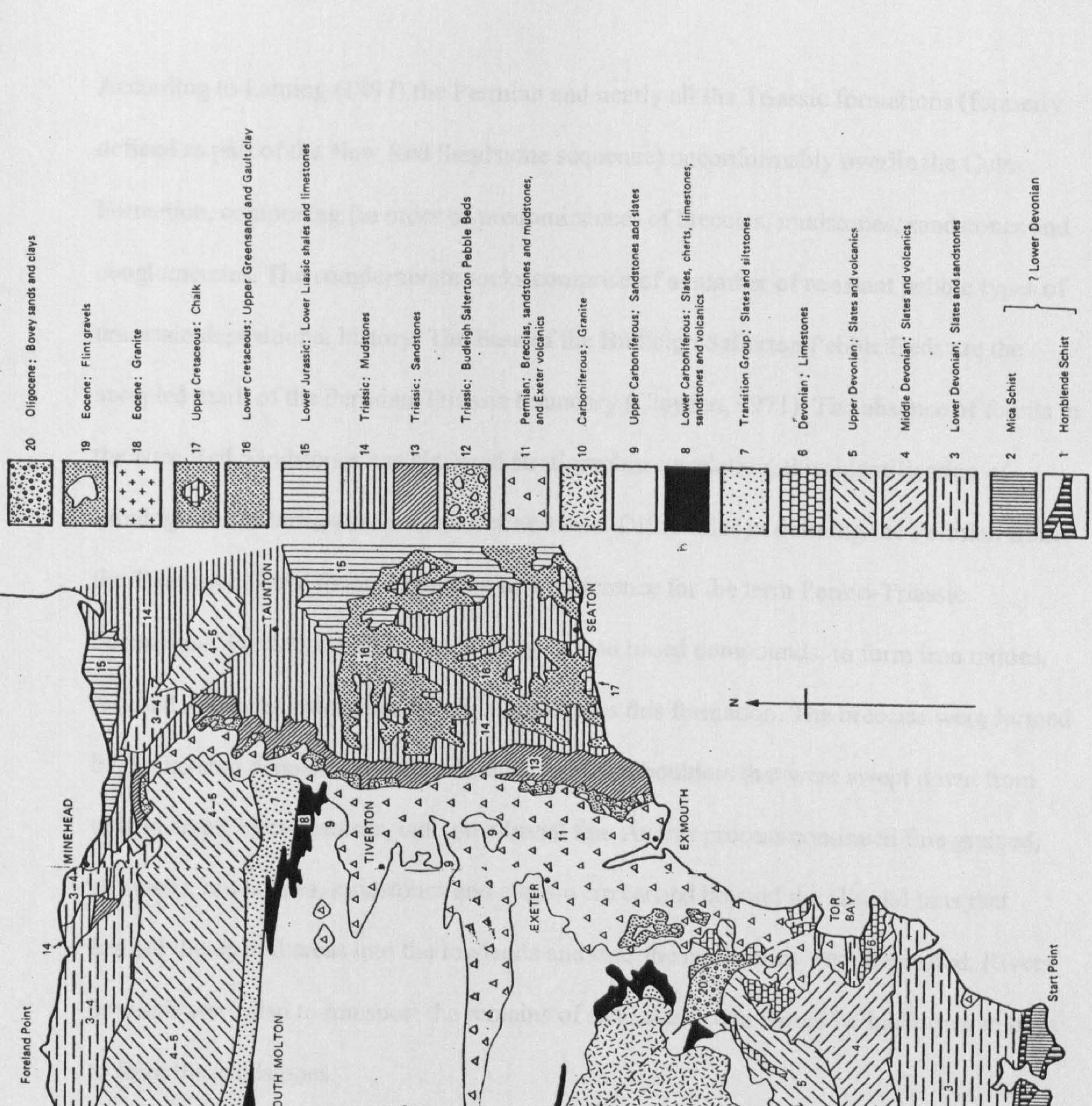


Figure 3.2 The Geology of Devon (adapted from Laming and Durrance, 1997)

According to Laming (1997) the Permian and nearly all the Triassic formations (formerly defined as part of the New Red Sandstone sequence) unconformably overlie the Culm Formation, comprising (in order of predominance) of breccias, mudstones, sandstones and conglomerates. The conglomerate rocks comprise of a number of resistant pebble types of uncertain depositional history. The base of the Budleigh Salterton Pebble Beds are the accepted mark of the Permian-Triassic boundary (Clayden, 1971). The absence of fossils in the New Red Sandstones has hindered stratigraphic correlation, thus identification of lithological similarities are used to define strata. Difficulties in defining the Permian from the Trias rocks have found resolution in a preference for the term Permo-Triassic Formations. Post-depositional weathering of iron based compounds, to form iron oxides, resulted in the red coloration which characterises this formation. The breccias were formed by the layered deposition of gravel, mud, sand and boulders that were swept down from upland areas, by rainstorms, onto an alluvial fan. As this process continued fine grained, siltstones, mudstones, sandstones and clays were carried beyond the alluvial fans that fringed the upland areas into the lowlands and thus the mudstones were deposited. Rivers or winds were also to transport the remains of sand dunes that would be laid down in beds to form the sandstones.

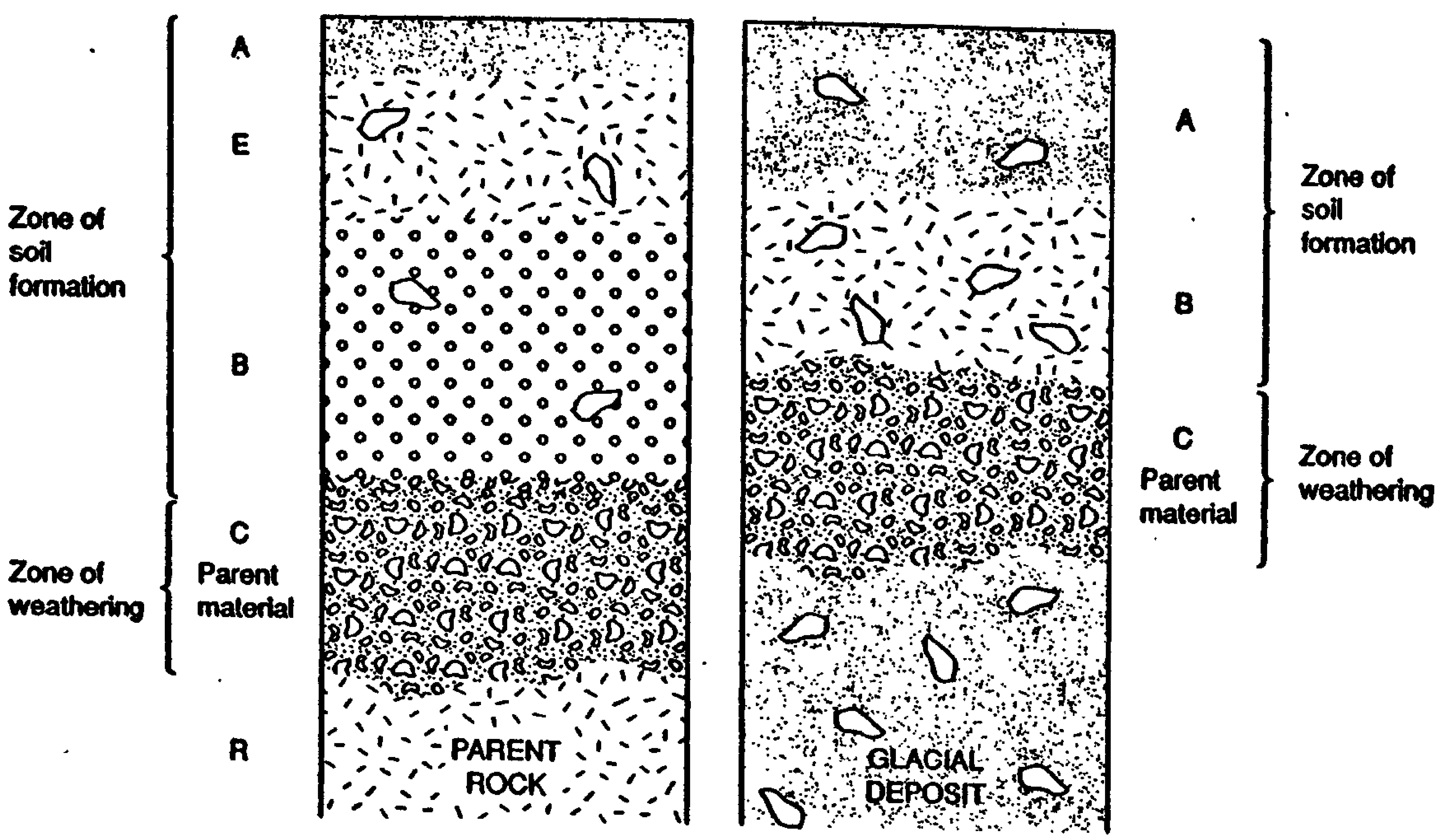
3.3.2 The pedological landscape of Devon as derived from the rocks of the Upper Culm and Permo Triassic Formations

The pedological landscape of the Permo-Triassic and Upper Culm formations is identified with the 'red soils' and 'Dunland soils' respectively. However, a pedalogical landscape is defined by natural processes. Therefore to interpret Devon's pedology we must first identify the processes of soil formation.

3.3.2.1 Soil formation

Selby (1993) has attributed the factors that influence soil formation to: the nature of the parent material, chemical environment and geomorphic stability. Indeed the acceptance and an appreciation of the relationship that exists between these factors have formed the basis for the mapping of soil units. Understanding the relationship between soil formation and landscape was important in developing a rationale for the selection of soils.

Naturally occurring soils are formed by one of two processes; transportation and weathering, or a combination of both. The in situ weathering of the Earth's mantle may be identified by three distinct weathering profiles, the solum, saprolite and finally any part of the profile that lies below the water table. The combined profiles of the solum and saprolite are known as regolith (Selby, 1993). McLean and Gribble (1985) discuss the formation of regolith by means of weathering processes that act on the integrity of solid rock to form residual soil deposits within the soil profile (see Figure 3.3(a)). Mechanical, chemical or biological weathering are all known to compromise the integrity of bedrock.



(a) Residual parent material **(b) Transported parent material**

Figure 3.3 Soil profiles on residual and transported parent materials (Smithson et al., 2002)

Biological weathering is the predominant process in the formation of the solum which defines that part of the soil profile that lies at the ground surface and includes the organic matter vital to the support of plant life and comprises of two soil distinct layers of soil, known as the A and B horizons.

The organic layer lies at the surface of the soil profile, and is the layer on which vegetation may be seen to grow. Exposure of this organic matter to the Earth's atmosphere results in decomposition, the products of which are acidic compounds (McLean & Gribble, 1985). These acids percolate downward through the soil to react with existing minerals at a lower level, within Horizon A, to produce soluble components which will in turn continue to migrate downward to the next soil layer, Horizon B. Thus Horizon A is the layer from which compounds are subsequently leached (or eluviated) while Horizon B is the lower layer of compound deposition (the illuviated layer).

Layers comprising of vegetation and Horizon A have little place in a discussion of earthen building construction as all organic soil matter is removed prior to soil selection for earthen building. Horizon B, which is more chemically stable is however, of more interest as is the lower horizon, Horizon C, the first layer of the saprolite which contains weathered bedrock formed in-situ by mechanical and chemical weathering.

The products from weathering are lighter and more easily mobilised via the action of gravity, air, water or ice than the parent. The migration of products formed from weathering to sites of deposition results in a soil formation process known as transportation. Figure 3.3(b) illustrates a typical soil profile defining soil formation by transportation. The transportation of weathering products effectively results in the erosion of the original locality. During transportation weathered products may undergo a substantial amount of comminution and sorting, resulting in the deposition of soils which exhibit a relatively high degree of natural grading (Selby, 1993). Barnes (2000) has provided a simplified diagram (Figure 3.4) to illustrate how this grading may be identified in accordance with the geographical landscape for soils transported via gravity and/or water.

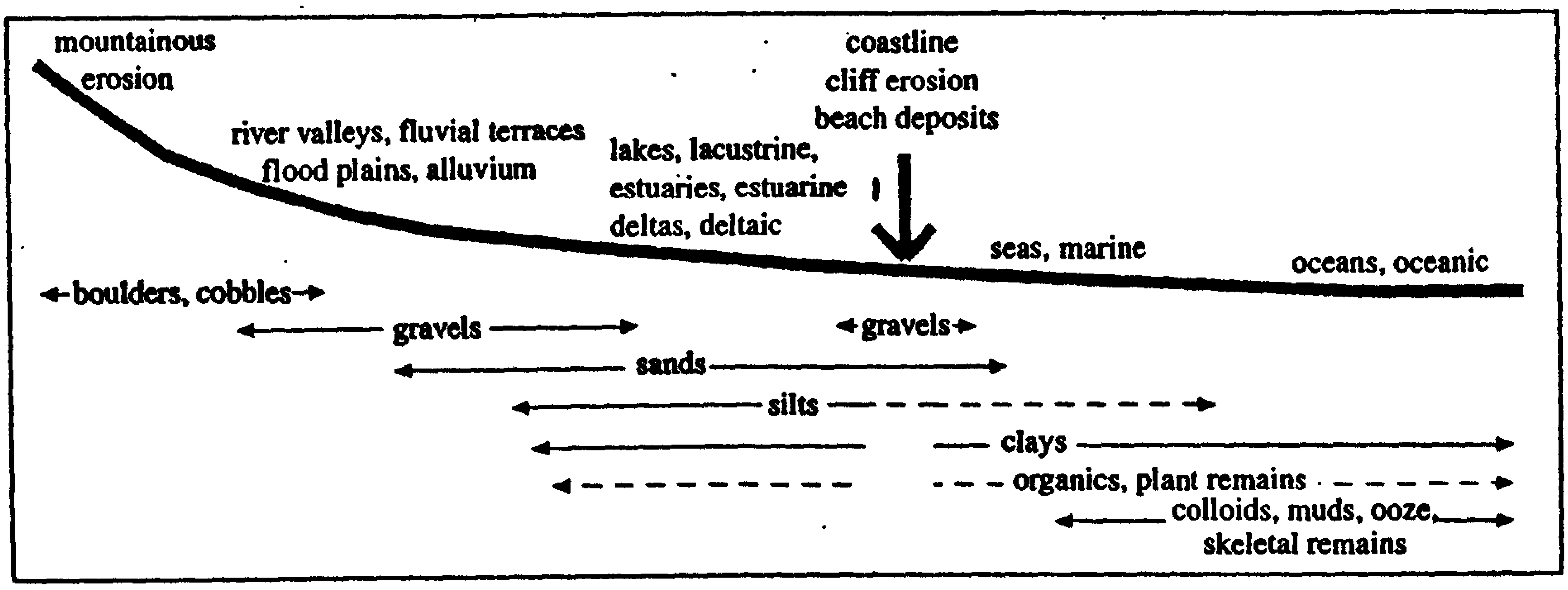


Figure 3.4. Simplified deposition environment for gravity/water-borne soils, Barnes (2000)

It is clear from Figure 3.4 that the nature of the matrix that results from soil formation processes is significantly identified with the geographical landscape. Large boulders and cobbles are associated with the highly eroded mountainous areas. Gravels, sands and clays may be found on lowland sites, the transported products of hillside erosion or the deposited products of water-borne soils. Implicitly landscape is synonymously linked to soil classification.

The location of historic cob buildings on Devon's landscape therefore became a consideration in the determination of selection sites. It was envisaged that the grading of soils associated with their location on the landscape would meet the geotechnical requirements of the selection criteria discussed in Section 3.2.

3.3.2.2 The red soils

The red soils of the Permian formations or 'New Red Sandstones', for which the County of Devon is famed, are dominated by the 'Crediton Series'. Indeed the pedology of Devon as a whole, is dominated by the Crediton Series which is described by Clayden (1971) as a "well graded gravelly loam developed from breccias and conglomerates". The mapping of this series is known to exhibit considerable range in both matrix and stone composition and is shown, on mechanical analysis, to contain a clay content of approximately 20 per cent within the solum and upper horizons of the saprolite. Below the solum, sand contents generally lie between 40 to 50 per cent. These ranges may be identified from Table 3.2 which reproduces the "Analytical data" presented in the "Memoirs of the Soil Survey of Great Britain, Exeter District" for specific soils relevant to this investigation.

The more gravely soils encompassed within the Crediton Series merge into the more sandy Bridgnorth Series, a browner soil of weaker structure (Clayden, 1971), and prevalent within the sandstone lowlands (see Figure 3.5.).

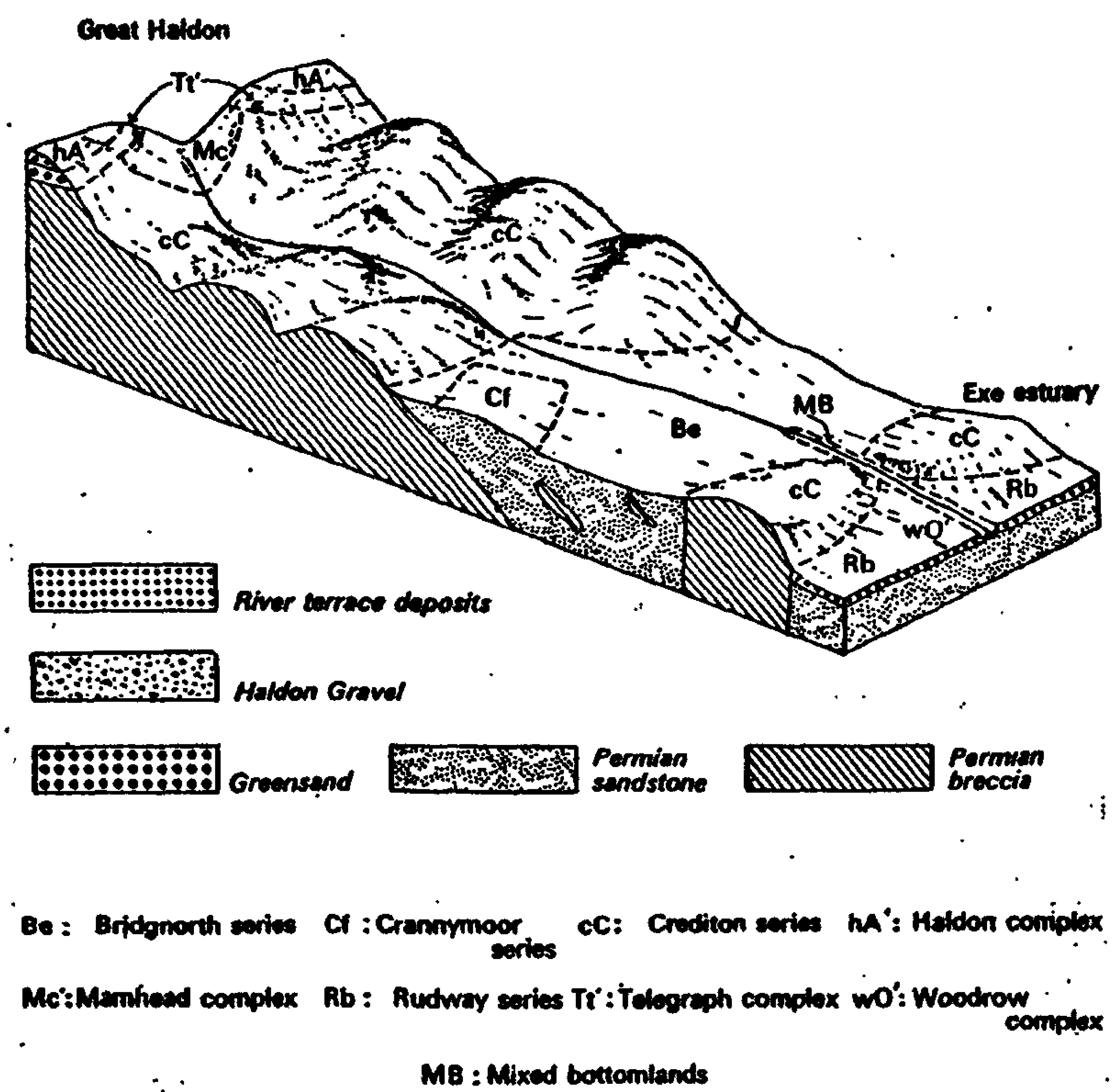


Figure 3.5. Soil pattern between Great Haldon and the Exe estuary (Clayden, 1971)

Soil Series	Profile no.	Horizon	Depth (mm)	Sand 2mm-50µm %	Silt 200-50µm %	Clay <2mm %	Loss on ignition %	Carbon %	$CaCO_3$ equivalent %	pH		Exchangeable cations (me/100g)					CEC (me/100g)	Percentage base saturation
										H_2O	M/100	Ca	Mg	K	Na	H		
Bridgnorth	SX 98/4325	Ap	0-200	74	17	8	2.8	1.1		6.5	5.9	4.7	0.2	0.15	0.03	3.5	8.6	59
		B1	200-380	79	14	7	2.4			6.2	5.6	2.8	0.1	0.15	0.06	3.2	6.4	50
		B2	380-610	80	14	5	1.5			6.3	5.5	1.5	0.1	0.05	0.04	2.2	3.9	44
		C	610-890	91	6	4	0.7			6	5.3	1.2	0.2	0.05	0.04	2.3	3.8	39
	SY 08/5249	Ap	0-200	72	20	9	2.8			5.1	4.6							
		AB	200-410	67	23	10	2			5.8	5.3							
		B	410-580	79	14	7	1.4			5.8	5.4							
		Cl	580-840	91	7	2	0.6			5.6	5.2							
Bromsgrove	SX 99/7497	A	0-200	48	36	16	7.1			6	5.2							
		B	200-610		33	15	3.3			5.8	4.8							
		C	610-890		52	18	2.4			5.6	4.7							
	SX 89/8594	Ap	0-130	39	43	18	14		0.1	7	6.2							
		AB	130-250	41	41	18	4.2		tr.	6.9	6.1							
		B	250-510	35	45	20	3.3			6.9	6.1							
			510-710	42	43	14	2.8			7.1	6.3							
		BC	710-910	52	43	15	2.3		tr.	7	6.1							
Crediton	SX 98/1773	Ap	0-180	66	20	13	4.8	1.6		6.9	6.1							
		B	180-360	74	16	9	2.7			7.2	6.3							
		C	360-610	76	17	6	2			7.2	6.3							
	De114	A	0-330	54	30	16	5		4.4	7.8	7.2	36.5	0.3	0.14	0.2	0.5	37.6	99
		B	330-530	52	28	20	3.6		0.5	7.7	7	15.5	0.3	0.13	0.19	0.8	16.9	95
		C	530-690	59	27	13	3.3		0.1	7.3	6.7	9.1	0.3	0.14	0.17	1.8	11.5	84
	SS 80/5410	A	0-180	41	34	24	9.5			6.1	5.2	11.3	1.4	0.21	0.31	6.7	19.9	66
		AB	180-360	49	32	19	9.7			6	5.1	6.3	0.8	0.16	0.2	3.8	11.3	66
		B	360-790	43	33	23	3.3			6.1	5.1	7.2	0.5	0.16	0.2	2.1	10.2	79
	SS90/7737	A	0-300	43	38	19	7.9			6.2	5.8							
		C	300-510	46	37	18	4			5.6	4.9							
Dunsford	SX 99/2762	A	0-80	12	55	29	19.1		9.5	4.1	3							
		B1s	80-230	24	46	27	7.4		1.8	4.6	3.9							
		B2s	230-410	37	38	23	6.9			4.6	4							
		BC2tx(g)	53-740	45	37	17	5			4.8	4							
	SX 79/9738	A1	0-230	15	50	33	9.3	3	3	5.4	4.5							
		A2	230-380	28	39	33	7.9	1.3	1.3	6.6	5.8							
		Bs	380-610	41	32	26	5.9			6.2	5.7							
		BCtx	610-890	41	35		5.5			6.3	5.6							
			890-102	55	33	18	5.4			6.3	5.5							
Halstow	SX 88/3181	Ap	0-230	21	46	32	9.1		6.3	5.6								
		B(g)	230-560		38	52	5.4		7.1	6.5								
		BC	560-760		37	43	5.7		6.9	6.3								
		Cg	760-910		31	38	5.5		6.7	6								
	SX 79/9536	Ap	0-230	22	46	31	8.7	2.4	6.3	5.4								
		B1(g)	230-380	5	42	48	6.1		7.3	6.4								
		B2(g)	380-510	5	45	48	6		7.6	6.8								
		BC	510-640	15	47	39	5.6		7.1	6.4								
		Cg	640-740	49	33	17	5.8		6	5								
Tedburn	De 42	Ag	0-180	17	26	58	11.5		5.5	4.8								
		B1g	180-380		38	50	5.7		5.4	4.5								
		B2g	380-660		41	55	5.8		5	4.1								
		BCg	660-860		43	43	5.6		6.5	6.2								
	Sx 79/9638	A1g	0-130	8	51	40	9.9	2.7	5.4	4.5								
		AB	180-300	15	46	38	5.5		6.3	5.4								
		B1g	300-530	7	50	43	5.3		5.8	4.7								
		B2g	530-760	5	51	44	5.2		5.4	4.1								
		B3g	760-1020	4	50	45	5.2		5.2	3.9								

Table 3.2 Analytical data on six soil series reproduced from the "Memoirs of the Soil Survey of Great Britain, Exeter District"

The Bridgnorth Series exhibits relative uniformity in most areas of its mapping with little stone content within the regolith. Soil horizons vary little except in colour and are generally composed of sandy loam of weak fine crumb structure. Clay content generally fails to exceed 12 per cent in the soil horizons below the level of the topsoil, while sand contents can lie between 70 to 90 per cent (see Table 3.2).

Soils of the Bridgenorth Series are sometimes known as the 'red sands' as opposed to the 'red loams', thus distinguishing them from the Bromsgrove Series into which these soils may also merge. The Bromsgrove Series denotes "well drained brown earths of silty texture developed on soft fine-grained Permian sandstones" (Clayden, 1971). From Table 3.2 it can be seen that clay content varies little through the soil profile lying at approximately 15 to 20 per cent but remains higher in the silty phase. Sand contents within this phase are similarly low, but may lie between 30 to 40 per cent in other profiles of the series.

3.3.2.3 The Dunland soils

Dunland soils (a commonly adopted term of reference which distinguishes areas of land predominated by red coloured soils from those coloured brown/grey-brown) overlie the shales, siltstones and sandstones of the Carboniferous Culm measures. These soils occupy much of the area to the south of the Crediton Trough. This area is also known as the 'Exeter Shale Hills' (Clayden, 1971), emphasising the inter-dependence of soil formation on landscape. Therefore it seems appropriate that the boundaries of the soil series' that define this group, namely Dunsford, Tedburn and Halstow, are defined by topographic variation.

Figure 3.6 shows the pattern of the soil series for the Exeter Shale Hills and illustrates the boundaries defining soil formation with the changing landscape.

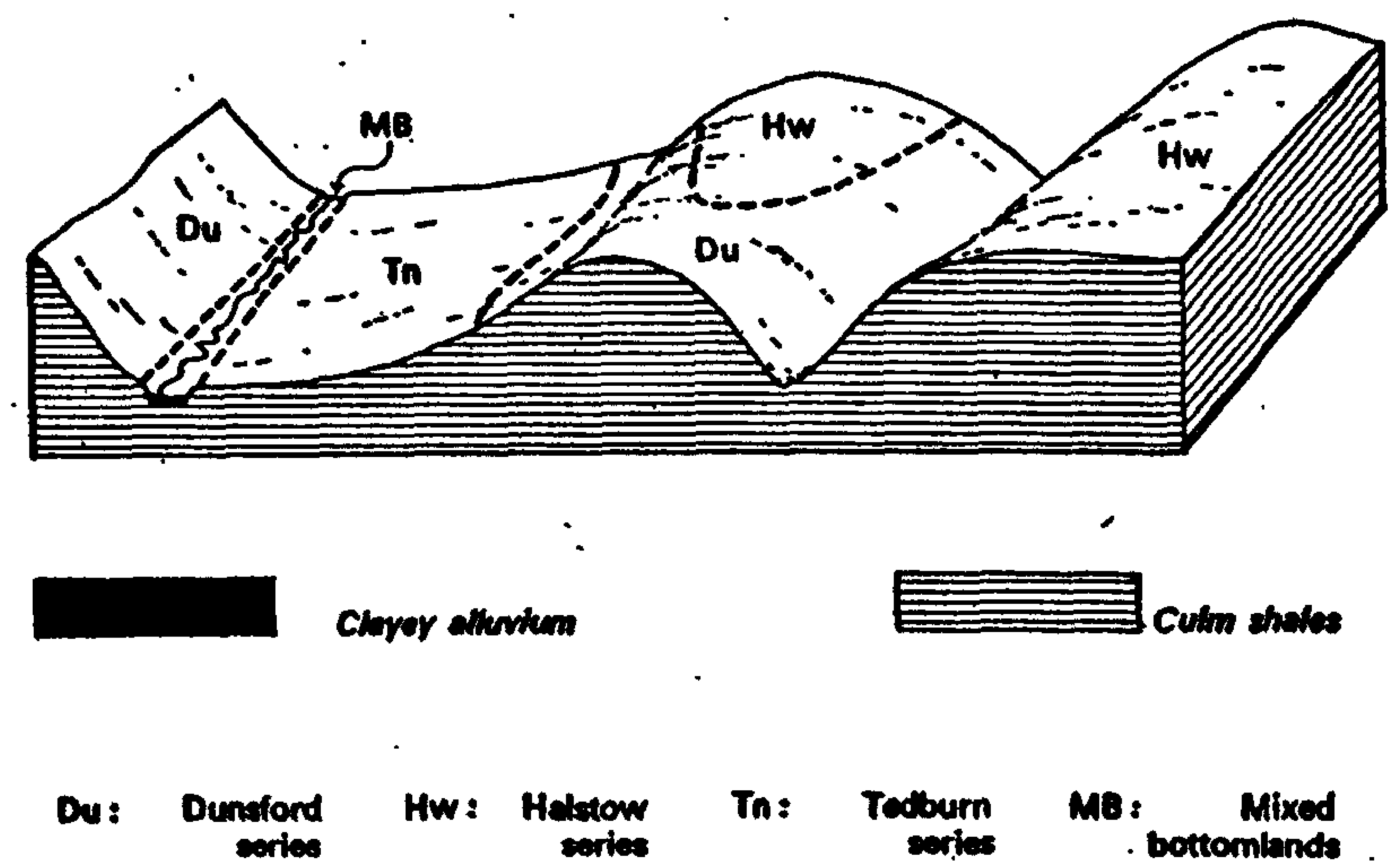


Figure 3.6 The soil pattern of the Exeter Hills, Clayden (1971)

The Dunsford Series, a series of shallow lying brown clay loams overlying shale, may be found on steep valley slopes that may be subject to appreciable run-off. The upper phase of this series consists of fine blocky structures of clay loam which increase in textural coarseness in passing down through the section. Fine shale and stone fragments of sandstones are present (although the quantities of these are not stated in the soil survey memoirs), while clay content remains relatively constant through the profile at 20 to 30 per cent (Clayden, 1971) (see Table 3.2).

The higher clay content of the Halstow series (approximately 30 to 45 per cent) is indicative of its area of occupation. The gently sloping interfluves on which Halstow may be characteristically mapped are subject to a similar degree of weathering than those experienced on the steeper valley slopes, but the significantly lower levels of erosion of weathered products results in the deposition of soils of higher clay contents. The upper phases of the solum comprise of blocky structured, silty clays. Passing down through the profile, these clays may be interrupted by bands of weakly structured loams containing shale fragments although these fragments are more apparent in the Dunsford Soil Series.

The final mapping unit to define the landscape of the Exeter Shale Hills soils is the Tedburn Soil Series. This series is predominately mapped on gentle footslopes receiving significant amounts of water that runs off the slopes of steeper ground. These soils are therefore water-logged much of the year and due to this their surface to bedrock profile indicates a variety of transitional phases. The increased gleying and mottling that physically identifies this series from that of the Halstow Series is also indicative of the higher clay contents within these soils. Table 3.2. shows that typical clay contents range from 50 to 60 per cent within the solum and the silt content lies between 35 to 45 per cent thus resulting in a negligible sand content.

The numerous descriptions of various soil series given above are, by no means, exhausted for either the area that overlies the rocks of the Upper Culm or those of the Permo Triassic Formations. However, in the discussion presented in Section 3.4, the influence of the information gathered during the desk study on the determination of selection sites is reviewed. This information is ultimately shown to focus soil selection about those areas defined by the aforementioned soil series specifically, and thus the descriptions above are similarly restricted.

The "Memoirs of the Soil Survey of Great Britain, Exeter District" had identified the topographical landscape occupied by the aforementioned soil series, believed to be indicative of matrix and hence geotechnical variation. The desk-study proceeded by reviewing the available geotechnical data for these soils that would confirm these variations and support soil selection in line with the criteria defined in Section 3.2.

3.3.3 Utilising the soil survey to establish the geotechnical characteristics of the selection sites

Many soil surveys may quote Atterberg limit values that are often used by geotechnical engineers to ascertain geotechnical behaviour. Unfortunately, as can be seen from the "Analytical data" reproduced in Table 3.2 from the "Memoirs of the Soil Survey of Great

Britain, Exeter District", no such insight was afforded this investigation. However utilising the tabulated values of 'cation exchange capacities' (CEC), inferences may be made to assist a geotechnical engineer, acquainted with the mechanisms that control the Atterberg limits.

Section 3.3.3.1 discusses those mechanisms that pertain to interpretation of the tabulated values of cation exchange capacities but does not purport to offer an exhaustive discussion on all the mechanisms that control the values of the Atterberg limits. Section 3.3.3.2 reviews the tabulated values of CEC for the six soil series highlighted in Sections 3.3.2.2 and 3.3.2.3.

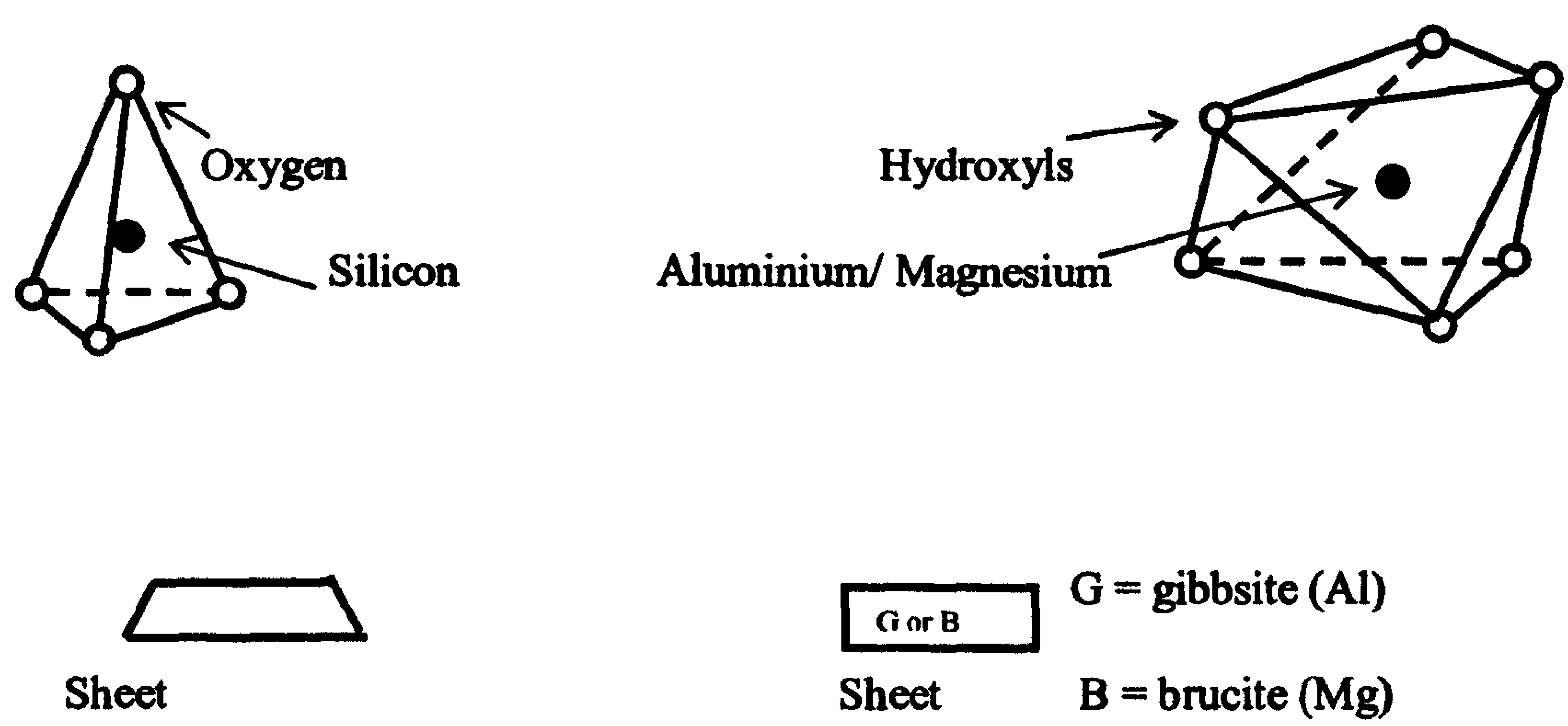
3.3.3.1 The mechanisms controlling the Atterberg limits (relevant to the interpretation of cation exchange capacity data)

According to Nagaraj and Jayadeva (1981) the liquid limit test, utilising the cone penetration apparatus, is essentially a measurement of the shearing resistance of a soil relative to its moisture content. As clay particles are sheared past each other, they are believed to achieve parallel orientation, a process verified by Muhanthan (1991). Hence the development of the parallel-platelet model wherein the water content at the liquid limit of clays is shown to be a function of their specific surface area, S, and their particle separation distance, d, (i.e. LL= 0.01Sd). While S is a physical property, d, is controlled by the physico-chemical properties of the clays.

Moore (1991) has also discussed the physico-chemical properties of soils with respect to their frictional and cohesional contribution to the shear strength of soils. He concluded that when clay is present in excess of 10%, the physico-chemical properties of that clay may prove significantly influential to its shear strength due to a reduction in the frictional coefficient. Moore has classified the physio-chemical properties of clays by their composition (percentage sand to clay particles), clay mineralogy and clay-water chemistry.

While clay mineralogy will define the specific surface area of the clays, S, and thus the frictional contribution to the shear strength and thus the liquid limits of the soils, it is also influential with respect to the cation exchange capacity (CEC) of the soil. The CEC of a soil has been defined by Bowles (1984) and Selby (1993) as the ability of clay minerals to exchange the cations within its structure for other cations. Such a reaction is measured in milli-equivalents per 100 grams of dry soil (Barnes, 2000). In order to explain these reactions it is important to understand the crystal structure of the clay mineral.

Most clay minerals are oxides of aluminium and silicon with smaller amounts of metallic ions substituted within the crystal. They are commonly referred to as alumino-silicates. The basic units are that of the silica tetrahedron (Figure 3.7 (a)) and the aluminium (or magnesium) octahedron (see Figure 3.7 (b)), and these bond together to form sheets. The way in which these sheets stack together to form layers, the bonding between these layers and the substitution of the aluminium and silicon ions for other metallic ions, explains the variety of naturally occurring soil minerals (Table 3.3). However, regardless of their bonding, layering, or ionic make-up the resultant mineral possesses a net negative charge on the exterior of the cluster.



(a) silicon tetrahedron and sheet representation

(b) aluminium/magnesium octahedron and sheet representation

Figure 3.7. The basic structure of clay

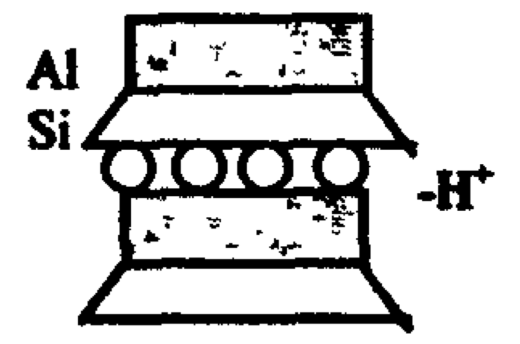
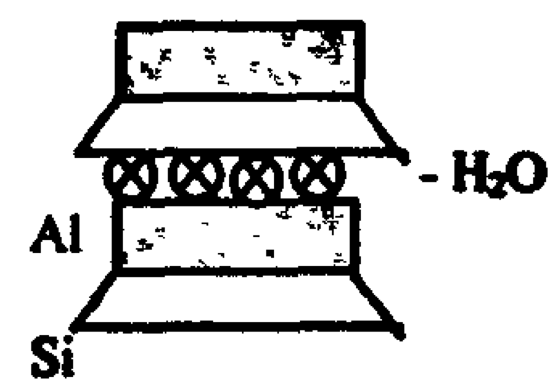
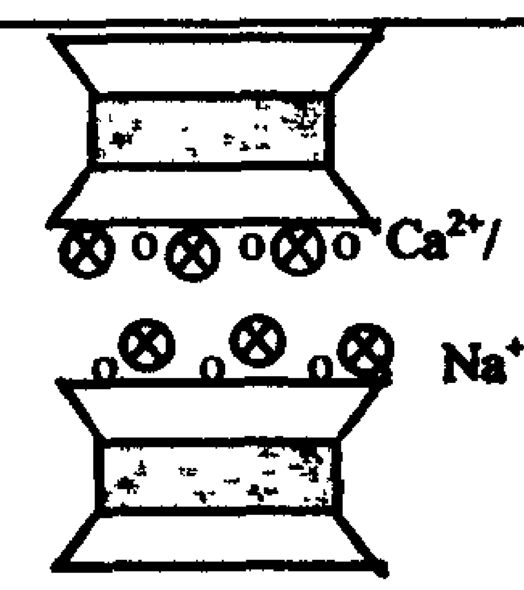
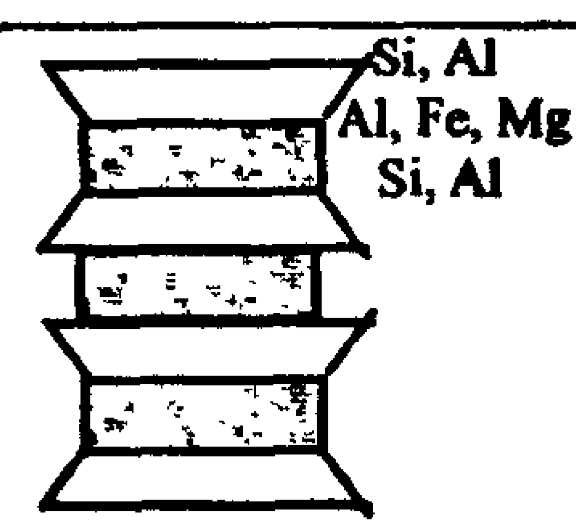
Layer mineral type	Layer mineral example	Schematic representation	Bonding between layers	Specific surface area (m^2/g)	Exchange capacity (me/100g)
1:1	Kaolinite		H^+ bonding + secondary valence	10 – 20	3
	Halloysite		Secondary valence	40	12
2:1	Montmorillonite		Secondary valence + Exchangeable ion linkage	800	100
2:1:1	Chlorite		Secondary valence + brucite linkage	5 - 50	20

Table 3. 3. Classification of layer lattice minerals, Moore (1991) and Selby (1993).

Where one tetrahedral sheet combines with one octahedral sheet (such as kaolinite or halloysite) a 1:1 layer mineral is formed; likewise the arrangement of two tetrahedral sheets either side of a single octahedral sheet represents a 2:1 layer mineral (Selby, 1993). The spaces separating these layers are known as interlayers. Due to the excess negative charge held by the clay mineral particles these interlayers generally attract cations such as Ca^{2+}, Mg^{2+}, Na^+, K^+ and H^+ which become absorbed onto the surface of the clay mineral. When clay layers share ions within an interlayer, a clay structural unit is formed; many such units accumulated together form a clay particle.

Clay minerals are constantly attempting to balance their net surface charge and this therefore gives rise to cation exchange within the interlayer. Where there is an absence of sufficient metallic ions to satisfy this charge deficit, clay units will begin to swell by taking in water into the interlayer, with the H^+ ion disassociating to attach itself to the negatively charged clay mineral face. The tendency for soils to do this defines their 'activity'. Skempton (1953) defines activity as the plastic index (ie LL-PL) per percentage clay size fraction. Activity is also shown to correlate with cation exchange capacity.

Generally higher values of liquid and plastic limits are associated to soils exhibiting higher cation exchange capacities, which is most attributable to 2:1 layer minerals as opposed to those of 1:1 layers. Section 3.4.3 considers the mineralogical data of the selected soils while Table 3.2 highlights the CEC tabulated for the six selection sites discussed in Sections 3.2.2.2 and 3.2.2.3.

3.3.3.2 Cation exchange capacities for six soils of the Upper Carboniferous and Permo Triassic Formations

On consideration of the CEC values presented in Table 3.3, the range of readings shown for Crediton, Bromsgrove, Bridgnorth, Dunsford, Halstow and Tedburn, offer little conclusive evidence of marked geotechnical variation between each series, as may be expected on consideration of the variation in topography in the selection sites.

Section 3.4 will determine whether or not these findings are borne-out by the geotechnical testing carried out on the actual soils selected.

3.4. Soil selection sites

Given the information gathered in the desk-top study, it was now possible to identify suitable sampling sites while also considering the need to meet the other criteria previously discussed in Section 3.2.

Recapping on these criteria it should be noted that soil selection was to occur from areas overlying the Upper Carboniferous and Permian/Triassic rocks of Devon, in accordance to the findings of Keefe (1998). Furthermore selected soils were to have identified historical use. The final criterion was to attempt to encompass a wide a range of soil matrices in the study. Of these initial criterion only the later became slightly modified during the process of site selection, after consideration of the desk-study.

As a result of the desk study concerning soil formation (Section 3.3.2.1), coupled with the findings of Sections 3.3.2.2 and 3.3.2.3, wherein the pedological landscape of Devon was identified, it was decided to pursue the effects of natural matrix variation on the structural behaviour of earthen building materials. Natural matrix variation is afforded by consideration of sampling from a catena sequence. Selecting soils from areas overlying the same parent rock but of progressively altering topographic formation, such as those exhibited by the Dunland soils which dominate the Exeter Shale Hills (see Figure 3.6), permits the engineering capacities of these soils, when used in cob construction, to be assessed with respect to soil weathering. Given that the areas defined by the 'Dunland' soils, pedalogically known as Dunsford, Halstow and Tedburn fulfilled other criteria considerations a decision was made to select these specific soil series. The redland soils of 'Crediton' and Bridgnorth also derived from the same parent rock but occurred on two differing areas of topographical boundaries; one of the Breccia Hills and the other of the Sandstone lowlands respectively (Clayden, 1971). Again, given their complicity with all other criterion considerations, the areas defined by these soils seemed an appropriate choice for soil selection.

Through this selection the opportunity was afforded to investigate naturally modified matrices as opposed to manufactured earthen matrices as had previously been investigated by Greer (1996). Thus the pedological discussion presented in Sections 3.3.2.2 and 3.3.2.3 orientates itself around the landscape in which these soils may be found.

The final adoption of sites for sampling was determined out in the field where potentially suitable sites were identified by virtue of the existence of an historic cob building constructed from the land on which it was founded. Upon identification, permission was gained from the landowners to sample from the nearby vicinity. Section

3.4.1 references these sites and Figure 3.8 illustrates the soil profiles gathered from the selection sites, accompanied by a descriptive commentary.

It is important to note that from the profiles presented in Figure 3.8, only that proportion of the profile containing B and C horizons were sampled for the purpose of this investigation. The decay that may be associated with the organic layer, Horizon A, renders it unsuitable for use in earthen building. Soils were dug in situ and then collected in twenty litre buckets. On returning to the laboratories, the soil within each bucket was mixed by hand to ensure the homogenisation of a soil's particle size distribution within each bucket, prior to further sampling from each bucket for the purpose of performing the geotechnical testing discussed in Section 3.5. Thus the sampled soils used to produce the geotechnical classification data (Section 3.5) and the engineering data presented in Chapter 5, may not necessarily be restricted to a specific horizon but may be a homogenised combination from Horizons B and C.

3.4.1. The geological description of the selection sites and presentation of the soil profiles.

Table 3.4 provides the reference data for the selection sites together with a location reference, and identifies the underlying geology pertinent to these sites and the relevant soil series (as indicated in the 'Soil Series Memoirs of the Exeter District').

Ordinance survey co-ordinates of site	Location Reference	Geology	Soil Series
SX 823008 - sheet 192 (1:50,000)	Chapel Down	Permian	Crediton
SX 878 938 - sheet 192 (1:50,000)	Trillow	Culm	Dunsford
SX 818 941 - sheet 191 (1:50,000)	Tedburn St. Mary	Culm	Tedburn
SS 884 065 - sheet 192 (1:50,000)	Stockadon	Culm	Halstow
SX 944 879 sheet 192 (1:50,000)	Exminster	Permian	Bridgnorth

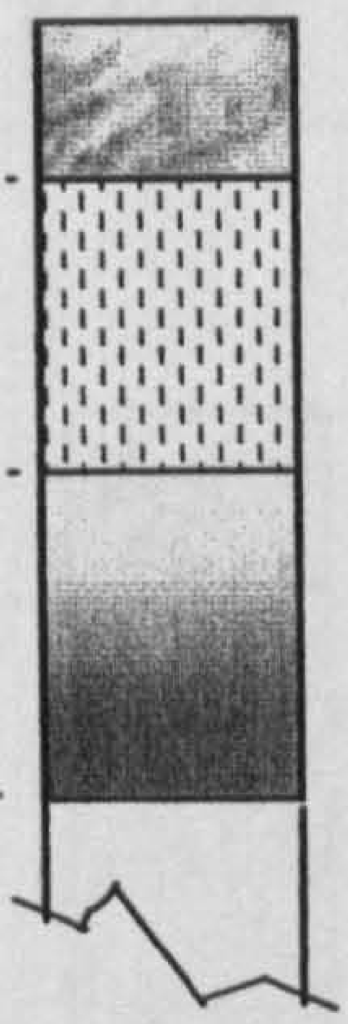
Table 3.4. Reference data for sampling sites

Figures 3.8 (a) to (e) illustrate the soil profiles relevant to each site, specified by their location reference, Crediton, Trillow, Tedburn St.Mary and Stockadon and Exminster respectively. A brief description of the site from which each profile was obtained, is also given.

Figures 3.8 (a) – (e) Pedological soil profiles of sites chosen for sampling

Figure 3.8. (a)
Chapel Down, Crediton (see vertical section, plate 3.1)

Horizon / *Description*

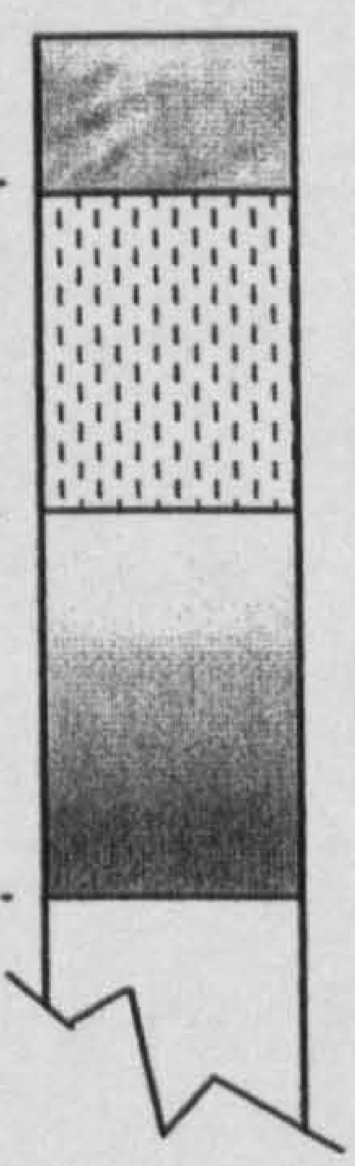


Horizon	Depth	Description
A	-200 mm	Organic topsoil (removed)
B	-500 mm	Weathered bedrock – traces of original bedding.
C	850 mm	Reddish brown sandy loam with fragments of weathered sandstone
D		Progressively firmer layered weathered bedrock of Permian Formation.

Figure 3.8 (b)
Trillow (see sample site, plate 3.2)

Samples were collected at a site 100m west of the the cob-built Trillow house at the break of valley slope with the valley bottom.

Horizon / *Description*



Horizon	Depth	Description
A	-300 mm	Dark brown stony organic
B	-1000 mm	Freely draining brown earth of clayey matrix with thin sandstone horizons.
C	-1600 mm	Freely draining brown earth with weathered fragments of slate and thin sandstones.
		Bedrock: Carboniferous slate with thin sandstones (Crackington Fm.)

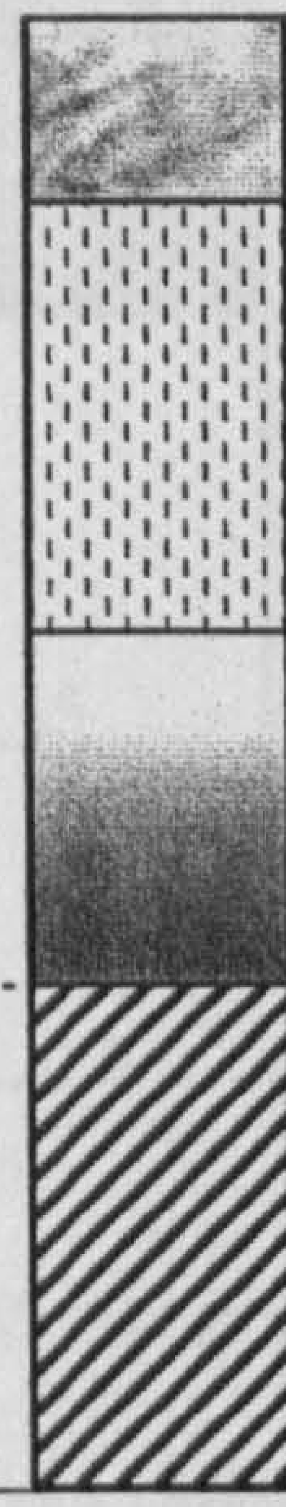
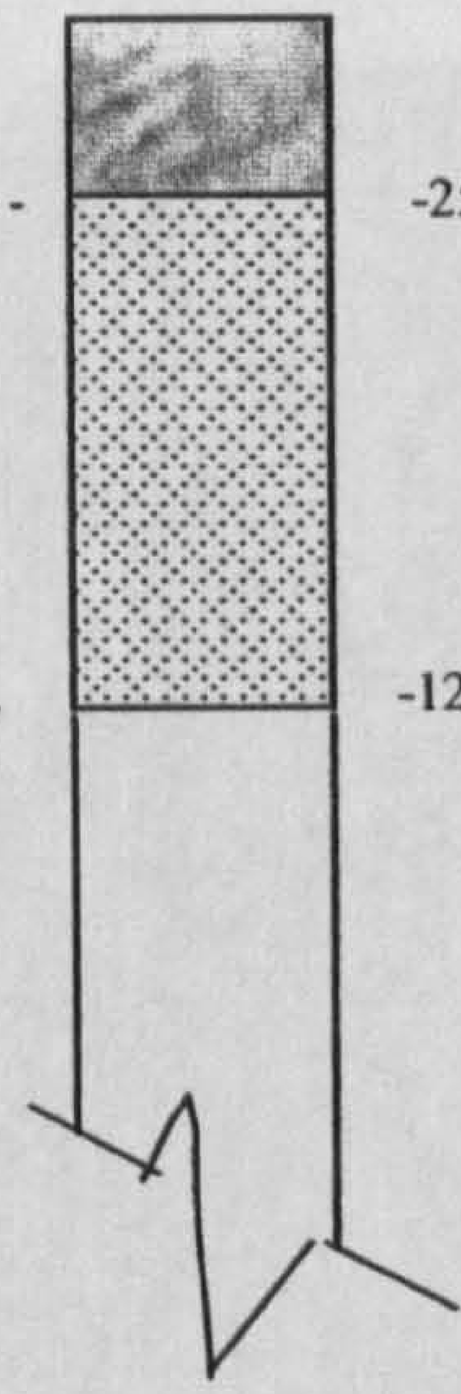
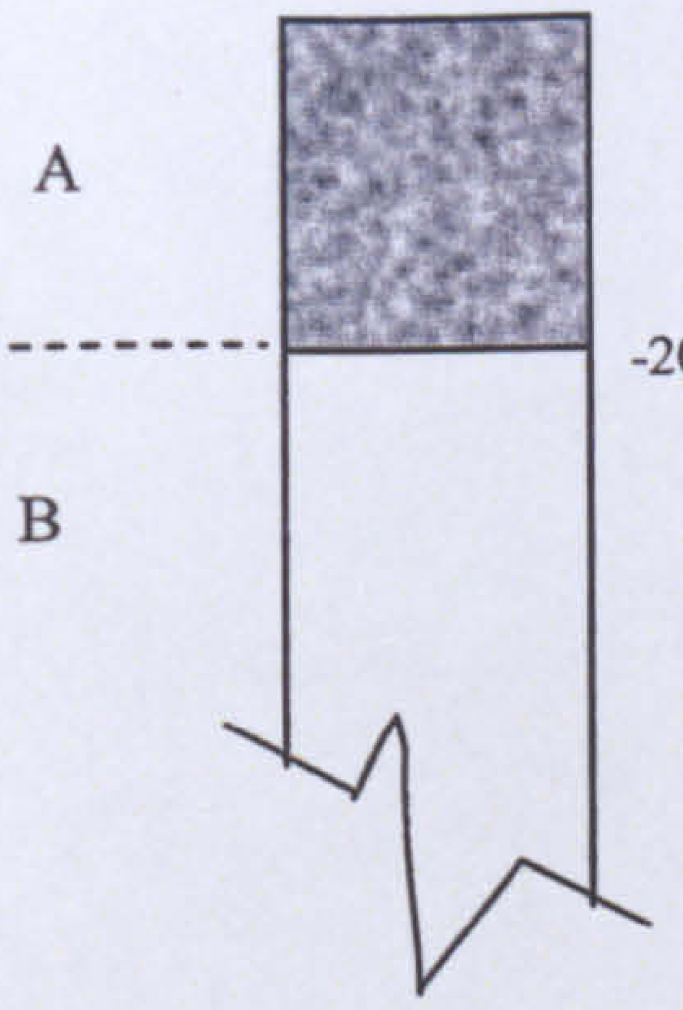
Figure 3.8 (c)	*Horizon*	*Description*
Tedburn St. Mary **(see plates 3.3 and 3.4)** Sampling was carried out from a building site at the eastern end of the village facilitated by site excavations that had created 1m deep footings exposing clayey sub-soil. Cob buildings occupy adjacent ground.		
	A (to -300 mm)	Dark yellowish brown organic earth.
	B (to -900 mm)	Dark yellowish orange and pale yellowish brown very clayey soil. Mottled between 300-700mm
	C (to -1130 mm)	Dark yellowish orange shillet of grain size , approximately 2mm.
		Approximately 3m to Carboniferous bedrock
Figure 3.8(d)	*Horizon*	*Description*
Stockadon **(see vertical section plate 3.5, sampling pile, plate3.6 and farmhouse plate 3.7)** Site of a cob farmhouse and associated out-buildings. The soil was sampled from an area east of the farm buildings where 1m of sub-soil had already been excavated for the purpose of exposing suitable cob-building material in order to carry-out repair work to outbuildings utilising traditional building techniques.		
	A (to -250 mm)	Reddish brown dark yellowish brown organic earth.
	B (to -1200 mm)	Reddish brown clayey silt
		Progressively weathered bedrock of Carboniferous Formation.

Figure 3.8(e)	*Horizon*	*Description*
Exminster Sample site overlooks Sentries Farm built from cob. Site already excavated to 1m to make way for new building work. Samples dug from this level.	A	200-300mm reddish/brown soil, removed.
	-200 / 300 mm	
	B	Fine grained weathered bed rock reddish sands with intermediate coarse bands of weathered Permian bedrock.



Plates 3.1 to 3.7 illustrate the environmental context of the sample sites showing views of the vertical sections from which the soil profiles have been constructed and described and/or evidence of the historic significance of the soil in its use as an earthen building material.

Plate 3.1 Chapel Down, Crediton, 2.5 metre vertical section

Plate 3.2 Trillow sample site

Plate 3.3 Tedburn St. Mary cob buildings

Plate 3.4 Tedburn soil profile

Plate 3.5 Stockadon vertical section

Plate 3.6 Stockadon sampling pile

Plates 3.2, 3.3, 3.6 u/s

Plate 3.7 Stockadon farmhouse

Once selected, each soil was subject to a series of geotechnical classification tests coupled with mineralogical identification in order to ascertain the nature of the materials collected which would ultimately facilitate the interpretation of its engineering properties as presented in Chapter 5.

3.5 The geotechnical and mineralogical classification of the selected soil series as determined in the laboratory.

The Soil Survey has already suggested values that may be attributed to each series in the determination of particle size classification, cation exchange capacity, etc. It is important to recognise that these values are determined from material collected at specific sites (as opposed to all sites of related pedalogical classification). These values have been included in Table 3.2.

The work presented below re-visits some of the parameters presented in Table 3.2 for each of the soil series selected. The purpose of this is to establish the validity of extrapolating the inferences made by this data, to all sites of similar soil series classification, and ascertain whether or not the information provided by the Soil Survey facilitates the identification of soil selection for earthen building construction.

The independent laboratory determination of these parameters is presented in this section together with a statement of the methodology used to collect this data. The findings of this work against the values presented in Table 3.2 will be discussed in Section 3.6.

3.5.1 The particle-size classification of the selected soil series

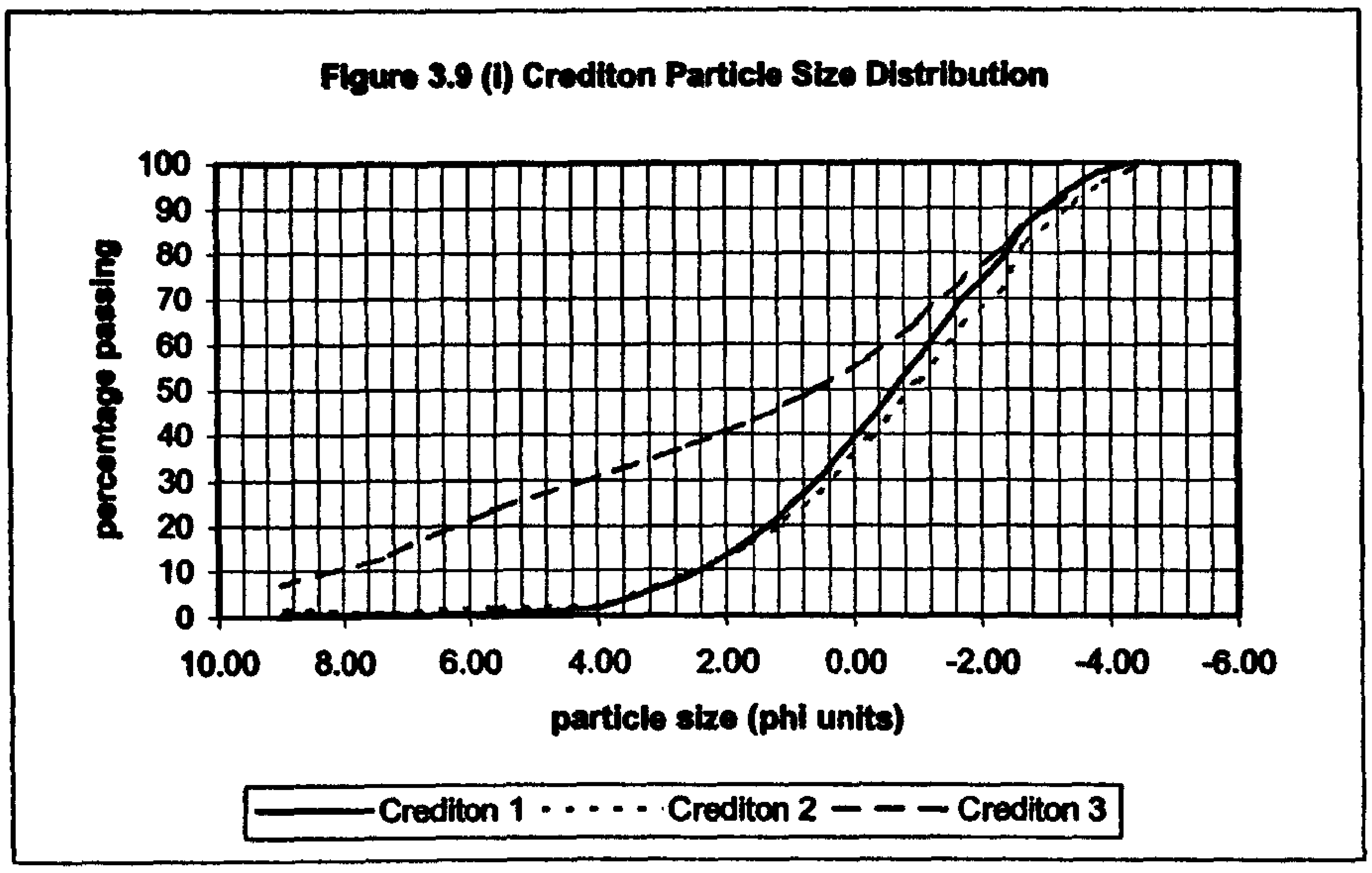
Table 3.5 presents the fraction size classification of each selected soil together with the associated variability attributable to each selection site. This is shown to facilitate the interpretation of the particle size distribution curves illustrated in Figures 3.9(i) to (v). For the majority of soils, the assessment of variability has been made after consideration of the results from five separate sievings of each soil; all sieving data may be found in Appendix 1. The values quoted in Table 3.5 for the Dunsford and Crediton Soil Series are the result of two and three separate soil sievings respectively: a material shortage prevented further particle size analysis.

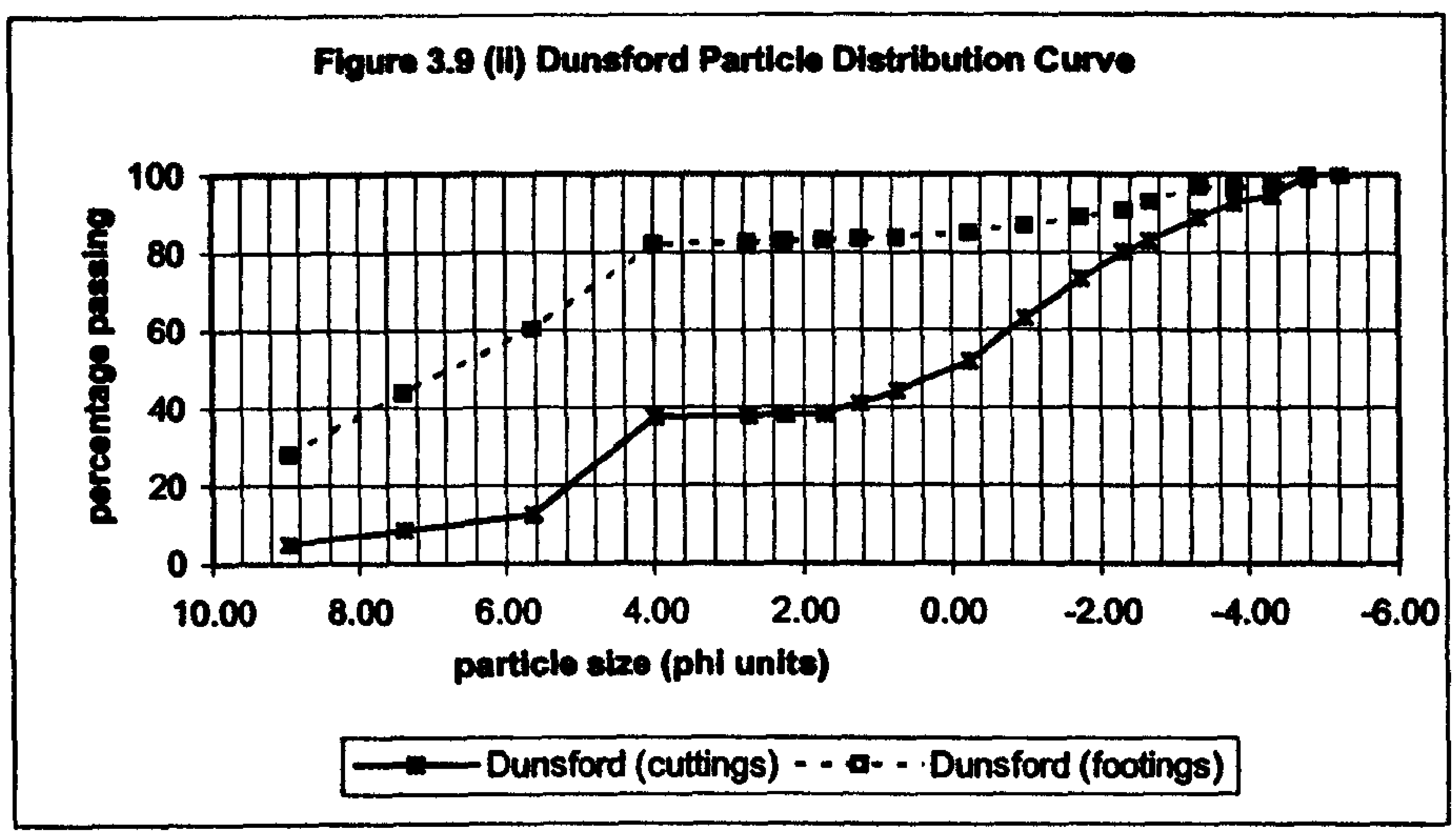
All work was carried out in accordance with BS 1377 (1990) and the classification of grain sizes into gravel, sand, silt and clay fractions, presented in Table 3.5, is also in accordance with this British Standard.

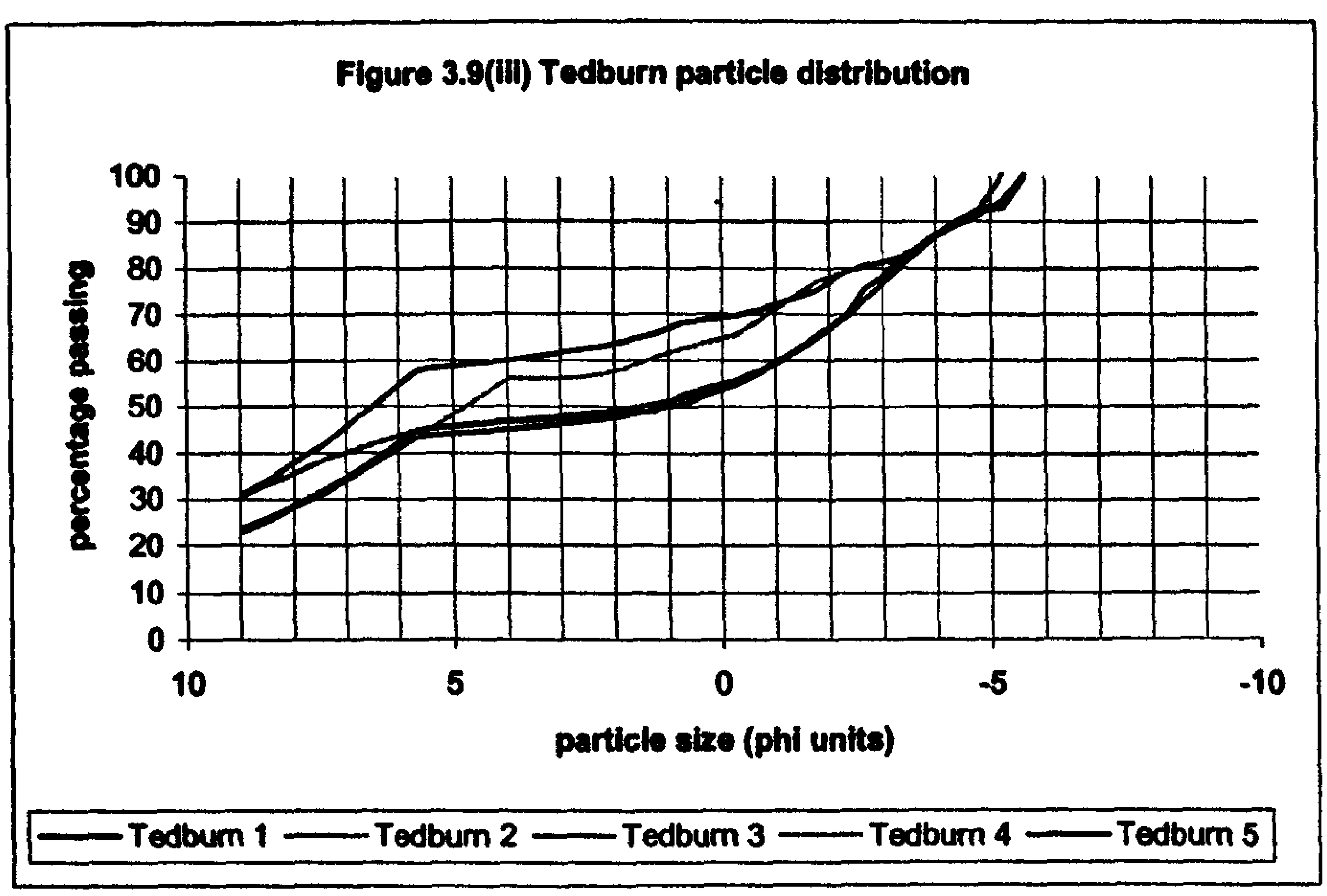
Soil series	Gravel % 60mm – 2mm	Sand % 2mm-0.06mm	Silt % 0.06mm-0.002mm	Clay % < 0.002mm
Crediton	42.4 ± *6.9*	48 ± *7.5*	2.1 ± *2.8*	2.9 ± *3.11*
Dunsford	13.2/ 36.78	4.69/ 25.64	21.74/ 24.84	5.13/ 28.19
Tedburn	35.69 ± *6.62*	13.33 ± *1.26*	25.42 ± *7.91*	26.36± *4.2*
Halstow	0.66 ± *0.225*	4.406 ± *1.679*	45.165 ±*3.413*	49.349 ±*0.98*
Bridgnorth	26.50 ± *9.53*	66.48 ± *2.80*	4.50 ± *8.76*	2.53 ± *3.35*

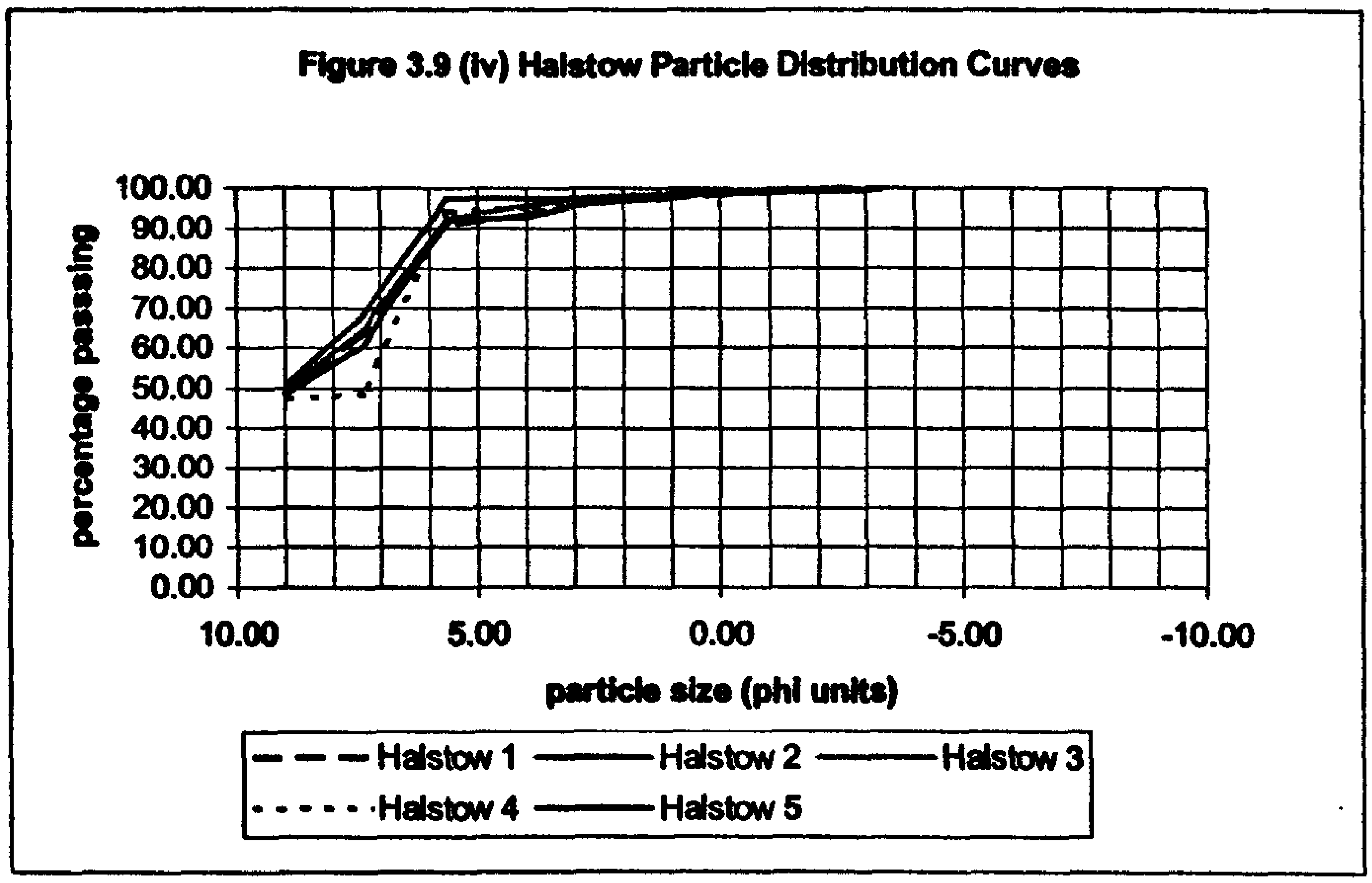
Table 3.5 Soil fraction percentages for selected soils.

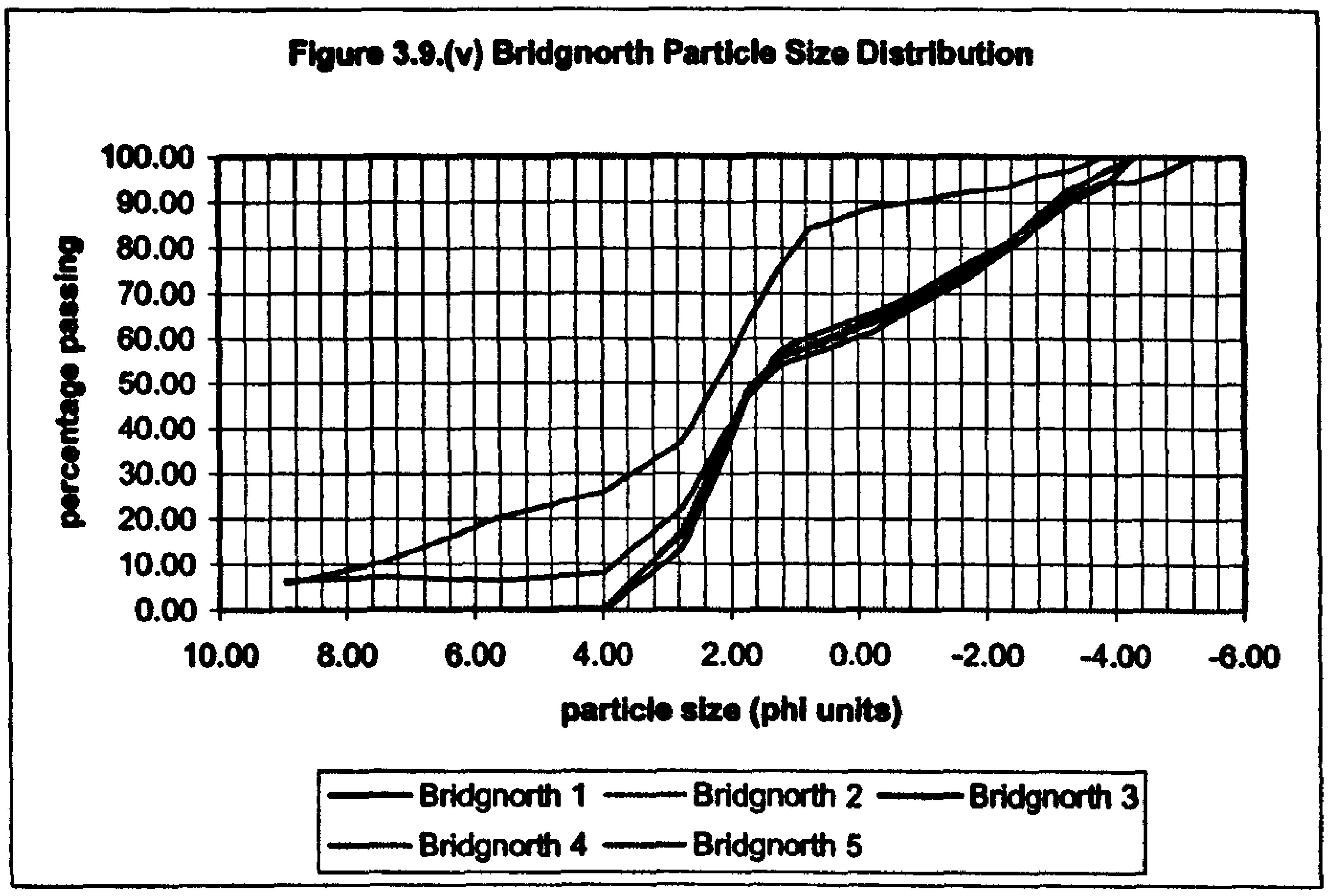
Figures 3.9 (i) to (v) Particle distributions for the selected soil series











Figures 3.9 (i) to (v) Particle distributions for the selected soil series

3.5.2 The Atterberg limit values of the selected soil series

Table 3.6 presents the laboratory-determined values of the Atterberg limits and their associated variability generally based on the results of five Atterberg limit determinations. The raw data from which Table 3.6 has been compiled is presented in Appendix 2.

The values quoted in Table 3.6 for the Dunsford Series indicate the mean value obtained for five separate tests and also the specific values obtained at two points of soil sampling, namely at the cuttings of a steep valley slope and at the valley bottom, in excavated footings. These specific points are included separately due to an 'inclination' of difference in the behaviour of the soil as it was being worked during the course of this investigation. These soils simply felt different in the hand. This was verified by the results obtained on compression testing the two sub-classes of this soil series, as indicated by the results presented in Chapter 5.

The Crediton Soil Series Atterberg results are produced from three soil samples since a material shortage prevented further work. The determination (A_S) is defined in Section 3.3.3.1 as the plastic index per percentage clay. Once again these values were determined in accordance with BS1377:1990, with the liquid limit testing being carried out utilising the cone penetrometer method as opposed to the Casagrande cup test.

Soil series	Liquid limit %	Plastic limit %	Plastic index %	Activity (A_S)
Crediton	36.6± 0.61	22.2± 1.47	17.62 ± 6.17	8.39
Dunsford	42.8 ± 6.46 Cuttings 36.9 Footings 53.2	26.3 ± 2.18 Cuttings 24.6 Footings 29.8	16.5 ± 4.3 12.3 23.4	Cuttings 2.40 Footings 0.82
Tedburn	48.1 ± 4.48	27.2 ± 0.88	20.9 ± 3.92	0.79
Halstow	69.6 ± 5.49	34.1 ± 1.58	35.55 ± 4.12	0.72
Bridgnorth	21.1 ± 1.65	3.48 ± 7.78	17.62 ± 6.17	6.96

Table 3.6 The Atterberg limits of the selected soil series and associated parameters.

3.5.3 The mineralogy of the selected soils

Utilising x-ray diffraction (XRD) techniques the breakdown of the mineralogy contained within that fraction of the soil sample defined as clay (less than 2microns) was analysed. The findings of this analysis are presented in Table 3.7.

Table 3.7 has also identified those minerals which may be classified as clays (in accordance with Brown, 1961), and the total percentage of clay minerals within each sample. For geotechnical purposes, it is considered reasonable to assume that all particles less than two microns are indeed clays, since their dimensions are akin to those of the clay minerals, although the actual nature of the minerals may not be that of a clay at all. Inspection of Table 3.7 highlights the presence of four clay minerals, namely kaolinite, chlorite, and geothite within the collected soil series'.

Kaolinite has already been highlighted in Table 3.3 as one of the group of 1:1 lattice layer minerals; a mineral with repeating layers of silica and alumina sheets. Each layer is held together by hydrogen bonding with the hydroxyl ions from the alumina sheets facing and bonding with the oxygen ions from the silica sheet. The strength of this bond is strong enough to prevent hydration between each layers thus kaolinite is defined as a non-expansive clay mineral (Yong & Warkentin, 1975). The strength of the hydrogen bonds also promotes the accumulation of many kaolinitic structures thus a clay particle may be formed from as many as 70-100 layers (Yong & Warkentin, 1975; Selby, 1993).

Chlorite is also included in Table 3.3 as an example of a 2:1:1 layer lattice mineral. This specific mineral is composed of a silica sheet, an alumina sheet, and either a second silica sheet or an alumina/brucite sheet. The identification of chlorite utilising X-ray diffraction techniques can be compromised by the presence of kaolinite since the reflection of X-rays can produce a similar pattern (Yong & Warkentin, 1975), hence the labelling "kaolinite + chlorite", for the Halstow series in Table 3.7.

The other clay minerals identified in Table 3.7, namely haematite and geothite, are not of the layer lattice type but lie within the group of clays known as the clay oxides. Haematite is an anhydrous iron oxide with a closely packed hexagonal oxygen/anion framework. Geothite is again of closely packed hexagonal oxygen/anion framework and is considered to be one of the most commonly occurring clay oxides (Selby, 1993). These iron oxides are known to be of low cation exchange capacity (Brady & Weil, 2000).

Muscovite is a mineral belonging to the three-layer-lattice mica group (Whitten, 1972). Although not regarded as one of the mica-type *clay* minerals, generically referred to as illites (see Bradley & Grim, 1961), they still contribute to the CEC of a given soil (Mitchel, 1976).

Soil Series	Mineral Content	% minerals capable of CEC reactions
Crediton	20% kaolinite 30% poorly crystalline muscovite 19% quartz 5% non-expandable mixed layer mineral 8% plagioclase feldspar 8% haematite	58%
Dunsford (cuttings)	30% poorly crystalline muscovite 24% quartz 10% feldspar, albite 20% chlorite (approx.) 5% poorly crystalline geothite	55%
Dunsford (footings)	30% poorly crystalline muscovite 29% quartz 10% feldspar, albite 1% anatase 20% chlorite (approx.) 5% poorly crystalline geothite	55%
Tedburn	10% kaolinite 45% poorly crystalline muscovite 26% quartz 1% anatase 6% poorly crystalline geothite	61%
Halstow	15% kaolinite + chlorite 28% poorly crystalline muscovite 9% feldspar, albite 27% quartz 1% anatase 8% poorly crystalline geothite	51%
Bridgnorth	25% poorly crystalline muscovite 45% orthoclase 6% haematite Remaining crystalline phase is quartz unable to be accurately measured due to presence of large amounts of feldspar.	31%

Table 3.7. Mineralogy of selected soil series.

3.6 The efficacy in utilising the soil survey in the selection of earthen building materials

Section 3.5 presents the laboratory data collection for the sampled soil series. This section considers how this data may be compared with the analytical data presented by the "Soil Survey" in Table 3.2 in order to assess its utility for soil selection in earthen building construction.

3.6.1. The extrapolation of the particle analysis data from the "Memoirs of the Soil Survey" to the selection sites of comparative soil series.

Comparing Tables 3.2 and 3.5 the first point of note is the difference in the prescribed fraction size limits for the sand and silt fractions. For Table 3.5 the silt fraction is expanded (at its maximum particle classification) to include particles of a further 0.01mm in diameter over that of Table 3.2; the sand fraction range is consequently reduced by 0.01mm (at its minimum particle size classification). Thus theoretically if Tables 3.2 and 3.5 are comparable, Table 3.5 would suggest slightly higher silt content over the values presented in Table 3.2 while sand content values may be slightly reduced. The classification of clay size particles is the same for each table. Gravel percentages are not given in Table 3.2.

Considering each series in turn, general comparative observations were made between these two tables considering only the data held on Horizons B and C of Table 3.2. It was also noted that the collected soil may indeed comprise of neither Horizon B or C alone but a combination of both (see Section 3.4.).

The Bridgnorth Soil Series is generally shown to indicate higher values of sand, silt and clay in Table 3.2 over that of Table 3.5. Of the Dunsford soils classified, the "footings" sample appears to offer better agreement on comparison than that provided by the "cuttings" sample, although Table 3.2 does suggest notably higher silt contents than either samples. For Tedburn soils, values of sand, silt and clay indicated in Table 3.2 lie approximately 1.5 times over those of Table 3.5. The particle size classification of the

Halstow soil series illustrates good agreement between each table while Crediton agrees well in terms of sand content, but little agreement is suggested between the Tables 3.2 and 3.5 on consideration of the silt and clay fractions.

3.5.2. Interpretation of the Cation Exchange Capacity readings from the "Memoirs of the Soil Survey" versus the Atterberg limit values of the selected soil series'.

Section 3.3.3.1 has outlined the links that can be made between the mechanisms that control the Atterberg limit values and the interpretation of CEC data. This section concluded by discussing the correlation between "activity" and CEC, adding that the higher the value of the CEC of a soil, the higher the Atterberg limit values are expected to be.

A rigorous investigation of these ideas is rendered virtually impossible by the lack of information provided by the "Memoirs of the Soil Survey of the Exeter District", as inspection of Table 3.2 will show that only two soil series, namely Bridgnorth and Crediton, have any CEC values presented. The Crediton soil series is shown to conform to the later conclusion summarised above, in that it exhibits higher values of liquid and plastic limit over those determined for the Bridgnorth Soil Series (see Table 3.6) which are supported by higher CEC (see Table 3.2). . The 'activity' values also reflect this trend with greater activity associated with the Crediton Soil Series and a lower value being attributed to the Bridgnorth Soil Series. Higher activity, Atterberg limit values and CEC values may be apparent for the Crediton Soil Series over those of the Bridgnorth Soil Series due to the increased percentage of clay minerals within the soil samples (see Table 3.7). While a potential relationship between "activity" and CEC values may be suggested here, no indicative relationship is apparent from a table of clay mineral properties presented by Selby (1993), which is reproduced in an adaptive form as Table 3.8.

Clay-mineral species	Activity A_s	CEC (me per 100g clay)
Montmorillonite	Ca: 1.5 Na: 6-13	80-150
Allophane	>3	25-70
Illite	0.5-0.9	10-40
Halloysite (hydrated)	0.1-0.4	40-50
Halloysite (dehydrated)	0.5	5-20
Chlorite	0.3-0.5	10-40
Kaolinite	0.3-0.5	3-15

Table 3.8 Properties of clay minerals (adapted from Selby, 1993)

A final measure of the "activity" of each soil series was obtained utilising an alternative method, *the methylene blue test.* This test is already familiar to soil scientists (Scott et al., 1996) and ceramists alike (Bolger et al., 1993), and has established itself for many years as part of the standard geotechnical testing procedures employed in France (Laboratoires des Ponts et Chaussees, 1990). But it remains little recognised, and is certainly not utilised within the British geotechnical industry. The exact procedure for performing this test is presented in Appendix 3 but a brief description of the test is outlined below.

The test is performed on a dry sub-sample of a soil undergoing particle size classification, wherein the particle diameter does not exceed sixty-three microns. The sample is put into suspension and subjected to the action of continuous agitation via the action of stirring and a specified amount of methylene blue dye solution is added at regular stages to the suspension. Between each addition of dye, the suspension is monitored by withdrawing a small amount of suspension and depositing it onto a piece of filter paper. Monitoring ceases when the dye is shown to saturate the interlayers of the clay-particle, appearing within the free-water of the clay-water suspension. The point at which saturation is reached determines the end of the test and the volume of dye added to the suspension determines the methylene blue value for the fine fraction (V_{B63}) which is then converted to a value for the soil sample as a whole ($V_{MB\ TOTAL}$). Table 3.9 illustrates the methylene blue values for each soil series converting them to an alternative measure of " activity"(A_{CB}) using the expression:

$$A_{CB} = V_{MB\ TOTAL} / \%\ \text{clay fraction.}$$

This expression of activity measures the quantity of blue dye fixed by 100g of clay minerals.

Methylene blue dye consists of an organic cation and an anion. When added to the clay suspension the cation within the dye is irreversibly exchanged with the interlayer cations within the natural clay. Thus Wang et al. (1996) proposed the use of methylene blue as an alternative measure of CEC. The reaction described here is effectively one of chemical adsorption. Physical dye to clay adsorption by weak van der Waals forces also occurs.

Lautrin (1989) explains that while this test could not be considered as an 'exact' measure of CEC its benefits to the practising geotechnical engineer lie in its ability to rapidly assess the quality of the clay fraction. Dinger (private communication, 1996) believes the test is capable of indicating more than this, and suggested it is a measure of the available *plastic* surface area of the clays and thus corresponds to the plastic performance of the minerals. The flat, hexagonal arrangement of the clay mineral surface is like that of the ice structure of a water molecule. The methylene blue dye is also attracted to this hexagonal flat arrangement and lies down as a mono- layer on these surfaces when carried by water in suspension.

Soil Series	A_S	V_{B63}	$V_{MBTOTAL}$	A_{CB}
Crediton	8.39	3.03	0.94	13.3
Dunsford				
Cuttings	2.4	1.43	0.54	10.53
Footings	0.82	1.98	1.54	5.46
Tedburn	0.79	2.18	1.31	4.23
Halstow	4.35	3.28	3.03	4.36
Bridgnorth	6.96	2.04	0.47	10.66

Table 3.9. The Methylene Blue Values of the Selected Soil Series.

The inclusion of the methylene blue values for the selected soil series is justified by its extensive use within the geotechnical industry in France, and its potential to simplify the identification of soils used in earthen construction (CNRS, 1995).

3.5.3 Conclusion

The "Memoirs of the Soil Survey of Great Britain – Exeter District", has been used to inform soil selection for this investigation into the soils of Devon for earthen building. In attempting to consider its efficacy it would be uncharitable not to acknowledge that the particular memoir under consultation is over thirty years old, written at a time when the utility of "Soil Surveys" were generally intended to assess land suitability for agricultural usage.

However as early as 1987, Lee and Griffiths were highlighting the possibilities of utilising pedological soil surveys to evaluate land use for planning and development. Dada (1988) investigated the limitations that the soil surveys held to their application in the geotechnical technicalities of engineering projects, but it is considered that many of the recommendations being made to improve the engineer's access to the soils maps were once again overtly targeted towards one group of specialists. In order to address the range of groups who might benefit from obtaining access to these surveys, Indorante et al. (1996)

identified that considerable changes would be required since the soil survey has seen little alteration in either concept or format for many decades.

Expanding the user groups of soil surveys may also encourage their use in less affluent countries reluctant to invest in the establishment of these surveys due to the difficulty in assessing the 'value' of their establishment (Giasson et al., 2000). Thus extrapolation of the idea of utilising soil survey for the selection of earthen building material is obviously limited to those countries where surveys already exist. Furthermore it should be recognised that different survey methods are employed internationally, and thus the utility of each survey can only be assessed independently.

In consideration of "The Memoirs of the Soil Survey of Great Britain for the Exeter District" (1971), it is not surprising that the impact of its contents was ultimately restricted to the desk-study selection of the sampling sites (see Sections 3.3.2.2 and 3.3.2.3), considering that Dada's (1988) call for change to the soil survey occurred approximately a decade after the publication of the aforementioned memoirs. The extrapolation of analytical data provided by the survey proved less useful in determining the suitability of sites due to its incompleteness and lack of fit with that determined in the laboratory. However it is envisaged that in light of the nature of the calls for revision an up-dated survey may in time prove highly effective in facilitating the procurement of suitable earthen building material. In the meantime the pedalogical survey remains a valid resource for the planning of earthen construction.

Chapter 4. The Development of a Test Methodology for Cob

4.1 Introduction

This Chapter considers the development of the test program for cob construction. It outlines the test programme, the rationale and supplementary studies which informed the test programme and justifies and explains the procedures adopted.

The main focus of the work that follows concentrates on the determination of the unconfined, compressive strength parameters of 'cob' mix. The adoption of the unconfined, compression test is justified in that it most appropriately represents the loading environment utilised in cob construction, subject to the definition of this earthen building technique given in Chapter 2.

The establishment of this engineering parameter, and the appropriate methodology adopted in its determination, is significant both to those who are often forced by building authorities to justify the strength carrying capacities of cob as a building material, and to those seeking to adopt alternative building technologies. It was therefore considered important to address both of these perspectives through the test program.

Finally, the test program also encompassed an investigation into the pore size distribution within cob samples, utilising a technique borrowed from the science associated with land management and agriculture: the pressure membrane test. The results from this test have been used to facilitate interpretation of the unconfined compressive strength values associated with the matrices pertinent to this study.

It will be seen from the test program that the matrix consideration in all investigations has extended beyond the soil/straw composite to establish the behaviour of the soil independently. Since soil is the most significant component of the cob matrix, knowledge of the independent component behaviour of the soil will aid interpretation of the composite material behaviour. All test results are presented in Chapter Five.

4.2 The resolution of issues related to the determination of the unconfined compressive strength

4.2.1 Establishment of sample shape and size

The rationale for basing the focus of this investigation on unconfined, compressive testing is given above. Considering the relevant literature that would inform the unconfined test methodology adopted, the main constituent of cob (soil) and the manner in which it was utilised, drew strong comparisons to work in both the fields of geotechnics and concrete technology thus a methodology developed, informed by each of these areas.

Traditional concrete compression testing practice is based on either the adoption of the concrete cube or the cylinder (Neville, 1983). While some earthen building specialists have quoted cube strengths for soils (Norton,1986), cylindrical samples were preferred over cubes due to their facility to offer planes that remain unrestrained by frictional forces between the material and the confining plates through which the compressive forces will act. This facility is ensured providing that the cylindrical height to cylindrical diameter ratio is maintained at a ratio of 2:1 (Neville, 1983). Frictional forces have been shown to artificially enhance the compressive strength values of concrete mixes and should be avoided if a true reflection of the compressive strength of the composite is to be ascertained.

Establishing a true compressive strength value is however further complicated by the effects of cylinder size. In his work on concrete, Neville (1983) has attempted to explain the significance of scaling effects on the values obtained in the compressive testing of concrete cylinders. Figure 4.1 illustrates these effects showing that a concrete cylinder of 150mm diameter will render a compressive strength value approximately 3% below that of a concrete cylinder (of similar mix) with a diameter of 100mm.

Preliminary testing on air-dried soil cylinders of 150mm diameter versus 100mm diameter (manufactured from two of the selected soils specified in Chapter 3) supports Neville's opinion that the general trend illustrated by the concrete cylinders will hold for all materials. However, the variation in relative strength is substantially lower for the concrete cylinders in Figure 4.1 than the soil samples tested. These results are presented as in Appendix 4.

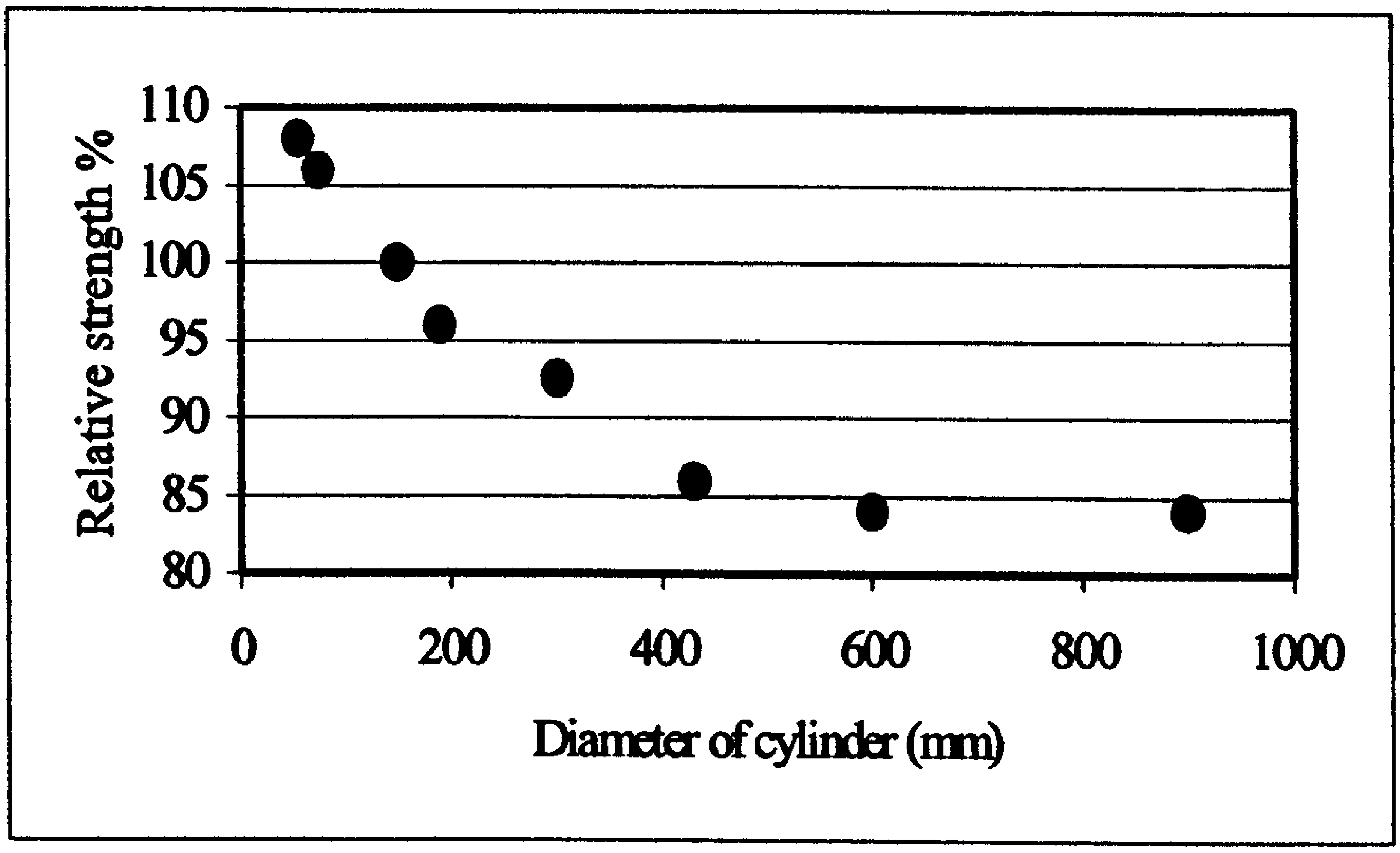


Figure 4.1 Compressive Strength Capacity of Various Sizes of 2:1 Concrete Cylinders Adapted form Neville (1983)

Krajcinovic (1989) discusses this trend further accounting for this phenomena via the effects of the increased proportionality of material cracks and fissures with increasing material volume. However unlike concrete, the soil and cob cylinders under test have no cementitious agents. The soil and cob cylinders are therefore far more heterogeneous in nature with more cracks and fissures available to negatively contribute to the cylinders' strength carrying capacity. Hence the larger variation in relative strength between cylinder sizes obtained from the preliminary testing of the selected soils than that suggested in Figure 4.1.

However from Figure 4.1, the ultimate result of increasing the surface area for the distribution of greater loads is shown to be counterbalanced by this negative strength contribution from increased fracture planes and micro-cracks with increasing material volume, resulting in no increase in the compressive strength carrying capacity of the samples being indicated. For the concrete cylinders in Figure 4.1, this point occurs at a cylindrical diameter of 600mm.

Establishing the plateau in the relationship between compressive strength carrying capacity and sample size diameter may appear to be the most appropriate means of determining sample size. Utilising the cylinder size at which this plateaux first occurs may be said to offer a true indication of the unconfined compressive strength characteristics of the soil/ cob cylinders. However if we consider the five soils sampled as defined and classified in Chapter 3, as akin to five individual concrete mixes, then it is likely that the strength capacity will plateau at five separate points for each mix. Thus it would be inappropriate to base the selection of cylinder size on this point given the need to minimise the effects of all controllable variables to aid result interpretation. Furthermore should the relationship between soil cylinder size and compressive strength capacity plateau at the same order of magnitude as that of the concrete cylinders, logistical constraints such as material storage, limitations of testing equipment, and physical limitations with respect to handling of cylinders by the operative would all become issues.

In light of these constraints and the variability in soil sample classification the selection of cylindrical sample size was determined on the basis of practicality and variable elimination. By adopting 150mm diameter, 300mm high cylindrical test samples, practical issues were considered concerning the accommodation of the majority of grain sizes within the cylinders (i.e. those particles <20mm) as determined from the soil distribution curves (Appendix 1). This ensured the representation of the selected soils within the cylinder, the compatibility of the test samples with standard testing equipment and minimisation of material storage facilities. Standardisation of sample size would also aid comparison between soils sampled and facilitate result interpretation as a function of soil matrix as opposed to complicating result interpretation by forcing the need for a sample size adjustment factor.

Development of the test program outlined in Section 4.3 also highlighted the benefits that could be gained from further standardisation in terms of result interpretation. It became apparent that in order to ascertain the benefits that would be obtained from using a given soil in 'cob construction' as opposed to the soil alone, considerable benefits could be gained by utilising the same soil sample for each test. This does not merely imply that soil sampled from the same site was adopted but that the soil used to form the cylinder for each test remained the same thus the soil matrix between each test did not differ. This would ensure that the constituents of the particle matrix remained constant between tests although particle arrangement could not be maintained.

However to achieve continuity of constituents of the particle matrix between the soil and 'cob' cylinder compression tests, re-hydration of oven-dried soil from the soil cylinder compression tests would be required to form the 'cob' for the cob cylinder compression tests.

4.2.2. The rehydration of soils

To investigate and analyse the results for a soil and cob cylinder, formed from the same particle matrix, it was necessary to oven dry the soils cylinders post-test, in order to ascertain their moisture content at the time of manufacture and test (the importance of which is explained in Chapter 5). Consequently although a soil and cob cylinder may contain the same particle matrix, the soil itself has been subjected to oven drying to 101°C (as required in the determination of moisture content to BS1377) between the production of these cylinders. Thus the cob cylinder must be produced from the re-hydrated soil used in the production of the initial soil cylinder.

Brown (1964), Farmer (1978) and Olivier (1989) support the argument against re-hydration of soils. Brown has suggested that the process of drying is significantly disruptive to the clay minerals within the soil mass, to result in permanent deformation. As already discussed in Chapter 3, the mineral composition of the soil has a significant role in defining the engineering behaviour of the soil and thus the disruption discussed by Brown may be enough to impact upon the compressive strength characteristics of a re-hydrated soil.

Brown's work may help to explain the findings of Olivier (1989) who claims that soils dried to water contents less than 3% to 4% will fail to achieve homogeneity when re-hydrated. Olivier's claim offers no indication whether or not this is due to a change in the chemistry of the mineral itself or in the distribution of the absorbed water within the clay mineral. The later case would be an example of structural alteration.

However, Joshi et al. (1994) have found that clay minerals do not undergo structural alteration prior to temperatures of 300 degrees centigrade, whereupon dehydroxylation occurred, i.e. the removal of OH^- ions in the form of water. Prior to this value being attained, only the mechanical free-water, contained within the pores and loosely bound to the clay particles through the double layer, is removed. Samples subject to this process alone were shown to re-hydrate when soaked in water.

Clearly conflict remains over the question of mineral alteration during oven-drying. Given the links between the mineralogy of soils and their influence on the Atterberg limits as discussed in Chapter 3, it seems reasonable to presume that these limit values may be capable of reflecting any significant change occurring to the structure of the soil minerals. If the oven drying and re-hydration of soils results in mineral alteration then it may be assumed that these alterations would also be reflected in the Atterberg limit values.

4.2.2.1 The effects of re-hydrating clays in the determination of Atterberg limits

Work carried out by Youssef (1961) and Laguros (1969) has shown that on conducting limit tests within an enclosed chamber to maintain the temperature to which the soil has been heated, a general decrease in the values of liquid limit with increasing temperature occurs. These workers explain this response in terms of the decrease in the viscosity of the water held within the double layer, at increasing temperatures. Implicit in this explanation is the idea that heat treatment within this temperature range is soley influential upon the properties of the free-water and not the clay minerals themselves.

Thus it may be assumed that once cooled, the liquid limit values may be shown to increase as the properties of the free-water reach equilibrium under the conditions of room temperature, and the more viscous nature of the diffuse double layer is re-established.

In order to resolve the issues concerning the appropriateness of oven drying/ re-hydration, for the purpose of this study, a crude testing programme was devised to validate the theories expressed by Youssef (1961) and Laguros (1969). Two of the five soils sampled (described in Chapter 3), were selected for the purpose of this work. One soil (Dunsford) was a representative derivative of the geology of the Carboniferous period, the other (Crediton), a representative derivative of the geology that defined the Permo-Triassic period. From these two samples, four separate samples were obtained which were heated to 40, 80, 100 and 130 degrees respectively. These samples were then allowed to cool until they could be handled and the liquid and plastic limits of these samples were obtained. These values were then compared with the values obtained for one air-dried samples of the same material. The results from this test are shown in Table 4.1.

Soil Series	Temperature °C	Liquid Limit %	Plastic Limit %
Crediton	Air-dried	31.75	11.03
	40	32.82	12.1
	80	30.6	9.67
	100	31.72	13.53
	130	31.72	13.53
Dunsford	Air-dried	43.8	16.29
	40	43.9	16.02
	80	41.0	14.84
	100	42.0	15.79
	130	41.8	16.31

Table 4.1. Atterberg limit values for heated soils

To support the work of Youssef (1961) and Laguros (1969), the values obtained for liquid and plastic limits should not indicate large variation given that these values were obtained post heating, once the soil sample was cool enough to handle. Clearly the scope of this initial investigation is not conclusive to determine the significance of the variations shown between values. Furthermore on re-appraisal of the methods used to obtain these values, no efforts were made to establish the actual temperature of the soil at the time of test. However if the theories postulated by Youssef (1961) and Laguros (1969) are correct, it is most likely that soils heated to higher temperatures would exhibit higher liquid limit values due to the decreased viscosity of the water held within the double layer. This is not illustrated by the data shown in Table 4.1.

Due to the inconclusive nature of this work, a further, more rigorous investigation was instigated, to directly determine whether the re-use of the soils presented in this work (described in Chapter 3) for the determination of associated compressive strength values, was indeed appropriate.

4.2.2.2. The effects of oven drying and re-hydration of soils on the compressive strength values of soil cylinders.

Eight 100mm diameter cylindrical samples of a given soil type were tested twice for compressive strength using the methods described in Section 4.4. After the first series of compressive strength values were obtained (Set 1), the samples were allowed to dry to 110 degrees centigrade and their manufacture and test moisture contents were determined. Each cylinder was then individually re-hydrated over a 72 hour period at the approximate manufacture moisture content used to produce the Set 1 cylindrical data, thus ensuring sample variation was minimised.

Set 2 cylindrical samples were then manufactured, adopting the same techniques as those employed in the manufacture of the samples used to produce the Test series 1 data. Upon drying in a humidity oven for the same period adopted for Set 1, the samples were compression tested and their manufacture and test moisture content obtained. Table 4.2 illustrates these values for each set.

Cylinder No.	Manufacture mc Set 1	Manufacture mc Set 2	Density Set 1	Density Set 2	Peak UCC Set1	Peak UCC Set 2
	%	%	*kg/m³*	*kg/m³*	*kN/m²*	*kN/m²*
1	26.2	28.19	1877	1856	567	506
2	25.2	27.97	1901	1875	524	571
3	25.9	28.44	1869	1878	537	475
4	24.8	27.56	1913	1860	583	568
5	25.7	28.64	1908	1818	539	539
6	25.0	27.58	1900	1874	600	387
7	25.6	28.39	1887	1842	572	564
8	25.3	28.18	1901	1854	588	539

Table 4.2. One-to-one comparison of soil cylinder compression values after oven-drying and re-hydration

The data sets were analysed using two independent, two sample *t*-tests with the null hypothesis that oven-drying to 110 degrees centigrade is not influential to the compressive strength capacity of the soil. This analysis produced the following results [t value = 1.613 , probability p = 0.131 , degree of freedom (df) = 14]. Given that the probability level exceeds 0.05 the null hypothesis is shown to hold and oven drying followed by soil re-hydration is not shown to significantly affect the performance of the soil in terms of its compressive strength characteristics. However it is noted that these results suggest the trend for compressive strength to decline if the soil tested has been re-tested after oven drying and re-hydration.

Given these results it was concluded that soils which had been oven-dried and re-hydrated, would be re-cycled for further compression testing. However their life would not extent beyond two test-cycles (thus one re-hydration cycle) and therefore successive testing, drying and re-hydration would not be necessary for the purpose of this investigation.

4.2.3. Sample density and compaction

In order to produce the cylindrical samples used throughout the compressive test programme, it would be necessary to ascertain the appropriate level of compaction to be adopted as part of the standardised manufacturing process. Consequently in order to do this, it was necessary to decide upon the desired resultant density which was required for the end-product.

The initial starting-point for determination of the end-product density specification was obtained from published data on typical density values for historic 'cob' buildings. Published values would suggest that these densities lie in the approximate region of 1200kg/m^3 to 1900kg/m^3, (Ley, 1995; Goodhew et al., 2000). It is difficult to qualify these density values which are likely to represent *'as sampled'* bulk density values. This term reflects the lack of knowledge of the saturation condition in the soil on sampling, which is suggested by the omission of any reporting of moisture content values. The determination of traditional cob densities from traditional cob buildings is also hindered by the destructive nature of sampling techniques and the difficulty of obtaining a regularly shaped sample from which volume might easily and accurately be calculated (Greer, 1996). Irrespective of these difficulties, the determination of traditional cob densities is further hampered by the variation in moisture contents found within a cob building (Trotman, 1993). Consequently the density range suggested above may reflect materials of wide ranging moisture contents and can only be regarded as approximate. Keefe (1998) has determined dry density values for cob used in traditional buildings, illustrating ranges between 1480kg/m^3 and 2090kg/m^3 determined for *re-constituted block*, however the methodology used to determine these values is undefined.

The methods employed in the production of cob buildings (see Chapter 1) were little concerned with method-specification, and it is conceivable that the deployment of modern day techniques concerning the placing of soils may well produce material with much greater density values. However, while the emphasise of this work is to look at the development of 'cob' as a future sustainable building material, the decision to establish a test methodology based on an ability to reproduce typical historic 'cob' density values, is deemed a consistent approach to sustainability. By establishing and assigning quantifiable engineering parameters to materials utilised in existing/historic cob construction, more knowledge of the structural performance of the material must aid and facilitate appropriate maintenance techniques to extend the life of these buildings, while providing technical guidance for the development of new structures utilising modern construction practices.

Section 4.2.3.1 outlines the method employed throughout this investigation to achieve the required compaction of the cob cylinders. Determination of the compactive effort was informed by two areas: (i) the required density of the end-product (ii) the moisture condition of the soil/cob matrix at manufacture. The issues concerning end-product density have already been discussed in Section 4.2.3. The issues concerning the manufacture moisture content of the soil/cob cylinders are relevant to the suitability of the manufactured cylinder for test.

If the soil/cob matrix proved to be 'too wet' on manufacture the samples produced would slump on extrusion from the moulds resulting in cylinders which would be unable to accommodate true axial loading due to an inherent off-set in the cylinder's vertical axis being introduced. Such an off-set would result in the application of an eccentric load which would induce bending stresses within the sample. Furthermore 'wet' matrices have a tendency to segregate on mixing leaving clay slurries in the base of the mixing bucket and bleeding the original mix of fines. The adoption of such a mix would there fore be unrepresentative of the bulk of the material classified.

On establishing the density required for the end-product and a hands-on understanding of the moisture contents suited to facilitate cylinder production, the method which would ultimately be employed as the standard method specification was developed by the trial and error modification of the Proctor test (Croney, 1998). This test was devised to allow the placement of fill materials in earthworks to be specified.

4.2.3.1 The modified 'light' Proctor test

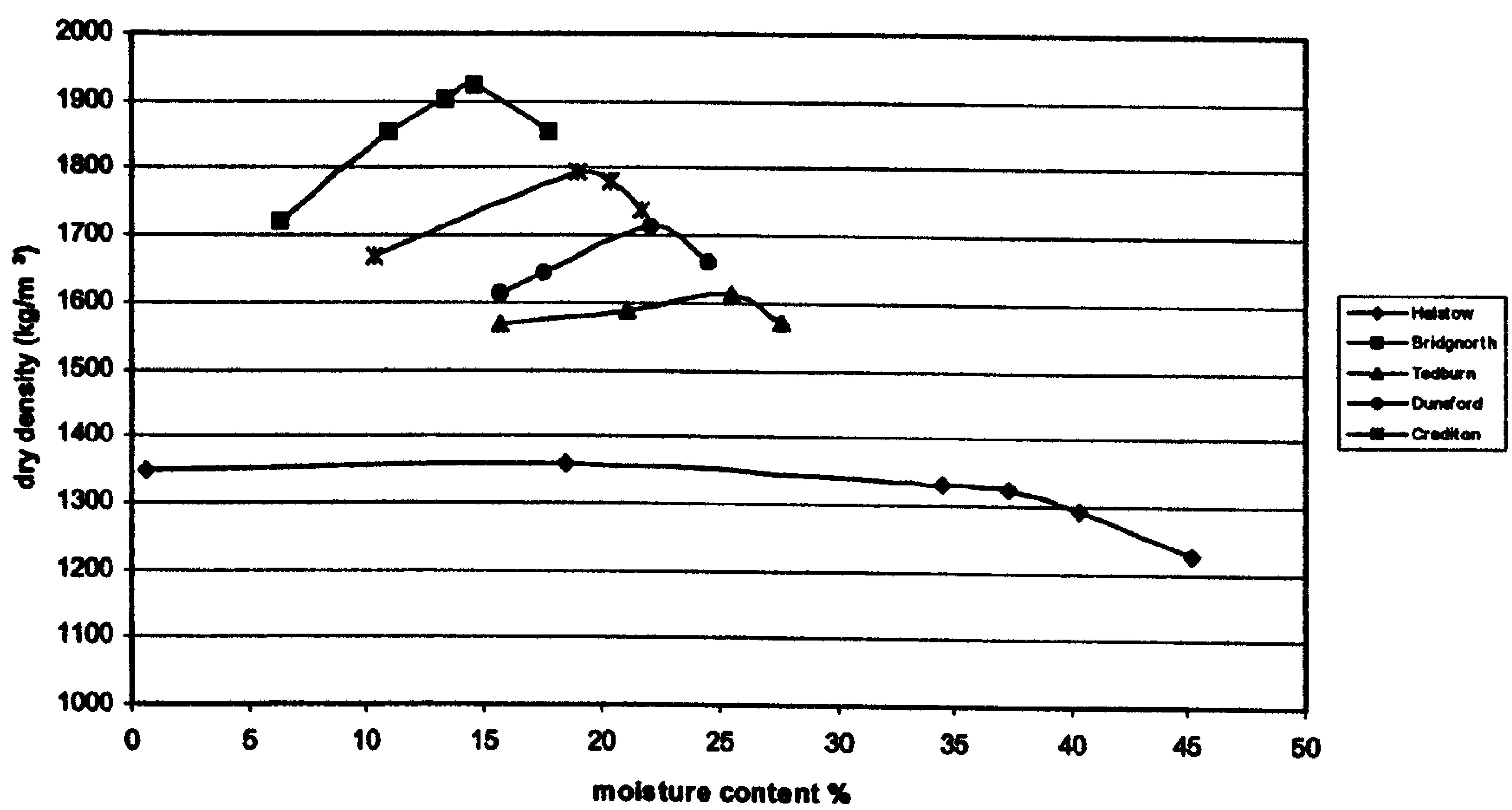
Croney (1998) offers a succinct description of the original Proctor test (or BS1377, Test 12) which involves the laboratory compaction of soil in a 101.6mm diameter and 116mm high, cylindrical mould via a manual or automated technique. The soil compaction occurs in three equal layers by a 2.5kg rammer that is allowed to fall a distance of 305mm before it hits the soil. This ramming action occurs 25 times per soil layer. Since the diameter of the rammer is 51mm, care should be taken to ensure that the ramming-blows are evenly distributed over the area of the mould into which the soil is being compacted. On compaction of the last layer of soil, the excess soil is removed flush with the top of the mould and the weight of the soil obtained together with the measured moisture content, to facilitate the calculation of dry density. Repetition of this test over a range of moisture contents illustrates the dry density, moisture content relationship of a given soil.

While the 'Proctor' test attempts to determine the achievable field densities of compacted earthen fills the purpose of the *'modified Proctor test'* developed here, is to ascertain the specification of compactive effort required to produce cob cylinders of an approximate density associated with the material used in historic 'cob' buildings. In attempting to achieve this, initial trials were carried out using the automatic compaction method of the Proctor test, as described above, with a modification made to the number of blows used to compact the soil in the mould. This modification resulted in the recommendation of a 'modified Proctor test' using a 7 blow compactive effort. It is also suggested that the extension of this method of compaction to the placing of 'cob', is a further modification from the original test that was purely concerned with the compaction of soil. The results from this modified test produced dry density, moisture content curves shown in Figure 4.2.

These curves represent the dry density, moisture content relationship for each of the five selected soil types with each point on the curve representing the mean value obtained from five compaction tests. The data used to produce these graphs together with the associated variability may be found in Appendix 5.

The graph in Figure 4.2 illustrates the validity of extending the Proctor test to provide a specification for the production of laboratory 'cob' cylinders. Using the 7-blow modification, the maximum dry densities obtained lie in the region of 1348kg/m^3 to 1925kg/m^3 reflecting bulk densities of 1851 kg/m^3 to 2206kg/m^3 respectively and are thus representative of typical values obtained for historic cob buildings. The extension of the Proctor compaction method, from soil to cob, is shown to be appropriate given that the addition of the straw fibre does not appear to adversely influence the method's efficacy to compact the 'cob' mix. This is illustrated by the small percentages of the standard deviations from the density means, Appendix 5.

Figure 4.2 Compaction curves for 5 Devon cobs utilising the modified light Proctor test



The extension of this method to on-site cob production is discussed in Section 4.2.3.2.

4.2.3.2 'Laboratory test cob' versus 'field cob'.

The method proposed for the compaction of the laboratory cob samples utilises a mould or 'former' in which the samples will be compacted. The sample is thus formed via a dual state of stress, the compacting action of the rammer and the lateral forces that are induced as the material is forced against the sides of the mould during compaction. This results in higher compaction values being realised at lower moisture contents than those experienced during the site manufacture of cob. As field cob is traditionally utilised in monolithic wall construction with no formwork and thus the material is only stressed by the action of the vertical ramming forces during placement (see Section 1.2.5), higher moisture contents are required to facilitate workability.

4.2.4 Strain Rate

For undrained compression tests Lambe and Whitman (1979) recommend a rate of strain that facilitates the time required to observe and record the relevant data. Barnes (2000) suggests that a rate of strain equating to 2 per cent of the length of the sample tested, is commonly adopted. This would equate to 4mm per minute in the case of the sample sizes utilised in this investigation.

The adopted rate of loading applied to the proving ring was 0.1mm per minute. This rate was quick enough to ensure undrained conditions while remaining slow enough to permit accurate recording throughout the test period.

4.2.5 Straw and the 'Cob' matrix.

From the discussion of cob construction presented in Chapter One, it can be seen that the literature is inconclusive on two issues when considering the addition of straw to produce the cob matrix; (i) the type of straw used (barley or wheat) and (ii) whether or not the straw was chopped prior to inclusion within the mix. This work does not set out to resolve these issues beyond the literature search as it is highly probable that such issues of detail in the practice of cob building varied between Devon villages, or the preference of cob masons. However, the significance of these issues to the inherent strength of cob should not be overlooked.

4.2.5.1 Barley versus Wheat Straw

Straw is essentially composed of cellulose (a crystalline linear glucose polymer) fibres. These discrete fibres are naturally embedded and bonded together by a continuous organic matrix known as lignin. Lignin, an amorphous polymer of aromatic benzene rings, cements these fibres together, Swamy (1988). The difference between barley and wheat straws will be defined by the difference in the percentage composition of these two chemical components.

Wheat straw with its higher percentage of cellulose possesses more structural rigidity. This enhanced rigidity can make it less malleable when worked into a cob matrix, possessing a tendency to spring-out randomly from a laboratory test-sample. However its higher fibre content is also likely to characterise wheat straw with higher tensile strength than that of barley straw which may characterise wheat cob with similarly increased strength capacity over barley cob as the straw is better able to accommodate the lateral stresses set-up under unconfined compression testing.

The UCC strength of cob samples will be also be shown to be influenced by frictional values (see the discussion of the impact of straw on the unconfined compressive strength of a cob matrix, presented in Section 6.3.2). The compositional difference between the wheat and barley straw is likely to induce a variation in the surface texture of the straw which may influence the frictional interaction at the soil/ straw interface. In the absence of information concerning the surface texture of these two straws or any micro-fibre study, this discussion can only develop speculatively. It was therefore considered more informative to ascertain the potential difference in the use of these straws within a give particle medium, to form cob, through laboratory investigation . Appendix 6, presents the results from the comparative testing of seven Bridgnorth wheat cob and eight Bridgnorth barley cob cylinders produced in accordance with Section 4.4.1 and tested in accordance with Section 4.3.3.1. These results indicate higher strength may be realised with the adoption of barley cobs.

The findings of Appendix 6 are presented for completeness. However although the aim of this project is not concerned with the optimisation of the properties of Devon cob, the larger proportion of the available literature does advocate the traditional use of barley straw. Therefore this project focuses on the utilisation of barley straw inclusion within the cob matrix.

4.2.5.2 Chopped or unchopped straw.

Although the literature remains inconclusive about the practice of the straw chopping during cob construction a practical design was made to chop the straw lengths during the test-program in order to improve the dimensional reproducibility of the samples produced for testing. Chopping the straw length to match the diameter of the cylindrical mould, avoided the occurrence of long lengths of straw, compressed against the side of the mould potentially, poorly embedded within the soil rich matrix, from springing out during extraction from the mould. This not only increased the difficulty of achieving accurate dimensional records but could also compromise the integrity of some of the samples produced and the strength capacities obtained from such samples.

Clearly the length of a reinforcing element has an impact on the ability of that element to reinforce. For example in consideration of Figure 2.1, short straw fibres (2-3 cm) would have little influence over the prevention of crack propagation (mechanism 2) within a matrix since there would be little opportunity to mobilise the tension capacity of fibres poorly embedded within a cob matrix and thus smaller strength capacities would be exhibited. Furthermore short straw lengths provide less continuity of reinforcement within the sample as opposed to longer lengths which are afforded more opportunity to 'lap' to achieve continuity and transfer load. While the arrangement of straw is much more random than that of steel, this situation is to some extent analogous to reinforced concrete.

4.2.5.3 Straw Content within the 'Cob' matrix

The determination of how much straw should be added to the soil samples to form the cob matrix was informed by the availability of relevant literature. The Technical Panel of Devon Historic Building Trust (1992) recommends a straw content of 1.5 % to 2.5 % by weight. Goodhew (1993) deconstructed a single original cob sample to obtain a fibre content of 1.25% by weight of sample analysed. While this offers the best insight into the actual straw amounts originally adopted, consideration of the mixing methods employed in traditional cob construction does present the possibility of large variations in straw dispersal through the mix.

The potential for large variations of straw content within the cob matrix was highlighted by Greer (1996) through a compositional analysis of eight new cob bricks selected from a large quantity of similar bricks manufactured for use in a repair scheme to a traditional cob house. Skilled craftsmen, appointed to execute these repairs, adopted traditional building methods and techniques. The analysis of the cob bricks found that the straw content of the cob matrix, within these bricks, ranged from 1% to 2.5 % of the total weight.

Given the need for consistency with in the experimental program to facilitate comparative analysis and in consideration of the project philosophy to look towards the promotion of 'cob' construction as a future building material, consideration was given to the recommendations given by Saxton (1997). Saxton suggests that an optimal straw content for cob lies between 1.0% to 1.5%. Thus a decision was taken to adopt a mix incorporating 1% straw by weight to form the 'cob' matrix.

4.2.6.Drying conditions

The cylinders produced for testing were all dried within an environmental chamber where drying conditions could be regulated in terms of temperature and humidity. Hydrological temperature and humidity means were considered for the months of March to September when 'cob' buildings would traditionally be erected due to the more favourable drying conditions (see Chapter 1). However, these means were found to vary quite considerably between these months. Consequently, a decision was made to maintain the temperature at twenty one degrees centigrade (approximately ambient with the temperature of the laboratory to ensure that the opening and closing of the chamber would not result in significant disruption to the drying conditions within) and to subject the cylinders to a relative humidity of seventy five percent.

4.3 The Design of the Unconfined Compressive Strength Test Program

Recent work (Greer, 1996) concerning the compressive strength characteristics of 'cob' has focused on the discussion of the soil matrix, investigating the contribution of each of the soil fractions: gravel, sand and clay by manufacturing 'artificial' soil mixes. This work has obvious potential in the widespread development of earthen building technologies. However, it appears to remain heavily focused on the inter-particle relationships of soils alone with no presentation of work investigating or analysing the 'cob' matrix behaviour under unconfined compression. Thus this work cannot claim to be directly applicable to 'cob construction'.

Figure 4.3 outlines a test-program directly focused on determining the UCC values for cob manufactured using each of the five selected soils discussed in Chapter 3. A complementary supporting test-program carried out on the selected soils alone, aims to facilitate the interpretation of the UCC values established for the relevant cob matrices.

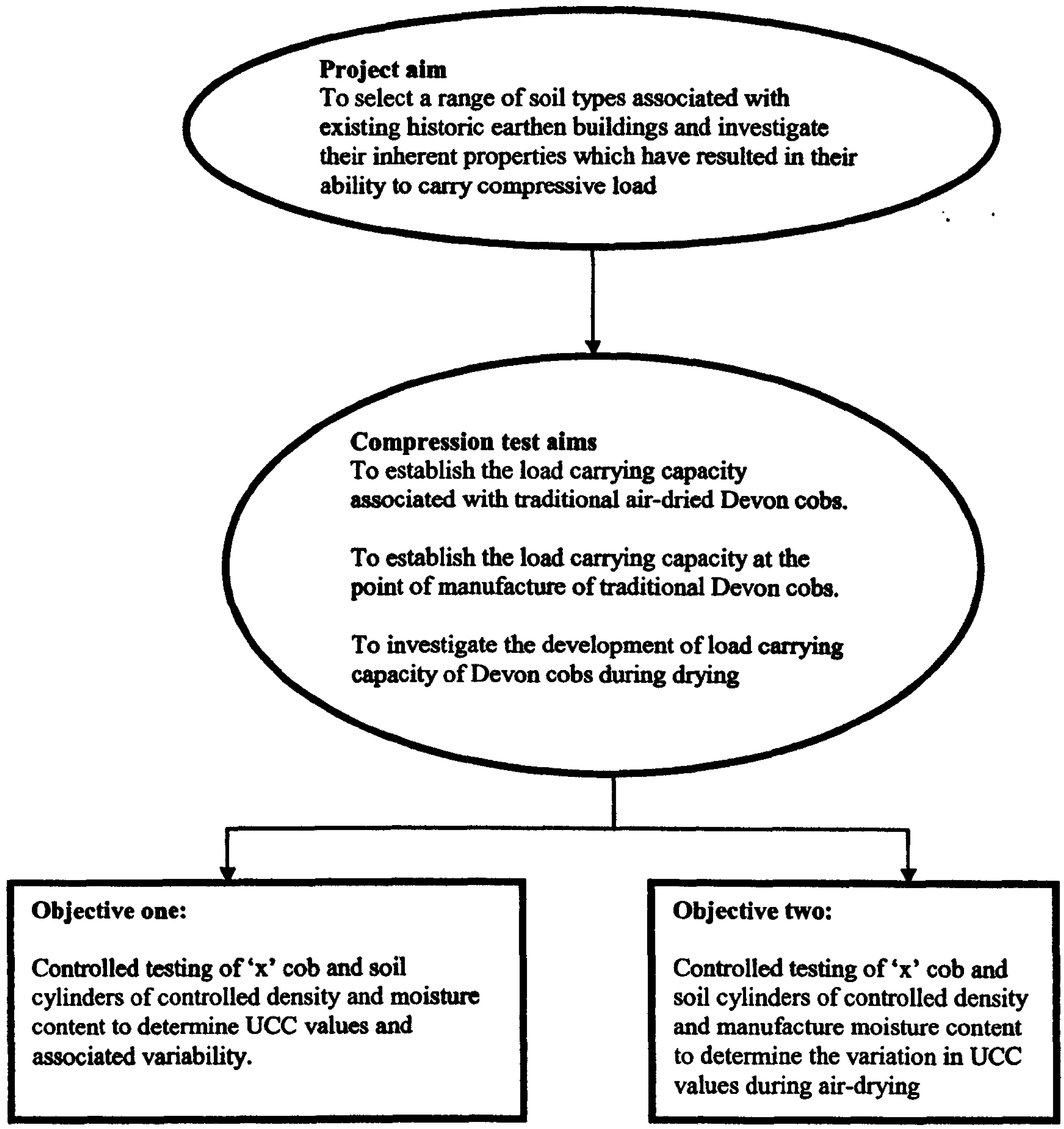


Figure 4.3 Test programme and objectives

4.3.1 Objective 1

Objective one seeks to fulfil the needs of practitioners and regulatory bodies within the construction industry forced to justify or seek justification of the strength carrying capacity of cob as a building material. The minimum values are representative of the compressive strength characteristics at the time of placing while the optimum values are determined after a period of air-drying. Tests were conducted on the soil and soil plus straw ('cob') cylinder to facilitate comparison and discussion on the behaviour and values associated with each.

4.3.2 Objective 2

Objective two seeks to facilitate strength prediction to guide construction practices ensuring appropriate 'curing periods' between walling lifts. The importance of moisture limits within the cob matrix to maintaining the structural integrity of the material has already been identified by Saxton (1995). However this work failed to identify the importance of variations in other parameters such as density and remains limited to one soil type, sampled from the Teignmouth breccias.

4.3.3 The Test Program

In order to fulfil the objectives targeted, a three series test program was devised. This program is explained in detail below and outlined in Figure 4.4.

4.3.3.1 Test Series One, Optimum compressive strength capacity:

Using the selected soil eight 'soil' cylinders were manufactured in accordance with Section 4.4; these cylinders were air-dried in a climatic chamber at a temperature of 21 degrees centigrade and a relative humidity of seventy five percent. The cylinders were considered to have reached equilibrium with the oven settings when no successive weight loss through moisture evaporation was indicated over the period of five days. After drying, the cylinders were unconfined compression tested (in accordance with Section 4.4). The cylinders were then oven-dried to 110 degrees centigrade for the purpose of ascertaining their moisture contents at relevant stages.

Once the manufacture moisture contents for the soil cylinders were ascertained, the soil cylinders were individually re-hydrated to this moisture content and mixed with 1% straw, by weight, to produce a cob matrix. This matrix was left to hydrate over the period of one week during which daily hand-mixing would occur to ensure an even distribution of moisture within the mix. Eight 'cob' cylinders were then manufactured in accordance with Section 4.3. These cylinders were then allowed to dry in the humidity chamber under the same conditions experienced by the soil cylinders. Once dried, the cylinders were unconfined compression tested (in accordance with Section 4.5.) and their dry weights obtained.

This process was then repeated for each of the five soils selected. The results for Series One tests are presented in Chapter 5.

4.3.3.2 Test Series Two, Minimum strength capacity:

In accordance with the testing and manufacturing procedures for the optimum unconfined compressive strength capacity, an eight number, soil cylinder group was manufactured in accordance with Section 4.4. The original conception of the test programme had envisaged that these cylinders would be manufactured at the manufacture moisture contents of Test Series One cylinders. To achieve this the soil, initially adopted for the manufacture of the soil cylinders, would have been hydrated from an oven-dried state to ensure the correct moisture content was achieved. A successive hydration would have been employed to manufacture the cob cylinders. Given the conclusions of Section 4.2.2.2 concerning the use of rehydrated soils, this was not considered to be advisable.

Once manufactured, the cylinders were then subjected to immediate unconfined compression testing, in order to ascertain their compressive strength carrying capacity at manufacture. The cylinders were then dried at 110 degrees in order to determine their dry weight and thus their manufacture moisture contents were determined.

After the manufacture moisture contents for the soil cylinders were ascertained, the soil cylinders were individually re-hydrated to this moisture content and mixed with 1% straw to produce a cob matrix. This matrix was left to hydrate over the period of one week during which daily hand-mixing would occur to ensure the an even distribution of moisture within the mix. Eight 'cob' cylinders were then manufactured in accordance with Section 4.4. These 'cob' cylinders were then subjected to immediate unconfined compression testing (in accordance with Section 4.5), post manufacture, in order to ascertain their compressive strength carrying capacity at manufacture. The cylinders were then dried at 110 degrees in order to determine their dry weight and thus their manufacture moisture contents were determined.

This process was then repeated for each of the five soils selected. The results are presented in Chapter 5.

4.3.3.3 Test Series Three, Variation in UCC with moisture content

Using the selected soil eight 'soil' cylinders were manufactured in accordance with Section 4.4, these cylinders were air-dried in a climatic chamber at a temperature of 25 degrees centigrade and a relative humidity of seventy five percent. The amount of drying to which each cylinder was subjected varied. This aimed to ensure that the cylinders were subject to unconfined compression testing at various stages along their drying curves which had been obtained during monitoring of the drying curves of the Test Series One test cylinders. It was hoped that this would facilitate the targeting of a reasonable range of moisture contents at which the soil cylinders would be unconfined compression tested.

After a targeted drying period, the cylinders were unconfined compression tested and the load application via the proving ring and corresponding deflections recorded. The cylinders were then oven-dried to 110 degrees centigrade for the purpose of ascertaining their moisture contents at relevant stages.

Once the manufacture moisture contents for the soil cylinders were ascertained, the soil cylinders were individually re-hydrated to this moisture content and mixed with 1% straw to produce a cob matrix. This matrix was left to hydrate over the period of one week during which daily hand-mixing would occur to ensure the an even distribution of moisture within the mix. Eight 'cob' cylinders were then manufactured in accordance with Section 4.4. These cylinders were then allowed to dry in the climatic chamber under the same conditions experienced by the soil cylinders. Once dried, the cylinders were unconfined compression tested (in accordance with Section 4.5) and their dry weights obtained.

This process was then repeated for each of the five soils selected. However, instead of eight cylinders, fifteen cylinders were produced for the soil sampled from Stockadon area in order to observe more extensive behaviour of the soil cylinders' compressive strength capacity along the drying curve.

Again the drying of the soil cylinders allowed the manufacture moisture contents to be determined and the soil cylinders could then be individually re-hydrated to this moisture content and mixed with 1% straw to produce a cob matrix. This matrix was left to hydrate over the period of one week during which daily hand-mixing would occur to ensure an even distribution of moisture within the mix. The 'cob' cylinders were then manufactured in accordance with Section 4.4. These 'cob' cylinders were then subjected to unconfined compression testing (in accordance with Section 4.4) over a targeted time-period, informed by the drying curves obtained from monitoring the drying process of Test Series One (cob matrix cylinders). The cylinders were then dried at 110 degrees and their moisture contents at relevant time period determined.

The results for Series Two tests are shown in Chapter 5. It should be noted that results are shown for only fourteen 'Stockadon' cob cylinders due to the loss of material that occurred for one cylinder when transferring it to the oven for drying, from the compressive testing apparatus. The loss of this material would therefore result in problems achieving compatible densities and matrix between the soil and cob cylinders thus this cylinder was not re-hydrated to form the corresponding 'cob' cylinder.

4.4 The production of cylinders for soil and cob compression tests

Upon sampling, the soils described in Section 3.4 were placed into twenty litre capacity plastic sealed buckets. These buckets proved useful mediums in which to hydrate the soils in preparation for testing. The process of hydration, manufacture, testing, drying and re-hydration etceteras from the point of soil selection, has been shown in Figure 4.3.

To maximise control of the test program it was initially envisaged that it would be advantageous to manufacture the soil cylinders of all the soil series sampled, to the same moisture contents and densities thus limiting variables and facilitating interpretation of the results obtained. Obviously by the very nature of the original soil sampling criteria outlined in Section 3.2, this situation is impossible between these soils as a more clayey soil will, by virtue of its composition, require more water to promote its plasticity to enable it to be compacted into a mould. Furthermore to control density for all the selected soils, the compaction criteria would have to vary between soil type which then questions the validity of promoting earthen building construction as a viable future technology if placement of the material is so highly determinate on specialist prediction. Thus the seven-blow Proctor was established, as outlined in Section 4.2.3.1.

Establishing the seven-blow Proctor as a method specification for the production of the soil and cob cylinders afforded the author a consistent means by which to obtain the densities desirable to match those found in existing historic buildings. Furthermore this method would also easily accommodate further modification for development of material of improved densities and strength capacity. Thus the seven blow Proctor outlined in Section 4.4.1 was the adopted compaction specification for the soil and cob cylinders utilised in the test programme described in Section 4.3.3.

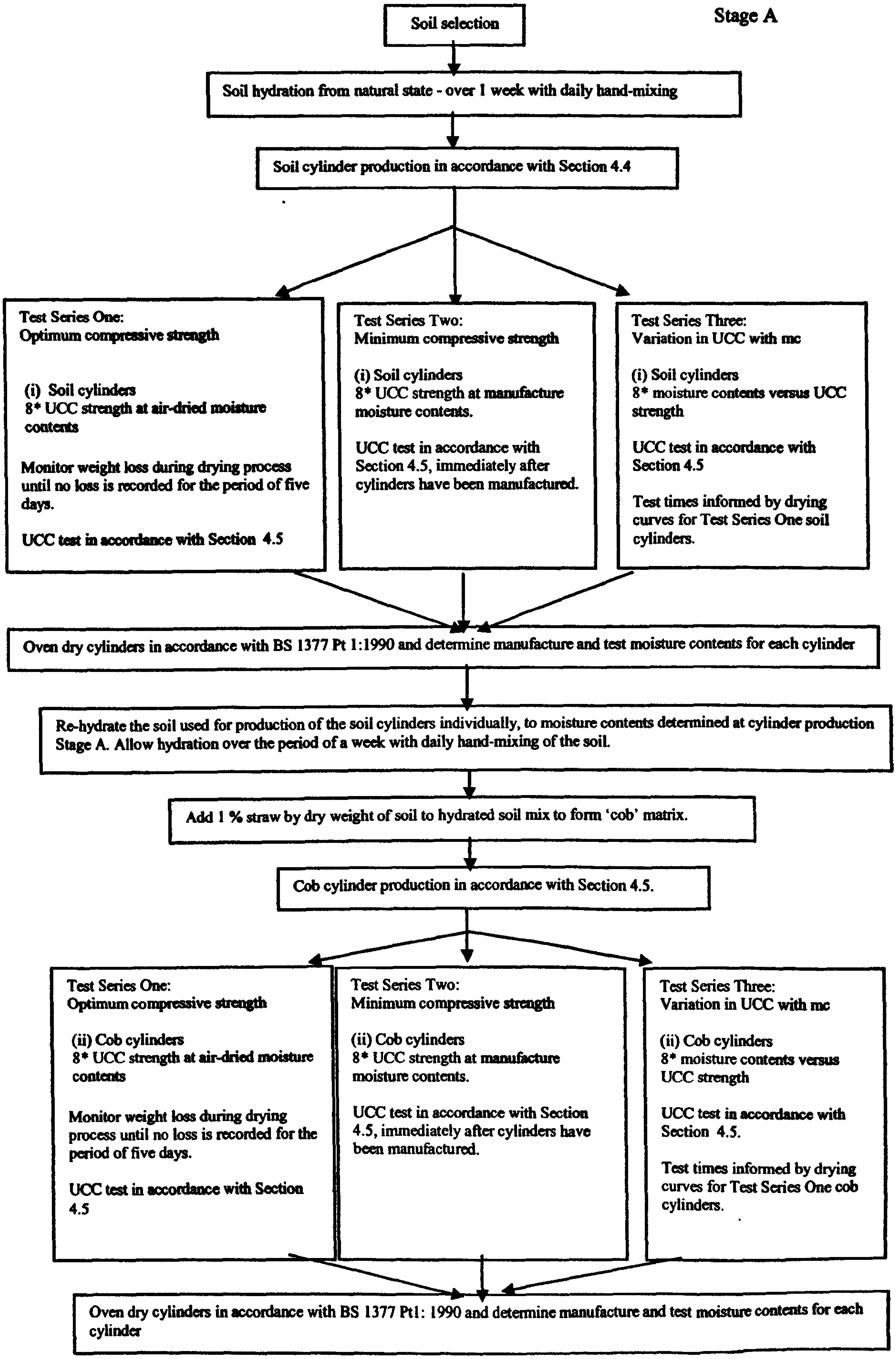


Figure 4.4 Test Program cylinder production and test cycle

4.4.1 Compacting the soil or cob matrix to form the test cylinders

The material was compacted in three equal layers using a 2.5kg manual Proctor rammer that was allowed to make contact the soil seven times per layer within a 150mm diameter by 300mm high cylindrical mould. Care was taken to ensure that the 51mm diameter, ramming blows, struck the soil evenly over the area of the mould into which the soil was compacted. On compaction of the last layer of soil the soil extruding from the mould was struck-off flush with the top of the mould.

The soil and cob cylinders would then be extruded vertically from their moulds using a vertical jack. The moulds did not require to be greased to ease extrusion as the manufacture moisture contents of the cylinders provided enough lubrication to facilitate this process.

4.4.2 Establishing positions for dimensional recording

Once extruded from their moulds the cylinders were weighed, and their heights and circumferences recorded using a measuring tape. Appendix 7 contains the manufacture data for all cylinders produced. It was important to establish points about which these records could be re-checked as drying progressed. It was also important to ensure that the measurements were being taken consistently with the tape held plumb. Thus prior to being weighed, a series of tailor's pins were inserted into the cylinders at third points of the cylinder's height. Joshi et al. (1994) adopted a similar method to facilitate the determination of sample volume. The measurements obtained and used to determine specimen volumes proved effective when assessed against mercury-displacement methods.

These pin positions allowed the tape to rest about the circumference point ensuring lack of skew in positioning of the tape when taking these measurements. The pins also established reference positions for the recording of height about the circumference of the cylinder at three positions from which a mean value was obtained. These pins remained in place throughout the drying period to permit any monitoring of the cylinders to continue prior to compression testing.

4.5 The unconfined compression testing (UCC) of soil/ cob cylinders

The unconfined compression testing of the test cylinders commenced after the prescribed drying period which would have been dependent on the test-type specification; ie. Test Series One to Three of Figure 4.4. Prior to testing, the circumferential dimensions and heights of all cylinders to be tested would be taken. Testing was carried out on a Wykeham Farrance compression-testing machine with the cylinders being loaded via a proving ring at the compressive rate of 0.1mm per minute. Figure 4.5 provides a diagrammatic illustration of the laboratory apparatus used for the compressive testing of the cylinders.

The soil was compression tested to obtain its permissible optimum strength. The test would continue until approximately 10% of the peak strength had been lost or until the integrity of the sample appeared to be compromised on further application of the compressive load. This occurred to ensure that the integrity of the sample would never be sufficiently compromised to render the sample incapable of being man-handled without collapsing. If this had occurred the manufacture weights of the cylinders would have been in error as material to be dried was lost in transfer from the test machine to a metal tray for the purpose of placing in the oven to dry.

As depicted in Figure 4.4, tested cylinders would then be dried in accordance with BS 1377 Part 1. On obtaining the dry weight of the sample, the manufacture and test moisture content of the test cylinders could be obtained.

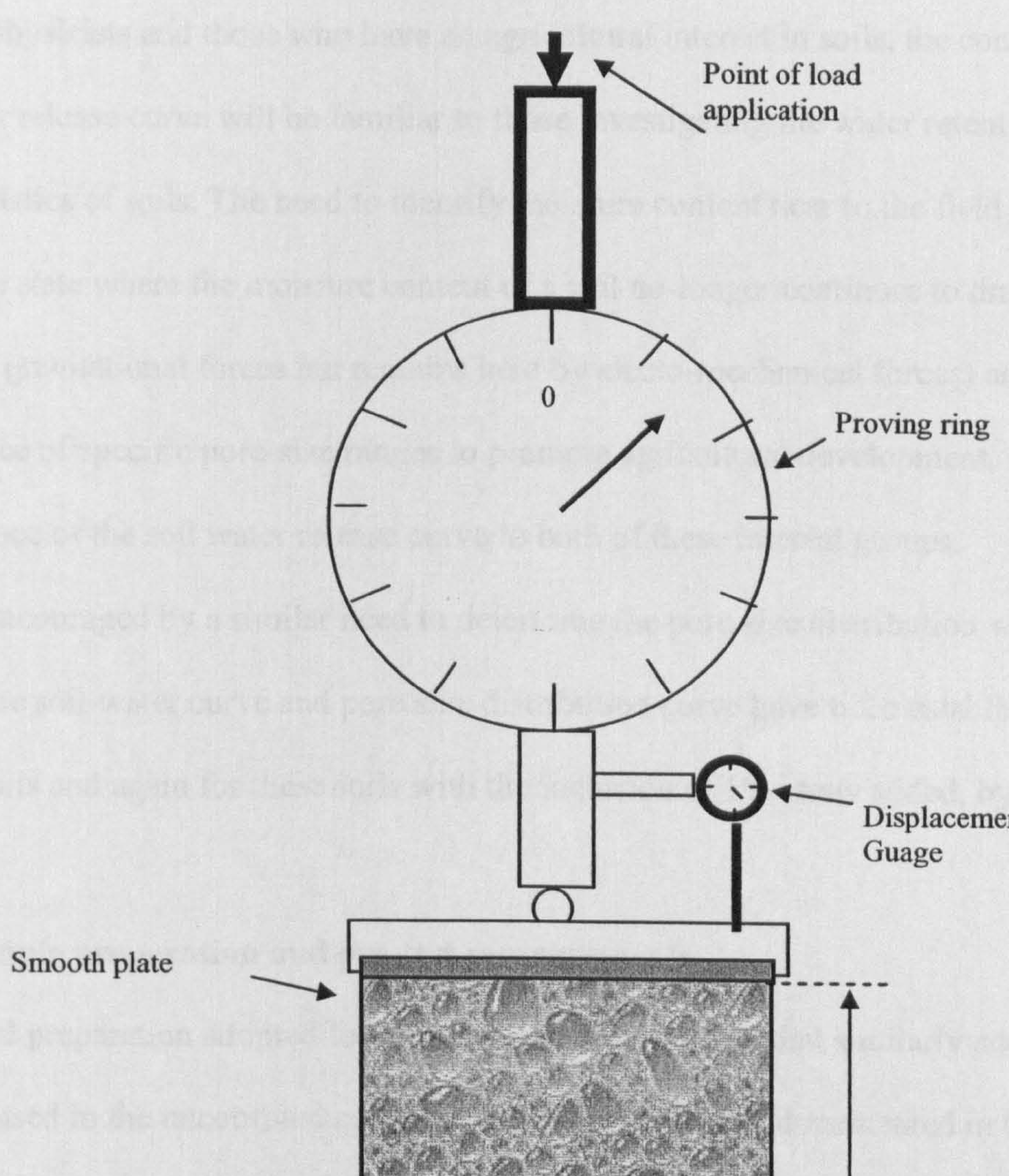


Figure 4.5 Diagram of Compression testing apparatus

4.6 Pressure membrane tests

For soil physicists and those who have an agricultural interest in soils, the concept of the soil water release curve will be familiar to those investigating the water retention characteristics of soils. The need to identify moisture content near to the field capacity state (the state where the moisture content of a soil no-longer continues to drain under the action of gravitational forces but remains held by electo-mechanical forces) and the importance of specific pore-size ranges to promote agricultural development, secured the significance of the soil water release curve to both of these interest groups.

Encouraged by a similar need to determine the pore size distribution within a 'cob' matrix, the soil-water curve and pore size distribution curve have been established for five Devon soils and again for these soils with the inclusion of 1% straw added, by weight.

4.6.1 Sample preparation and pre-test measurements

The initial preparation adopted for this investigation, follows that similarly adopted for the samples used in the unconfined compression tests, previously documented in this Chapter. This test was carried out on soil and cob samples formed from the materials sampled, as discussed in Chapter 3. The soil and cob (selected soil to which 1% straw has been added by weight) samples were hydrated over time and then hand compacted into a 100mm diameter mould in one layer, using the seven blows from a Proctor hammer. The maximum height of the test-sample is constrained by the height of the test-apparatus and will therefore lie in the region of 250 to 350 mm. Once the sample was produced its height, weight and diameter was immediately recorded. This information is shown in Table 4.3.

Since the soils had previously been homogenised, the issues discussed by Hall et al. (1977) regarding heterogeneity within a texturally homogeneous soil horizon were not regarded as being applicable and thus sample sizes did not necessarily require to conform to the minimum volume recommendation of 200cm^3. However it can be seen from Table

4.3 that on manipulation of the pre-test data collected, only one sample (Stockadon soil) failed to meet this volume.

Soil Sample	Sample type	Pre-Test Weight (g)	Pre-Test Height (mm)	Pre-Test Diameter (cm)	True Bulk Density (kg/m^3)	Sample Volume (cm^3)
Stockadon	Soil	349.07	20.7	33.4	1899.2	183.8
Crediton	Soil	489.35	27.1	33.1	2070.9	236.3
TDSTM	Soil	518.78	31.5	33.3	1866.1	278.0
Exminster	Soil	631.92	35.0	33.5	2021.5	312.6
Becut		583.55	32.5	33.0	2072.3	281.6
Stockadon	Cob	461.76	32.1	33.4	1602.2	285.0
Crediton	Cob	421.82	24.2	33.4	1963.8	214.8
TDSTM	Cob	513.62	32.7	33.2	1790.86	286.8
Exminster	Cob	528.96	33.7	33.5	1757.3	301.0
Becut	Cob	440.67	26.0	33.3	1925.2	229.4

Table 4.3: Pressure membrane pre-test data

4.6.2 Pressure membrane apparatus.

The pressure membrane apparatus (shown in Figure 4.6) consists of a chamber into which the samples tested are placed. Once inside the chamber, the samples are subjected to air pressure, used to force out water from the samples' pore spaces. Increasing air pressure forces water out of smaller and smaller pore spaces. By using a semi-permeable membrane (Visking) to line the bottom of the chamber, the air pressure is retained while the passage of water leaving the chamber was unimpeded.

The amount of water extracted under a given pressure is monitored daily until water extraction did not exceed 3mg over successive days. At this point the sample is said to have equilibrated under the air pressure applied, Hall et al (1977).

4.6.3 Pressure membrane test procedure

The samples to be pressurised were placed in two layers within the pressure membrane apparatus. The 'cob' samples were placed on one layer and the soil samples formed the other layer. A Visking membrane separated each layer. The pressure chamber was then subjected to a range of pressures (0.1bar, 0.3bar, 0.5bar, 1bar, 3bar, 5bar and 15bar) over time (Landon, 1991). The samples were left to equilibrate under each pressure application.

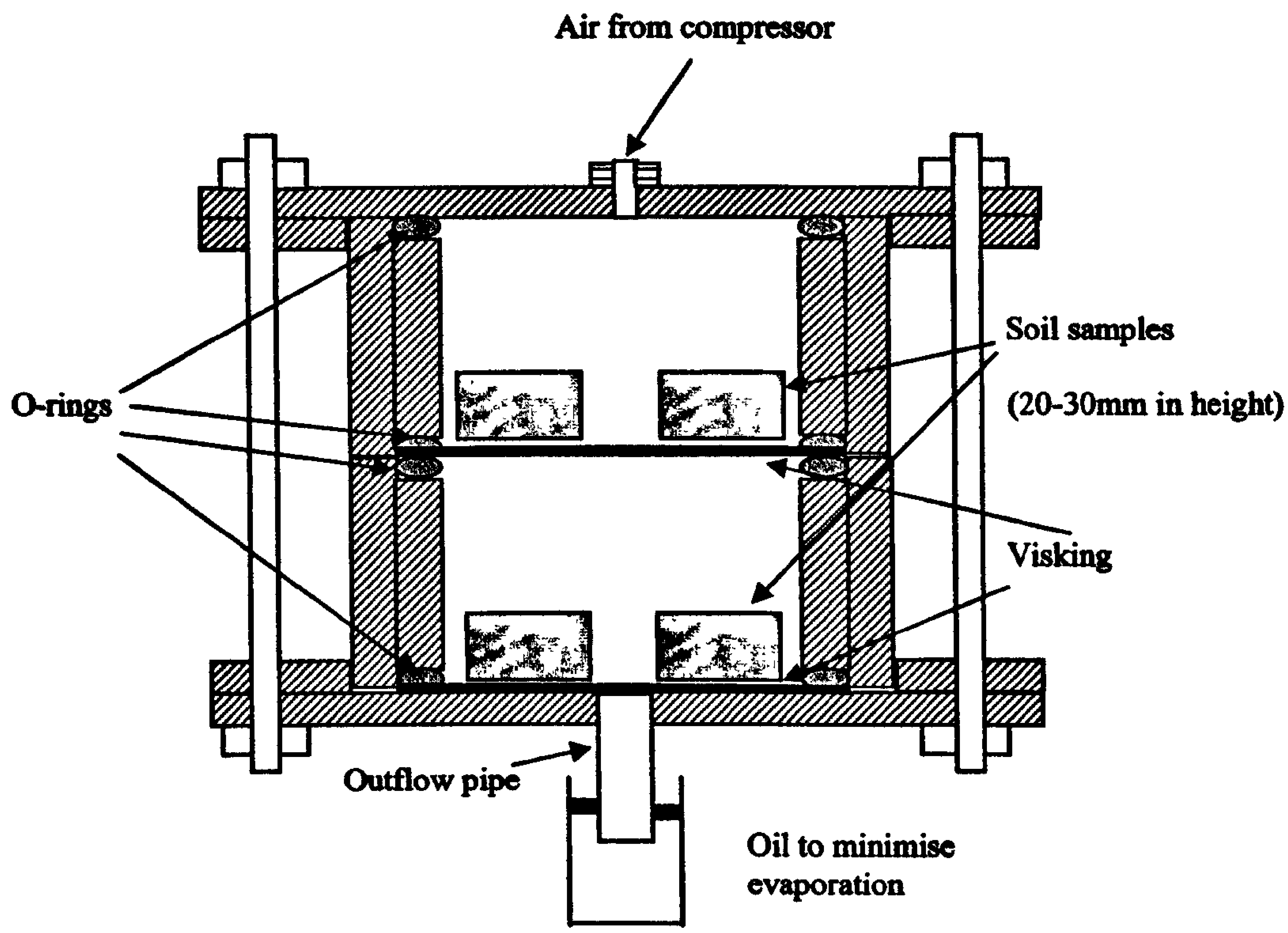


Figure 4.6 Pressure membrane cell

Once equilibrium was achieved (determined via daily monitoring of the amount of water extracted from the chamber) the samples were removed from the chamber and weighed. Once this was done the samples would be returned to the chamber and an increased pressure applied.

Given that each pressure application can be linked to a specific pore diameter using the approximation from Landon (1991) :-

diameter of pore (cm) = 0.3/h , where h is the cm of water applied to the system

pore volumes can be equated to the volume of water released between each successive pressure application.

The results presented were carried out in compliance with the method adopted by the Soil Survey of England and Wales (see Hall et al., 1977) and may be found in Chapter 5.

4.7 Summary

This Chapter has attempted to highlight the relevant issues (and the resolution thereof) pertinent to the establishment of the test methodology. The manufacture and testing process has been illustrated as being common to each of the five soils selected in Chapter 3. The pressure membrane has been introduced as a means of fabric classification to facilitate cob specification. The following Chapter, Chapter 5, will convey the test results produced from adherence to the test methodology and attempt to interpret and explain the significance of all test results.

Chapter 5. Unconfined compression testing and pressure membrane results for the selected soils and respective cobs.

5.1 Introduction

This chapter will present the results gathered during the compressive strength program adopted in this investigation, as outlined in Section 4.3; and the results from the pressure meter test, described in Section 4.6.

As illustrated in Figure 4.4, the compressive strength testing separates into three unique issues of cross-comparison for the soil and the cob cylinders. These issues concern the determination of UCC strength on air-drying the test cylinders, the determination of UCC strength on initial manufacture of the test cylinders and the development of UCC strength of the cylinders upon air-drying. Essentially these areas are respectively concerned with the maximum (long-term) compressive strength load capacity, the minimum (short-term) compressive strength load capacity and the development of load carrying capacity (intermediate strength) for the soil and cob cylinders over the period of curing. A definition of 'strength' is discussed in Section 5.2.

The pressure membrane results offer a means by which to address the fabric of tested matrixes by highlighting the volumes of specific pore sizes contained therein. For all areas of investigation, the results of the soil cylinder samples will be compared to those of the relevant cob cylinder samples to facilitate discussion of the cob matrix and the role of the straw used in the manufacture of the cylinders. Where applicable, statistical methods will be employed to ensure that the data associated with the manufacture of a particular soil series' soil-cylinders and cob-cylinders validate such a comparison.

5.2 A definition of strength for a particular matrix

The results from all the compressive strength test groups (air-dried test, post manufacture test, and moisture content versus unconfined compressive strength test) are plotted in the form of stress/strain graphs to illustrate the development of strength within each cylinder up to failure and, where possible, slightly beyond. The requirement to monitor the moisture contents of samples necessitated the test cylinders remaining relatively intact, to facilitate handling, and this affected the continuation of load application to the test sample under consideration.

The test sample groups are defined as follows: Crediton soil cylinders, Crediton cob cylinders, Dunsford soil cylinders, Dunsford cob cylinders, Tedburn soil cylinders, Tedburn cob cylinders, Halstow soil cylinders, Halstow cob cylinders, Bridgnorth soil cylinders and Bridgnorth cob cylinders. The unconfined compressive strength results for Test Series One are displayed in Table 5.1, and the Test Series Two results are contained within Table 5.2. Discussion of the values contained in Tables 5.1 and 5.2 is given in Sections 5.3 and Section 5.4 respectively. Tabulated values refer to peak and yield strength, and much research has been done in defining the application of these terms to a particular soil test moisture condition (see Figure 5.1; Atkinson, 1993).

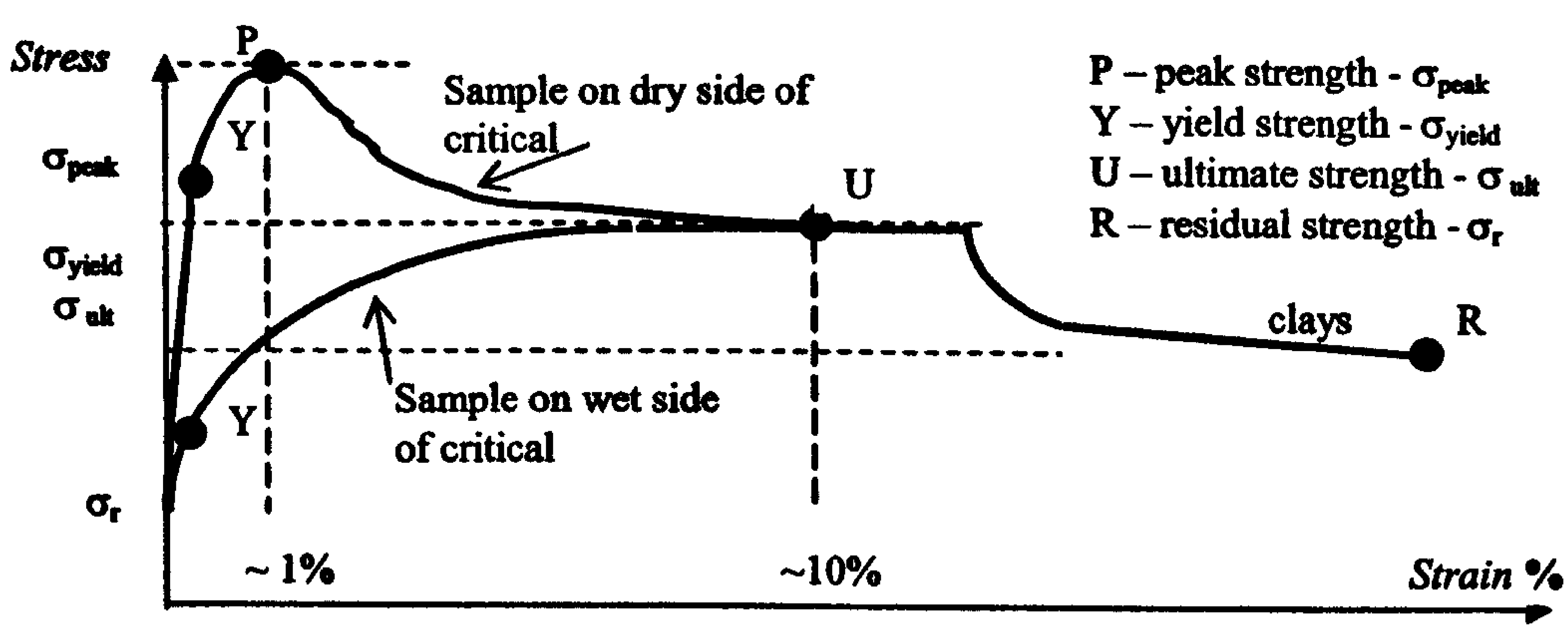


Figure 5.1 Typical stress versus strain behaviour of soils (Adapted from Atkinson, 1993)

Consider the soil sample in Figure 5.1 tested on the dry side of critical. The initial response of the soil cylinders illustrates that the relationship between stress and strain remains constant, up to a point that is defined as yield strength (see Figure 5.1, point Y). During any stage of this loading prior to this point, the strain deformation is recoverable and the soil may be said to behave elastically. Elastic behaviour may be explained in terms of the response of soil particles themselves, or of small rotations between contacting soil particles, insufficiently large enough to wholly dissociate particles and are therefore recoverable.

Beyond yield strength, the deformation of the soil is such that while some particles do behave elastically and rotate about their point of contact, others become totally dislocated from each other. Deformation due to dislocation is irrecoverable. At this point the soil is dilated. The dual action of elastic behaviour, coupled with that of plastic (non-recoverable) behaviour continues until peak strength is achieved (point P on Figure 5.1).

On achieving peak strength, a further increase in load application to the sample results in the relative movement of both the sand and clay particles that make up the soil. This is known as turbulence. Here particle movement promotes further straining, opening-up the soil matrix, thus reducing its load-carrying capacity until the ultimate or constant volume state is reached (point U, see Figure 5.1). For reasons outlined at the beginning of this section, testing ceased prior to the establishment of point U for Test Series One.

For the wet soil matrix, point U may not be determined from the experimental data but may represent the strength of the soil at a limiting value of strain (Barnes, 2000). This situation may be required due to the excessive period of work-hardening which follows yield-strength for wet soil matrixes. This work-hardening describes the continual increase in unconfined compressive strength load capacity as the cylinders continue to deform to accommodate the increased load application by achieving a denser structure, Barnes (2000).

Table 5.1 tabulates the mean P and associated Y values for the associated test samples for Test Series One in which the cylinders were unconfined compression tested after prolonged air-drying. Table 5.2. presents unconfined compression values for the sample groups at manufactured moisture contents, the Series Two Tests. The experimental data from which the values contained within these tables are derived may be found in Appendix 6.

Test sample group	Average peak unconfined compressive strength (kN/m^2)	Approximate yield strength (kN/m^2)
Crediton soil cylinders	360.75 ± 17.55	160
Crediton cob cylinders	721.34 ± 24.43	300
Dunsford soil cylinders	564.25 ± 27.5	300
Dunsford cob cylinders	709.44 ± 31.68	400
Tedburn soil cylinders	372.98 ± 21.7	200
Tedburn cob cylinders	478.92 ± 43.91	300
Halstow soil cylinders	1234.84 ± 118.87	600
Halstow cob cylinders	1185.52 ± 95.49	650
Bridgnorth soil cylinders	1030.76 ± 125.14	500
Bridgnorth cob cylinders	1188± 134.4	550

Table 5.1. Characteristic unconfined compressive strength values of air-dried soil/cob cylinders, Test Series One tests.

Test sample group	Average peak unconfined compressive strength (kN/m^2)	Approximate yield strength (kN/m^2)
Crediton soil cylinders	81.89 ± 4.20	30 – 40
Crediton cob cylinders	274.09 ± 41.0	150
Dunsford soil cylinders	100.76 ± 9.21	40
Dunsford cob cylinders	179.84 ± 29.26	75-100
Tedburn soil cylinders	96.39 ± 14.82	20 – 40
Tedburn cob cylinders	138.39 ± 11.82	30 - 40
Halstow soil cylinders	96.20 ± 4.51	80
Halstow cob cylinders	159.83 ± 11.9	80
Bridgnorth soil cylinders	122.87 ± 9.97	60
Bridgnorth cob cylinders (values averages of 5 from 8)	312.17 ± 4.01	200

Table 5.2. Characteristic unconfined compressive strength values of cylinders tested immediately post manufacture, Test Series Two tests.

5.3 Results from Test Series 1: air-dried unconfined/undrained compressive strength

Sections 4.4 and 4.3.3.1 describe the manufacture and procedure for the determination of the air-dried unconfined/undrained compressive strength values applicable to each of the five soil series soil and cob cylinders. In each instance, eight samples were produced and tested to determine the variation that may also be associated with these values. To ensure that variation is not a factor of the cylindrical sample manufacture technique, standardisation of the compactive effort used to produce the cylinders has resulted in the adoption of the 7-blow Proctor, as outlined in Section 4.2.3.1.

Table 5.3 illustrates the effectiveness of a standardised compaction technique in achieving replication of the density of the cylinders produced for each test-group at the point of manufacture. Good homogenisation of the material matrix during manufacture, as highlighted in Section 4.3.3.1, is also supported by the results contained in Table 5.3 via the small values of standard deviations in moisture content between test cylinders. Thus these values validate replication in the samples produced. In validating the replication of cylindrical sample groups, manufacture controls can be deemed as satisfactory. Manufacture data for the cylinders within each test-group may be found in Appendix 5.

During manufacture of the cob samples for the Test Series One tests, outlined in Section 4.3.3.1., the manufacture moisture content of the soil cylinders was intentionally targeted on rehydration of the soil cylinders prior to the addition of straw, to produce cob cylinders. Table 5.3 illustrates the success gained in achieving this. Maintaining moisture contents over the soil and cob cylinder tests was considered important in order to facilitate discussion comparing a soil series' soil matrix with a soil series' cob matrix, since moisture content is critical to soil bulk density and thus strength. Table 5.3 contains further observations of test moisture content and density, made to ensure that replication of values within sample groups was maintained post air-drying up to the time of compression testing.

In the case of test bulk density, Table 5.3. shows that there is more variation about the mean for these values than those exhibited by the manufacture bulk density values. To ascertain the significance of the variability associated with each parameter where control was deemed important, a two- way analysis of variance (ANOVA) was carried out to test the hypothesis which assumed that cylindrical samples, within and between test groups, did not vary in terms of moisture content at manufacture / test and bulk density at manufacture/ test for the straw/ no straw condition.

Cylindrical sample group	Mean bulk density @ manufacture (kN/m^3)	Mean moisture content @ manufacture (% by weight)	Mean bulk density @ test (kN/m^3)	Mean moisture content @ test (% by weight)
Crediton soil cylinders	2128 ± 19.25	16.63 ± 0.58	2027 ± 19.74	4.81 ± 0.38
Crediton cob cylinders	2034 ± 18.41	18.5 ± 0.17	1826 ± 12.14	4.25 ± 0.13
Dunsford soil cylinders	1988 ± 20.55	25.48 ± 0.47	1894 ± 15.49	5.43 ± 0.13
Dunsford cob cylinders	1871 ± 20.89	27.48 ± 0.41	1793 ± 14.40	6.74 ± 0.17
Tedburn soil cylinders	2078 ± 16.30	26.48 ± 1.34	1966 ± 75.64	6.11 ± 1.57
Tedburn cob cylinders	1879 ± 17.51	26.38 ± 0.23	1716 ± 9.55	4.54 ± 0.19
Halstow soil cylinders	1835 ± 6.73	34.05 ± 0.29	1684.2 ± 51.78	5.39 ± 0.08
Halstow cob cylinders	1792 ± 14.85	34.44 ± 0.30	1613 ± 27.86	4.23 ± 0.001
Bridgnorth soil cylinders	2066 ± 25.28	11.68 ± 1.10	1894 ± 23.20	1.07 ± 0.03
Bridgnorth cob cylinders	1919 ± 11.70	11.36 ± 0.18	1754 ± 23.00	1.10 ± 0.18

Table 5.3. The statistical means and deviations in the manufacture and test densities and moisture contents for each sample group in Test Series 1 (air-dried cylinders)

Parametric selection was initially limited to moisture content and bulk density at manufacture which are both influential in the development of peak strength. This selection stemmed from the rationale that if these parameters were deemed to be controlled at manufacture, then controls would be maintained at test as all samples would be subject to the same environmental conditions until this time. With the appearance of larger variations in these parameters at the point of test, questions concerning parametric control were of further concern. Clearly bulk density at test or manufacture would be significantly different for the soil cylinder/ cob cylinder groups within a given soil series. However, in order to ascertain the value of peak unconfined compressive strength that may be attributed to the soil and cob condition for a given soil series, it would be desirable for the bulk density at test /manufacture to be controlled within each cylindrical grouping.

Despite adopting a test methodology which aimed to control moisture content between the cylindrical groupings of a given soil series (see Chapter 4), variations in the moisture contents at the point of manufacture and test were noted, Table 5.3. The significance of these variations in moisture contents at manufacture and test condition, required determination in order to test the null hypothesis. Analysis of variance (ANOVA) was thus adopted.

5.3.1 Test Series One ANOVA

On comparing the soil cylinder/ cob cylinder condition for each soil series, moisture content and bulk density at manufacture and moisture content and bulk density at test were analysed to determine whether differences in these values within sample groups were significant. Four two-way ANOVA tests were run, one for each dependent measure (moisture content and bulk density at manufacture and moisture content and bulk density at test). For each two way ANOVA the independent variables were soil type and straw condition. The results of each two-way ANOVA were reported separately, and the ANOVA tables for each analysis are displayed in Tables 5.4, 5.5, 5.6 and 5.7.

For all four Two-way ANOVAs, there were significant main effects of soil type and of cylinder type. As expected, there were significant differences between values for all four dependent measures across soil series. There was also a main effect of cylinder type for all four dependent measures. Values for all four dependent measures were higher for the cob cylinders than for the soil cylinders. However, of most interest are the significant interactions. These indicate that the difference between values for cob cylinders and soil cylinders is significant for only some soil types. Tukey HSD tests were used as a means of follow-up analyses for these interactions.

Source	df and F value	MSe	p-value
Soil (S)	$F(4, 70) = 179.73$	863.05	$p < 0.000001$
Cylinder type (C)	$F(1, 70) = 218.37$	863.05	$p < 0.000001$
(S) x (C)	$F(4, 70) = 6.68$	863.05	$p < 0.001$

Table 5.4. Results of Two-Way ANOVA, dependent measure bulk density at manufacture

Source	df and F value	MSe	p-value
Soil (S)	$F(4, 68) = 2895.40$	0.41	$p < 0.000001$
Cylinder type (C)	$F(1, 68) = 27.71$	0.41	$p < 0.0001$
(S) x (C)	$F(4, 68) = 11.23$	0.41	$p < 0.000001$

Table 5.5. Results of Two-Way ANOVA, dependent measure moisture content at manufacture

Source	df and F value	MSe	p-value
Soil (S)	$F(4, 69) = 143.01$	1114.45	$p < 0.000001$
Cylinder type (C)	$F(1, 69) = 411.87$	1114.45	$p < 0.000001$
(S) x (C)	$F(4, 69) = 18.53$	1114.45	$p < 0.000001$

Table 5.6. Results of Two-Way ANOVA, dependent measure bulk density at test

Source	df and F value	MSe	p-value
Soil (S)	F(4, 68) = 200.69	0.28	$p < 0.000001$
Cylinder type (C)	F(1, 68) = 10.50	0.28	$p < 0.01$
(S) x (C)	F(4, 68) = 17.91	0.28	$p < 0.000001$

Table 5.7. Results of Two-Way ANOVA, dependent measure moisture content at test

Follow-up analyses for bulk density at manufacture showed significant differences between cylinder types for all soil series (all at $p < 0.001$) except for Halstow ($p > 0.05$). As can be seen in Table 5.3 above, for the Crediton, Dunsford, Tedburn and Brignorth Series, mean bulk density values at manufacture were significantly higher for the soil cylinders than for the cob cylinders.

Follow-up analyses for moisture content at manufacture showed significant differences between cylinder types for only the Crediton and Dunsford Series (both at $p < 0.001$). Moisture content at manufacture values are significantly higher for the cob cylinders for both these series than for the soil cylinders.

Follow-up analyses for bulk density at test showed significant differences between cylinder types for all soil series (all at $p < 0.001$).

Follow-up analyses for moisture content at test showed significant differences between cylinder types for the Tedburn, Dunsford and Halstow Series (all at $p < 0.001$). As can be seen in Table 5.3 above, moisture content values at test were significantly higher for the soil cylinders than for the cob cylinders for both the Tedburn and Halstow Series. However, for the Dunsford Series moisture content values at test were significantly lower for the soil cylinders than for the cob cylinders.

The results of the analyses show that manufacture moisture contents of the Halstow, Bridgnorth and Tedburn series were deemed controlled between the soil and cob conditions. However test moisture contents were only controlled for the Crediton and Bridgnorth series. For bulk density at manufacture, the Halstow series was the only one where control was present between the soil and cob conditions. Finally, for bulk density at test, differences were significant for all soil series, as expected.

The next stage in the analyses was to test whether there was a significant difference in compressive strength as a function of cylinder type. In order to test this, it was envisaged that a two-way ANOVA would be used where the independent variables were soil type and cylinder type, with compressive strength as the dependent measure. However, given the results of the two-way ANOVAs reported above for bulk density at manufacture and at test, and moisture content at manufacture and at test, it was deemed necessary to include bulk density at test and moisture content at test as covariates in the analysis.

These test parameters were selected over the manufacture parameters (which also significantly varied) because they were deemed most influential to the peak unconfined compressive strength of these air-dried cylinders. Figure 5.1 illustrates the importance of the soil's moisture condition at test while the test bulk density values are relative to the particle matrix and reflect the manufacture conditions that therefore need not be included.

To summarise, a two-way ANCOVA was run to test the effect of soil series and cylinder type (soil/ cob) on the peak compressive strength values. The independent variables were soil series and cylinder type, the covariates were bulk density at test and moisture content at test, and the dependent variable was compressive strength. The results of the two-way ANCOVA are displayed in Table 5.8.

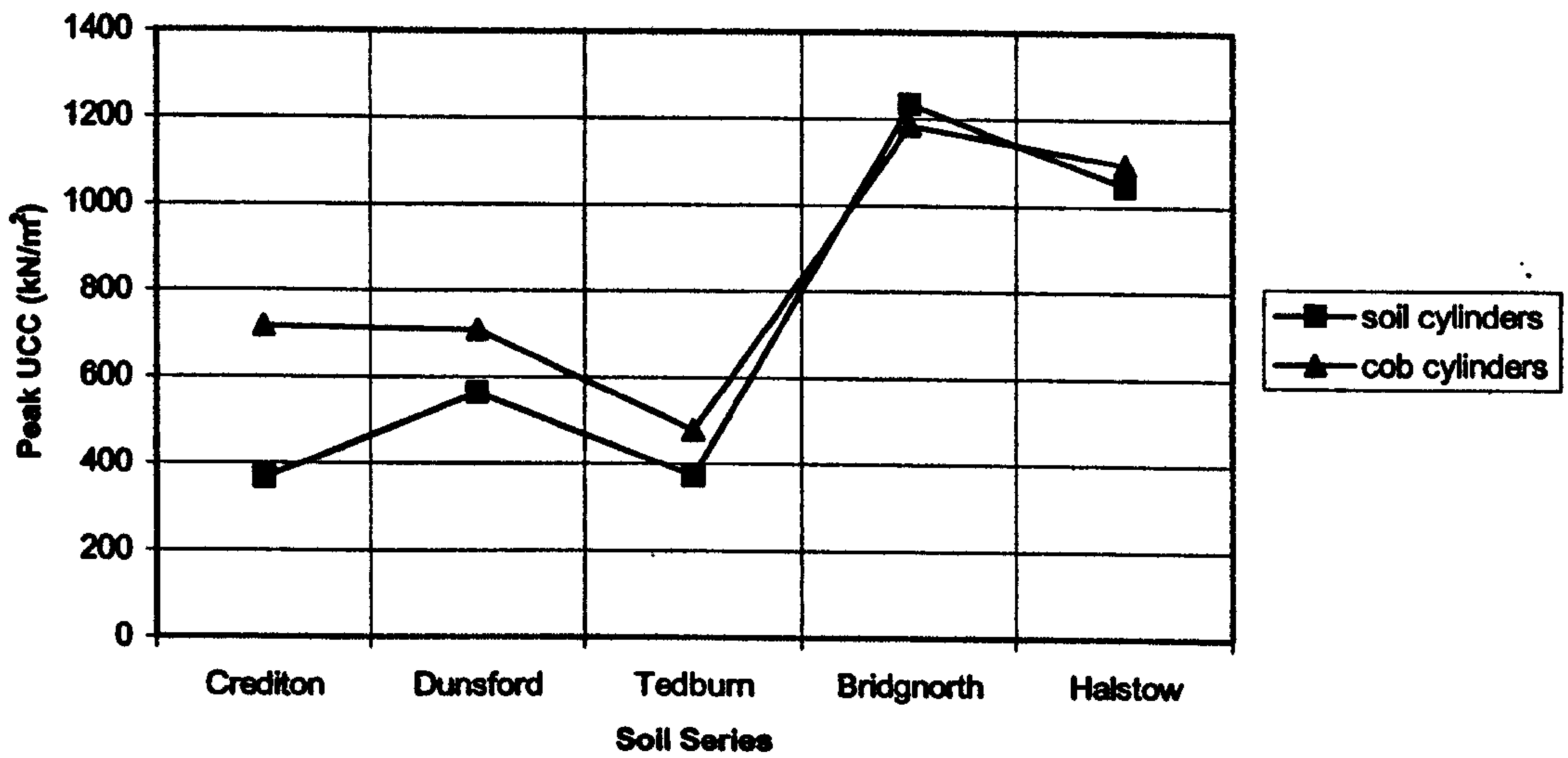
Source	df and F value	MSe	p-value
Soil (S)	$F(4, 65) = 73.67$	6399.27	$p < 0.000001$
Cylinder type (C)	$F(1, 65) = 16.53$	6399.27	$p < 0.001$
(S) x (C)	$F(4, 65) = 10.80$	6399.27	$p < 0.000001$

Table 5.8. Results of Two-Way ANCOVA, dependent measure peak compressive strength

Observation of this table shows that there was a significant main effect of soil series as expected. Of most interest were the significant main effect of cylinder type and the significant interaction between soil series and cylinder type. Across soil series, cob cylinders had a mean peak compressive strength value of 856 kN/m^2 compared with a mean value of 719 kN/m^2 for the soil cylinders. However, the significant interaction shows that the effect of cylinder type (soil/ cob) was not significant for all soil types. The means for this interaction are displayed in Table 5.1 above, and plotted in Figure 5.2 for each soil series and cylinder type. Follow-up analyses (using Tukey HSD tests) revealed a significant effect of cylinder type for the Crediton series ($p < 0.001$) and for the Dunsford series ($p < 0.05$). The effect was marginal for the Bridgnorth Series ($p = 0.06$), and was non-significant for both the Tedburn Series ($p = 0.22$) and the Halstow Series ($p = 0.95$).

This result provides the first real indicator of the potential contribution of straw to the compressive strength characteristics of in-service cob building materials. Previous work (Saxton, 1995; Greer, 1997) is too constrained by material selection to address this issue or to provide any insight into the breadth of functions afforded by straw inclusion. This work has shown the potential contribution of straw to the compressive strength of a traditional cob soil, to be soil dependent, and this will be discussed in more detail in Section 6.4.3.

Figure 5.2 Plot of means for Test Series 1, 2-way interaction
F(4,65) = 10.80; p<.0000



Plotting the stress/strain paths for all cylinders tested in Test Series 1 (the UCC testing of soil and cob cylinders after air-drying) illustrates the development of strength within each cylinder up to the point of failure, and as far beyond as handling will allow (Figures 5.3 to 5.13 inclusive). The following sections (5.3.2 to 5.3.5, inclusive) discuss these paths for all soil series and cylinder groupings.

5.3.2. The air-dried unconfined/undrained compressive strength of the Crediton Series soil and cob cylinders

Figures 5.3 and 5.4 illustrate the stress strain graphs for the unconfined compression testing of the soil and cob cylinders produced from the Crediton soil series, respectively. Appendix 6 contains the raw data from which these curves were produced.

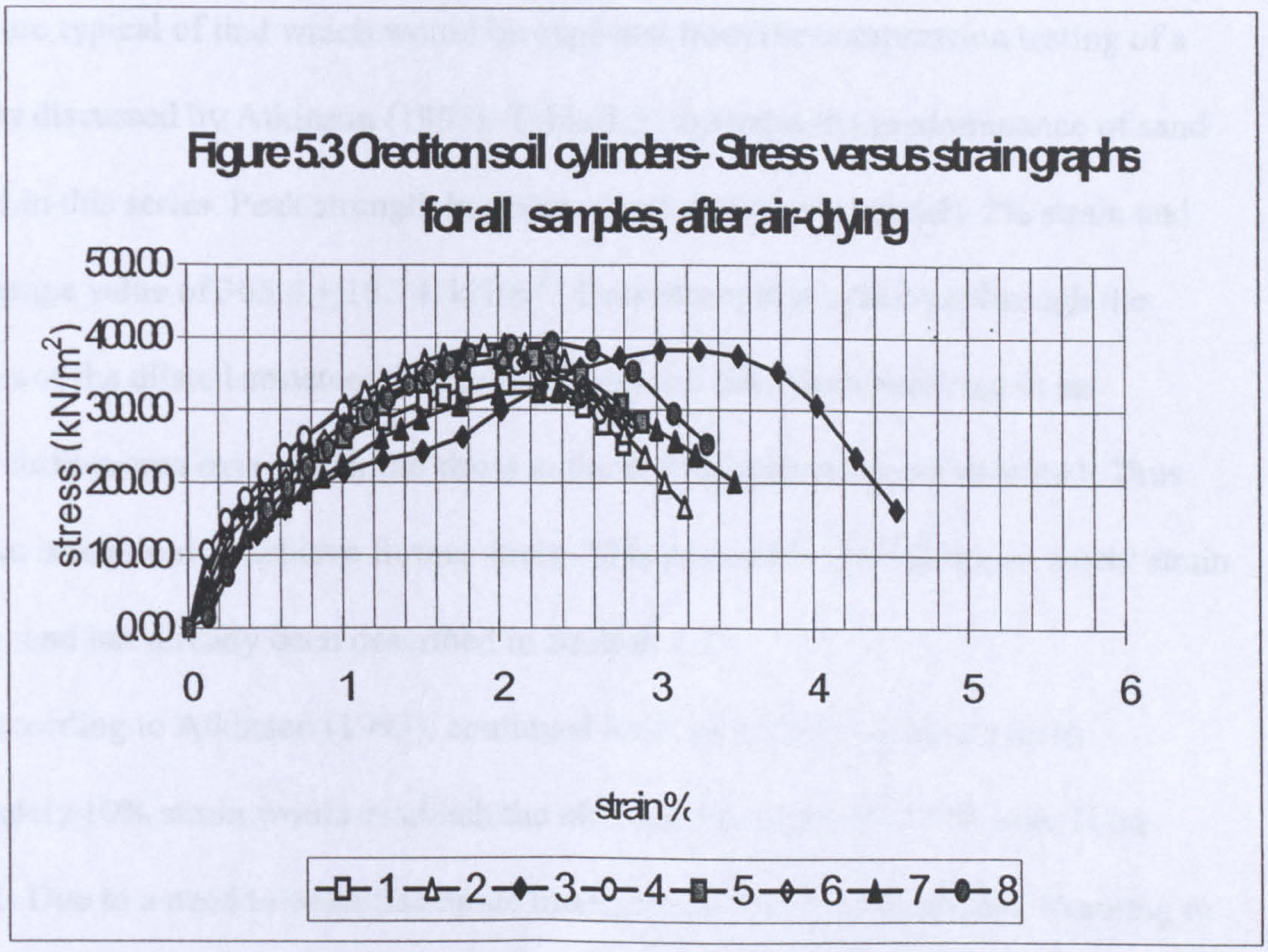


Figure 5.3 Crediton soil cylinders- Stress versus strain graphs for all samples, after air-drying

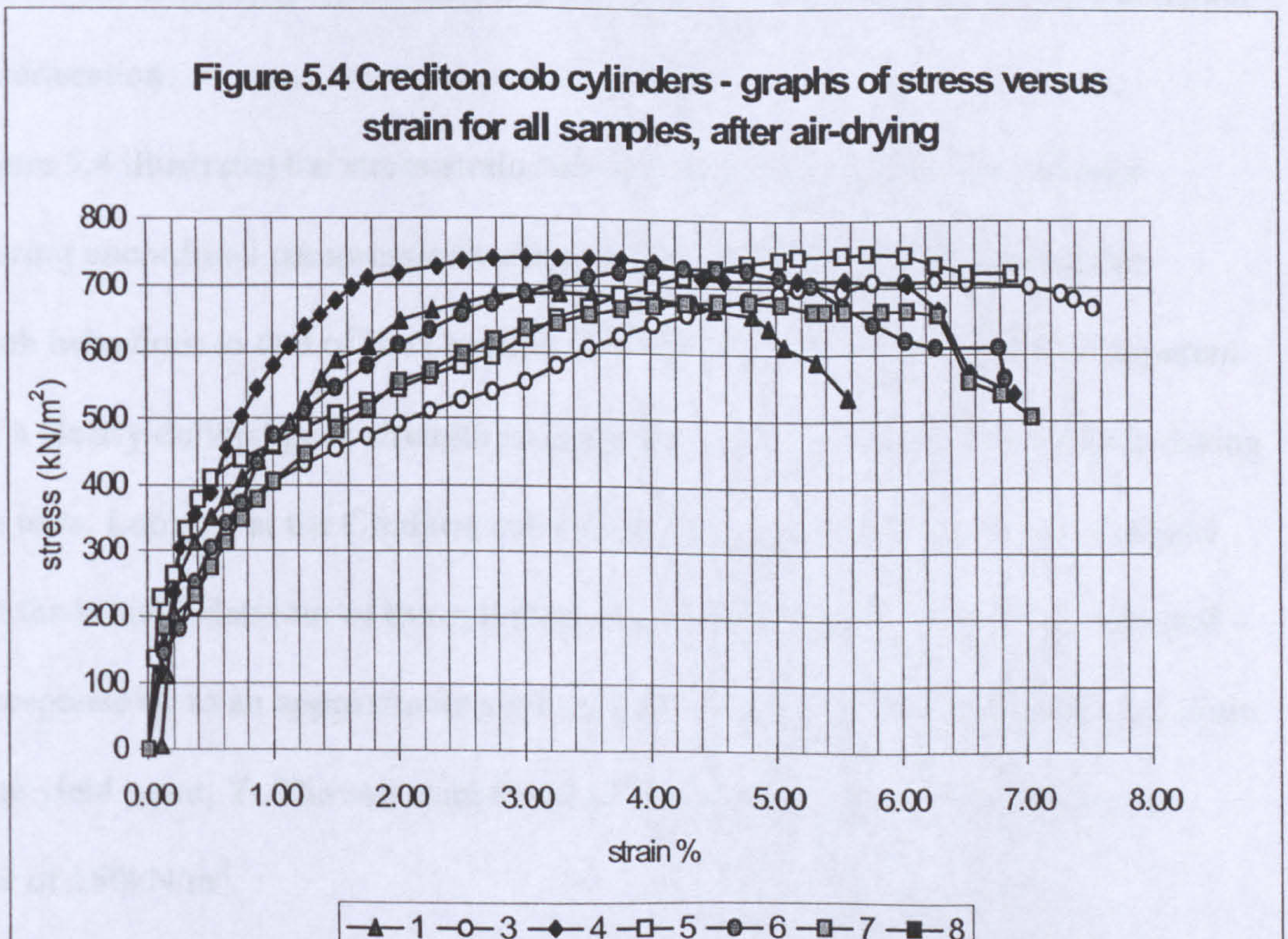


Figure 5.4 Crediton cob cylinders - graphs of stress versus strain for all samples, after air-drying

Considering Figure 5.3, the results of the Crediton soil cylinders, the graphs produced are typical of that which would be expected from the compression testing of a dry sand as discussed by Atkinson (1993). Table 3.5 illustrates the predominance of sand and gravel in this series. Peak strength has been reached at approximately 2% strain and has an average value of 365.4 $\pm$ 18.74, kN/m^2. Peak strength is achieved through the contraction of the dilated structure during elastic-plastic behaviour resulting in an increased surface area over which the stress in the soil sample may be distributed. Thus more stress is required to achieve further strain. This process is also known as work/ strain hardening, and has already been described in Section 5.2.

According to Atkinson (1993), continued loading of these cylinders up to approximately 10% strain would establish the ultimate load strength of the soil, U on Figure 5.1. Due to a need to ensure accurate monitoring of moisture contents, straining to this sort of magnitude was considered inappropriate due to the deterioration of the sample at these strains and thus problems in ensuring the sample remained stable enough to handle without deterioration.

Figure 5.4 illustrates the stress/strain behaviour of the Crediton cob cylinder samples during unconfined compression testing. Initial observations, comparing the Crediton cob behaviour to that of the Crediton soil behaviour, are focused on the apparent absence of a clearly defined peak strength so prominent in the Crediton soil samples during Series One tests. Looking at the Crediton cob cylinders during Test Series One, it would appear that the initial behaviour of the cylinders under load is similar to that of a dry soil - an elastic response up to an approximate stress value of 250kN/m^2 at an approximate strain of 0.3%, the yield point, Y. The soil samples exhibit a similar yield strain at the lower stress value of 150kN/m^2.

Beyond yield, strain-hardening appears to continue to increase the ability of the cob cylinders to sustain the applied loading. This extended straining, not exhibited by the soil cylinders is likely to be due to the binding capacity of the straw. As the straw fibres are forced into tension due to the lateral expansion of the test cylinders under strain, the dry soil particles are wholly dislocated and begin to fill any small voids in the cylinders' macro-structure which enables it to maintain loads at greater strains. The role of the various fractions within the cob matrix is further discussed in Chapter 6.

Considering the maximum loads applied to these cob cylinders, obtained from the stress/strain results contained within Appendix 6, it was determine that the average unconfined compressive strength of the Crediton cob cylinders as 718.3 ± 27.38 kN/m^2. This represents a strength capacity increase of approximately 96% over the value achieved by the Crediton soil cylinders.

5.3.3. The air-dried unconfined/undrained compressive strength of the Dunsford Series soil and cob cylinders.

Figure 5.5 and 5.6 illustrate the behaviour of the Dunsford soil and cob cylinders respectively when subjected to unconfined compression testing. The eight soil cylinders achieve an average peak unconfined compressive strength value of 564.25 ± 27.5 kN/m^2, while the cob cylinders show an increased strength value of 709.44 ± 31.68 kN/m^2. The addition of straw to the Dunsford soil matrix improves strength by approximately 25%.

Figure 5.5 Dunsford soil cylinders - Stress versus strain graphs for all air-dried samples

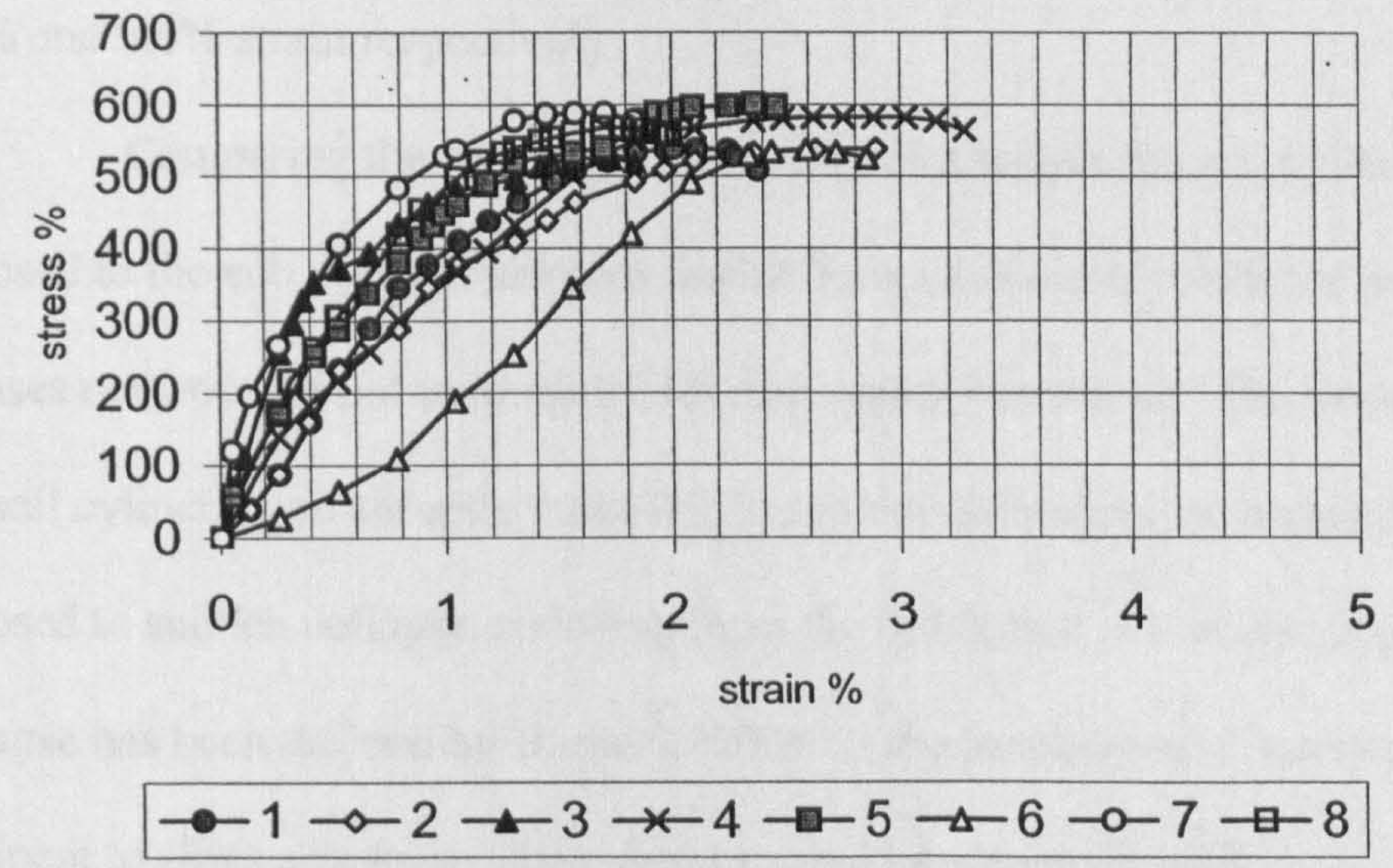
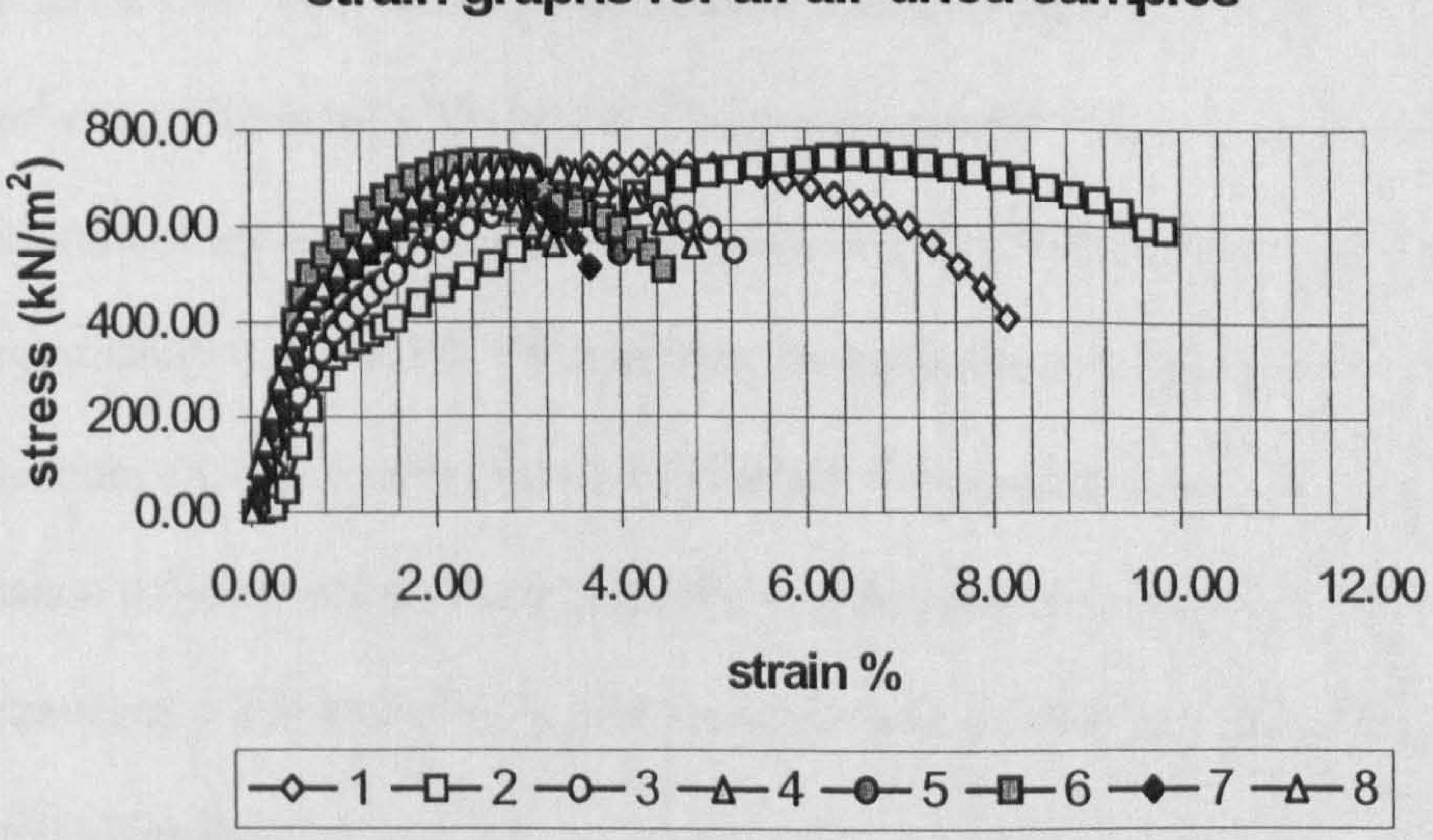


Figure 5.6 Dunsford cob cylinders - Stress versus strain graphs for all air-dried samples



Unlike the Crediton cob cylinders, the cylinders produced from Dunsford cob are shown to exhibit much less strain-hardening with a more definitive peak strength being produced. The majority of the cob samples achieve peak strength at approximately 2.5% strain with Dunsford cob test cylinders 1 and 2 attaining peak strength at approximately 4.5% and 6.6% strain respectively.

Comparing the stress/strain development within the soil cylinder samples as opposed to the cob cylinder samples, the differences lie soley with the magnitudes of stresses reached and not in terms of developmental behaviour. The stress/strain graphs of the soil cylinders are abruptly curtailed due to the difficulties in the handling of samples exposed to sudden collapse, resulting from the brittleness of the samples tested. Sudden collapse has been defined by Barnes (2000), as the breakdown of interparticle bonds, and is pertinent to clays and some silts subject to rapid undrained loading.

5.3.4. The air-dried unconfined/undrained compressive strength of the Tedburn Series soil and cob cylinders

The results from the Tedburn soil and cob cylinders, shown in Figure 5.7 and 5.8 respectively, illustrate similar trends to those shown by that of the Dunsford samples for Test Series One. The Tedburn soil cylinders achieve a peak strength of 372.98 $\pm$ 21.7 kN/m^2 at approximately 2% strain. This peak strength value is improved 28% by the addition of straw to form the cob matrix to 478.92 $\pm$ 43.91 kN/m^2 straining at approximately 4.4 to 7.3%. Thus at peak strength, the cob cylinders are straining two times the amount experienced by the soil cylinders. Comparing stress/ strain values at yield, the inclusion of straw within the soil matrix is again shown to improve the yield strength from approximately 200 kN/m^2 at 0.25% strain for soil cylinders to 280kN/m^2 at 0.85% strain for cob cylinders.

Figure 5.7 Tedburn soil samples - Stress versus strain graphs for all air-dried samples

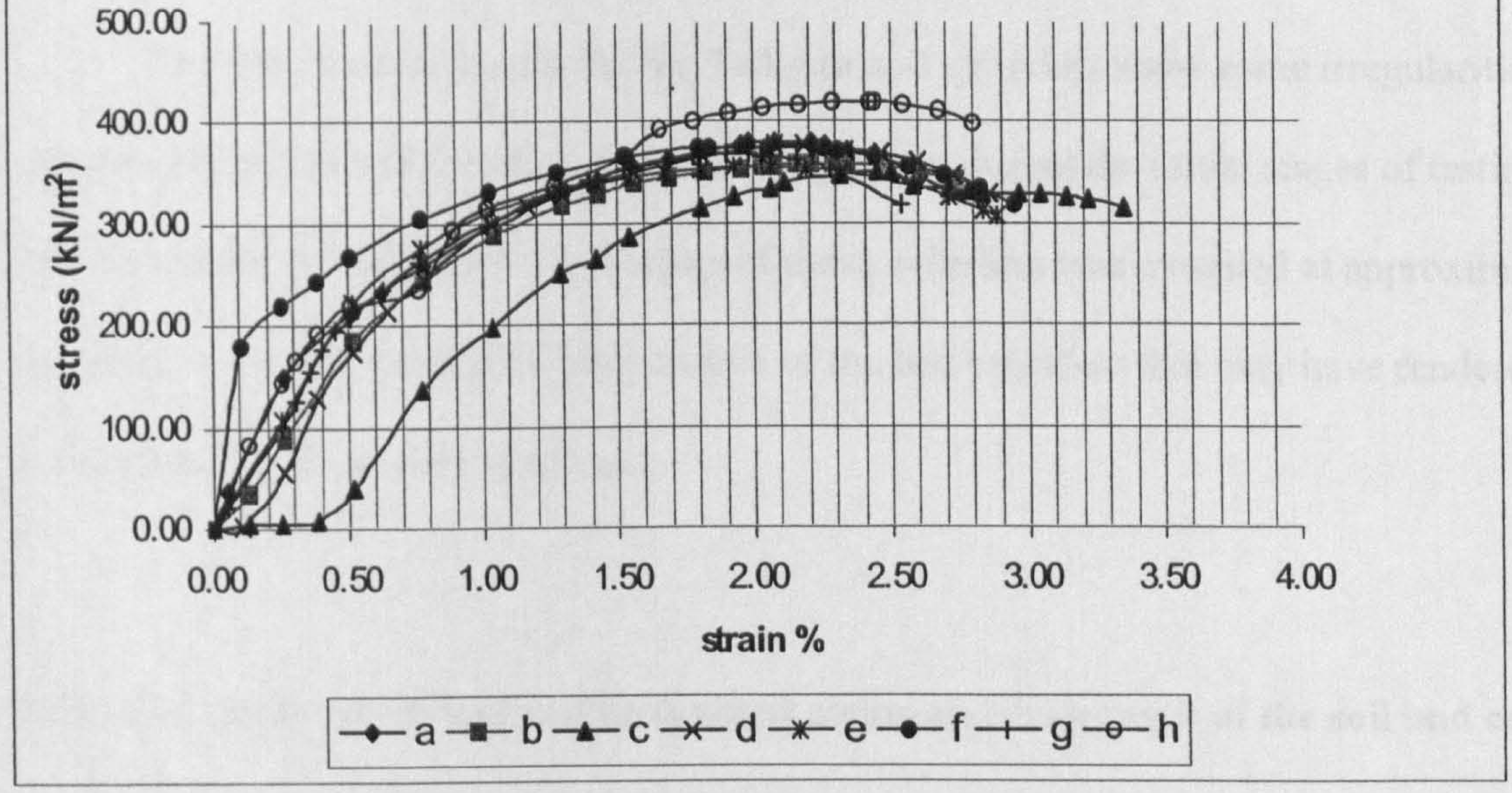
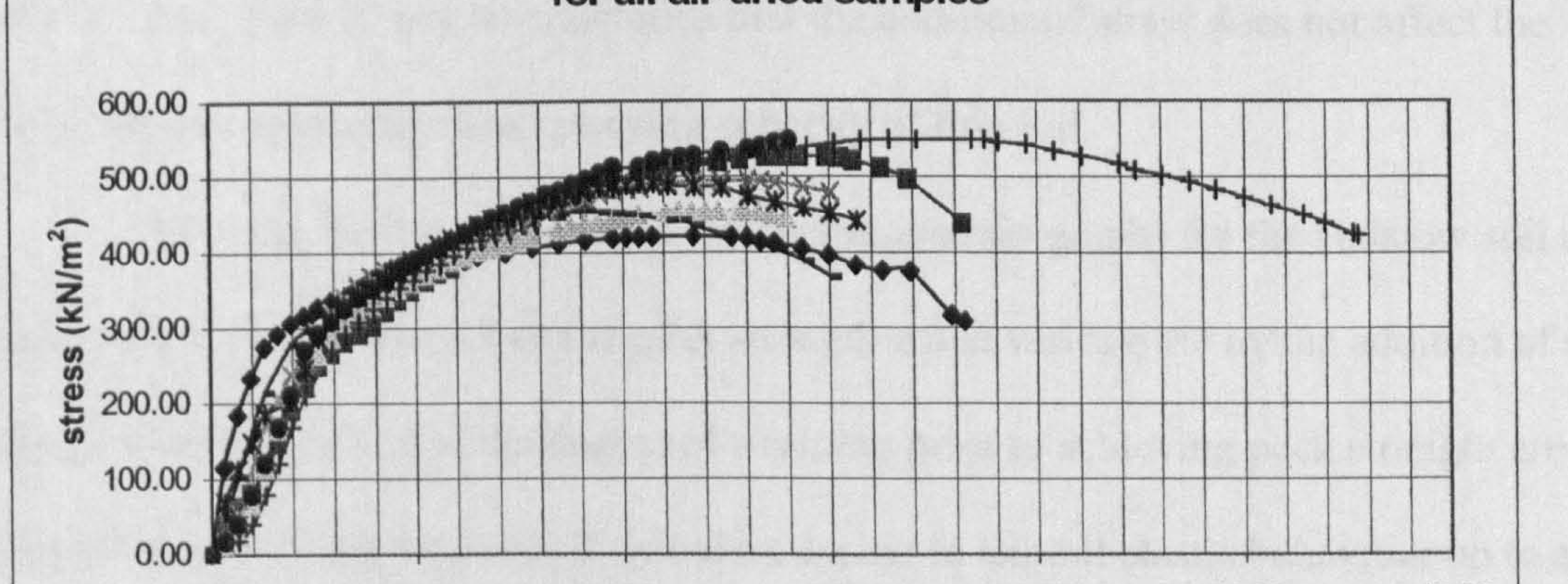


Figure 5.8 Tedburn cob cylinders - Stress versus strain graphs for all air-dried samples



As apparent from former observations of strength increases, the cob cylinders show greater variation from the mean than those determined for the testing of the soil series cylinders. This is to be expected given the randomness at which the straw fibres are free to align themselves during compaction of the cylindrical samples.

The stress/ strain graphs for the Tedburn soil cylinders show some irregularities possibly associated with bedding of the loading plates during the initial stages of testing, observe sample 'c' of Figure 5.7. Testing of these cylinders was curtailed at approximately 3% strain to prevent excessive deterioration of the test cylinders that may have rendered them unstable and prevent handling.

5.3.5. The air-dried unconfined/undrained compressive strength of the soil and cob cylinders of the Halstow Soil Series.

Considering Figures 5.9 and 5.10, it is apparent that the Halstow Soil Series fails to exhibit a notable increase in the peak stress value of unconfined compressive strength with the addition of straw to the soil matrix. Indeed the mean peak strength is shown to decrease by 1%. The variation in mean peak strength is approximately 10% regardless of the presence of the straw. Thus it may be concluded that the addition of straw does not affect the unconfined compressive load carrying capacity of this soil.

However, further observation of the stress/strain graphs for the Halstow soil and cob cylinders show that while the peak strength value varies little by the addition of straw, the yield strength, Y, and the degree of straining prior to achieving peak strength are both shown to alter. The Halstow soil cylinders appear to exhibit elastic behaviour up to an approximate value of 800kN/m^2 at 0.5 to 0.9% strain. From here elasto-plastic straining occurs with values climbing to peak around 1.4% to 1.6% strain. While this behaviour is general to the group, soil cylinder sample six shows peak strength being carried over a greater range of strain not exhibited by the other cylinders.

The cob cylinders for the Halstow series exhibit wide ranging strain values at which yield and peak strength may be achieved. Yield strength, as peak strength, varies little from that determined for the soil cylinders and lies at approximately 800kN/m^2. However the yield strains of the soil cylinders which lie between 0.5 to 0.9% are again below those exhibited by the cob cylinders at yield which range between 1.0 to 2.9 %, as suggested by Figure 5.10.

Both Figures 5.9 and 5.10 illustrate a rather abrupt increase in strength for sample '8' at 1% and 3.5% strain respectively. It is noteworthy to remember that sample '8' contains the same particular matrix for both the cob and soil cylinders as the manufacturing process adopted for individual cob cylinders utilises the 'spent' soil cylinders within a given test series, facilitating the possibility of discussing anomalies in stress/strain behaviour.

It is most probable that during elastic-plastic rotations in sample 8, a gravel particle has orientated itself in such a way as to cause an area of stress concentration which was, maintained on further work hardening as particles rotated and dislocated to support the load. While it is admittedly rather coincidental that such an occurrence should prove common to both cylinders, as the rehydration and manufacture of individual soil cylinders to form cob cylinders can only replicate the particle matrix and not the particle orientation, this would appear to be the case.

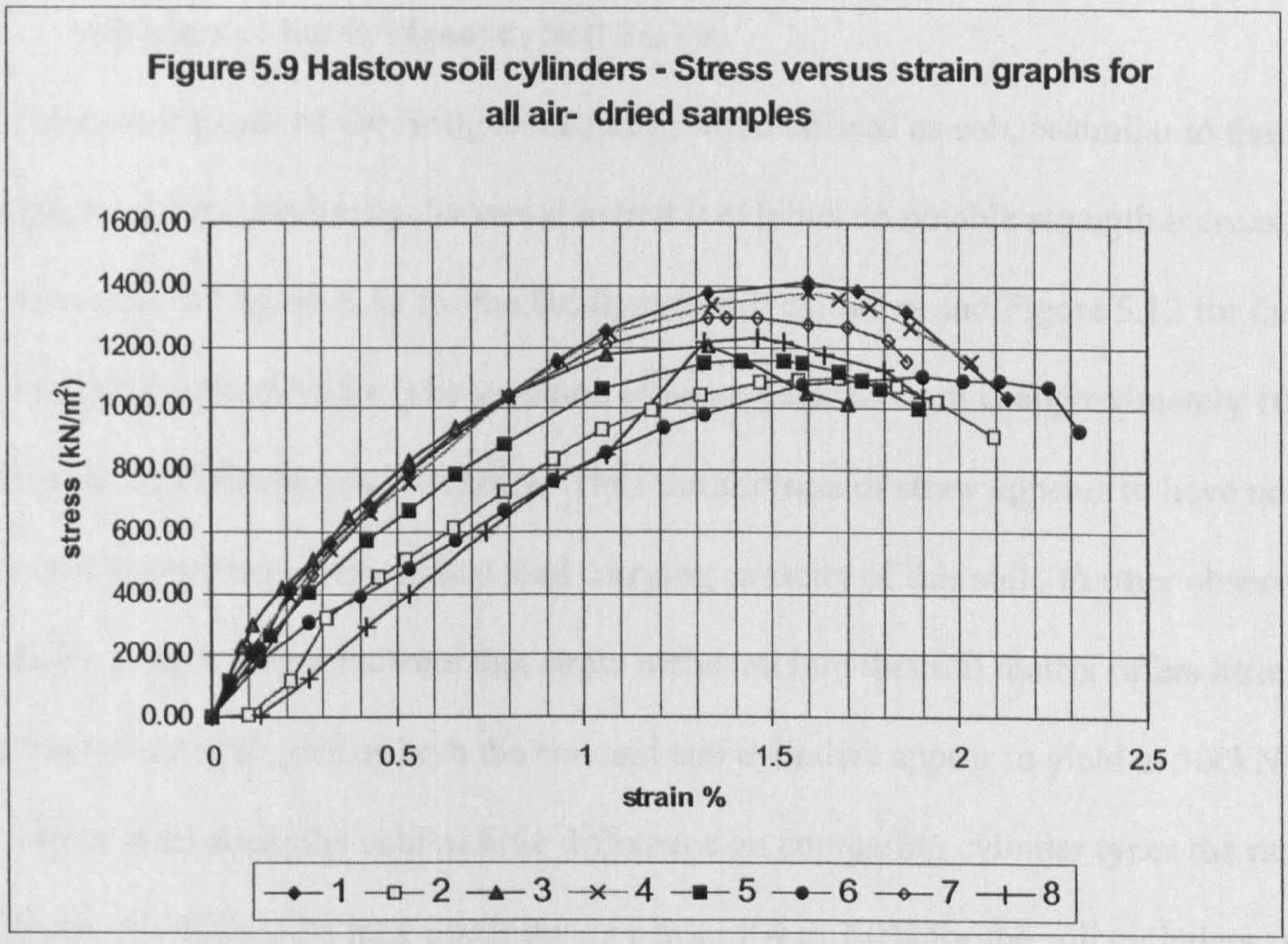


Figure 5.9 Halstow soil cylinders - Stress versus strain graphs for all air- dried samples

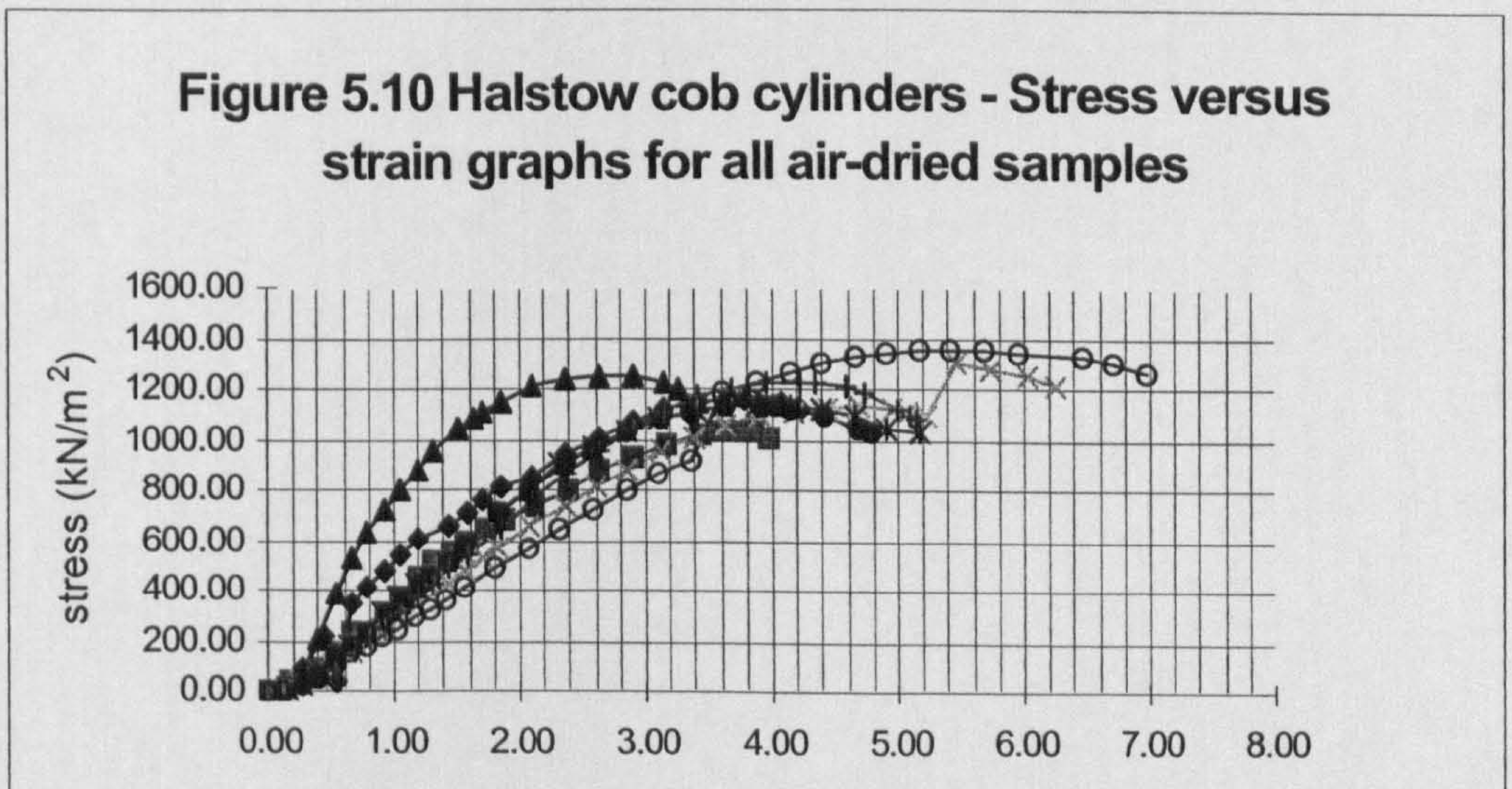


Figure 5.10 Halstow cob cylinders - Stress versus strain graphs for all air-dried samples

5.3.6. The air-dried unconfined/undrained compressive strength of the soil and cob cylinders of the Bridgnorth Soil Series.

The peak strength of the Bridgnorth series, when utilised as cob, is similar to that of the Halsow Series previously discussed in that it exhibits no notable strength increase. This is illustrated in Figures 5.11 for the Bridgnorth soil cylinders and Figure 5.12 for the Bridgnorth cob cylinder. The variation in mean peak strength is approximately 10% regardless of the presence of straw. Thus the addition of straw appears to have no affect on the unconfined compressive load carrying capacity of this soil. Further observation of yield strength values indicate that straw inclusion into this soil matrix offers little value in terms of strength gain as both the soil and cob cylinders appear to yield at 500kN/m^2.

While yield strengths exhibit little difference on comparing cylinder types the range of strains at which yield may occur do vary from 0.4 to 1.0% for the soil cylinders and 0.2 to 2.0% for the cob cylinders.

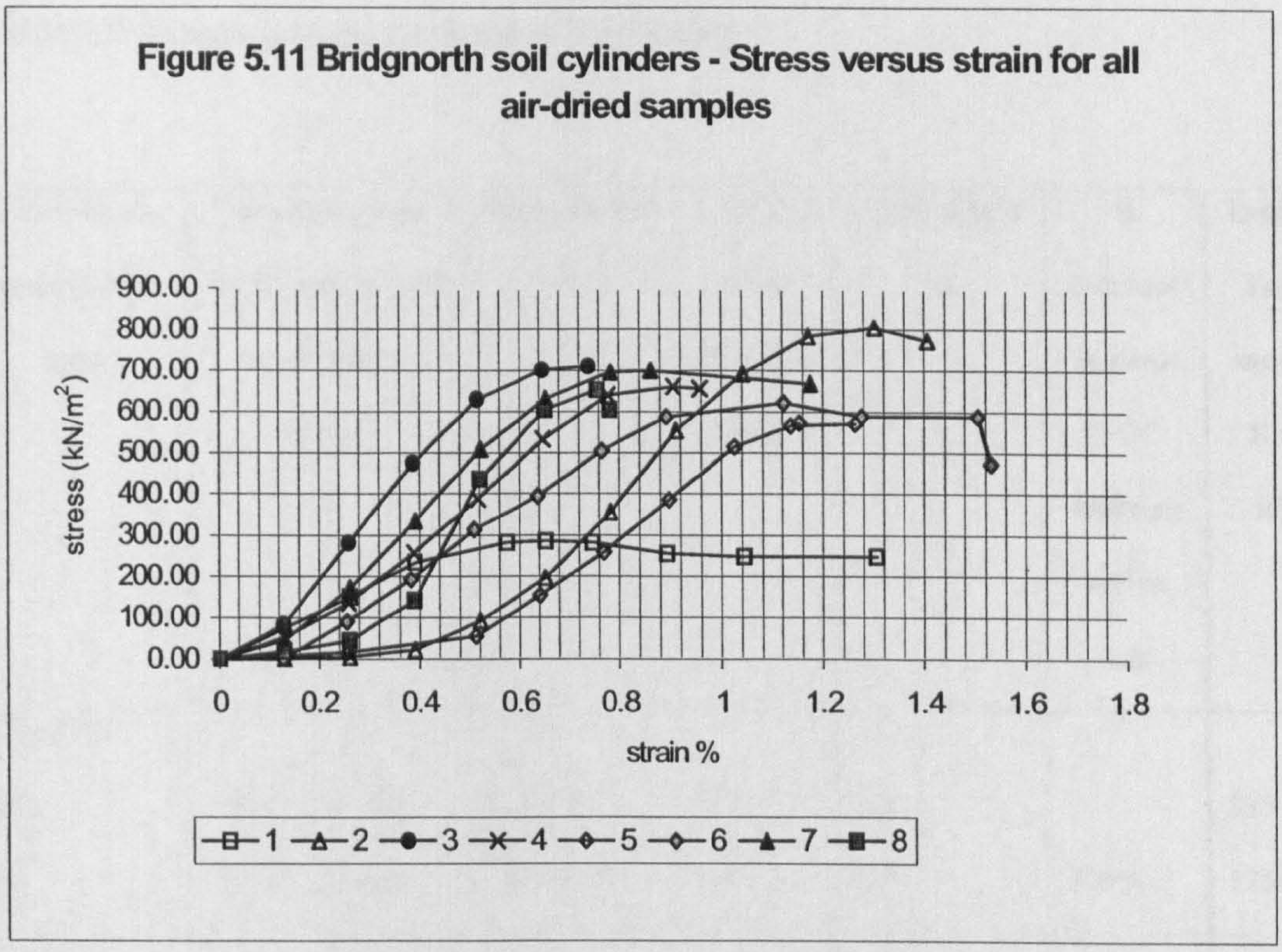


Figure 5.11 Bridgnorth soil cylinders - Stress versus strain for all air-dried samples

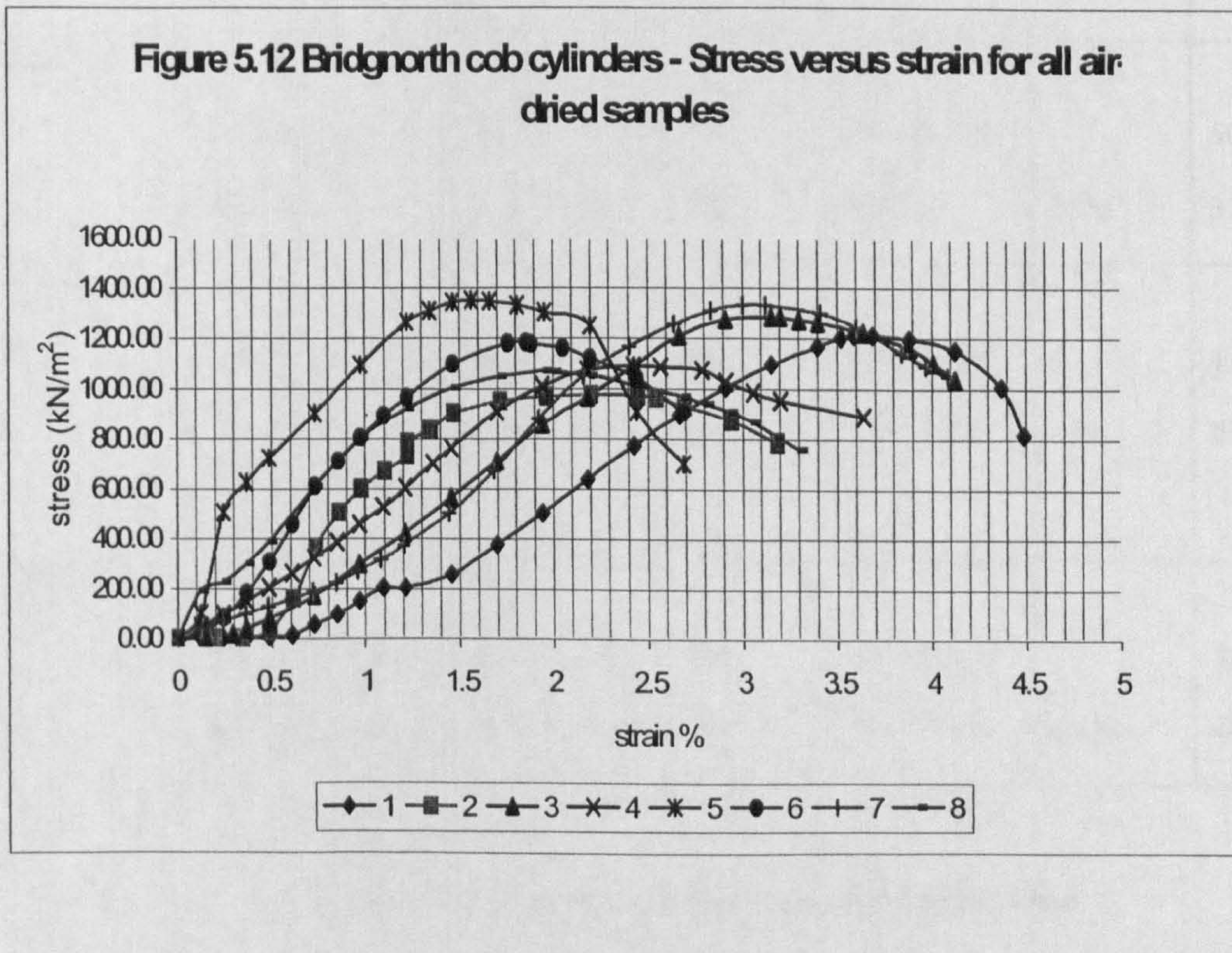


Figure 5.12 Bridgnorth cob cylinders - Stress versus strain for all air-dried samples

5.3.7 Conclusions drawn from Test Series One.

Table 5.9 summarises the findings of Test Series 1.

Soil Series and cylinder type	Average peak UCC stength and variability kN/m^2	Peak strain %	UCC Yield strength kN/m^2	Yield strain %	% increase in peak UCC utilising soil as cob	Indicative Young's modulus, E value kN/m^2
Crediton –						
soil	360.75 ± 17.55	2-3.3%	150	0.4		375
cob	721.34 ± 24.43	from 3.0%	250	0.2	100%	1250
Dunsford –						
soil	564.25 ± 27.5	1.6 to 2.8 %	260	0.4		650
cob	709.44 ± 31.68	2.25 – 6.3%	400	0.5	26%	800
Tedburn –						
soil	372.98 ± 21.7	2.2%	150	0.1 - 0.5 %		500
cob	478.92 ± 43.91	4.4 - 7.3%	280	0.85%	22%	329
Halstow –						
soil	1234.84 ± 118.87	1.4 – 1.6%	800	0.5 – 0.9%		1143
cob	1185.52 ± 95.49	2.9 – 5.0%	800	0.9 – 1.8%	-4%	593
Bridgnorth –						
soil	1030.76 ± 125.14	0.75 – 1.3%	500	0.4 – 1.0 %		714
cob	1095 ± 102.74	1.5 – 3.75 %	500	0.4 – 2.0 %	6.1%	417

Table 5.9. Summary Table for Test Series One

For the five soil series under investigation, all five samples were shown to have higher or equal yield strengths in the cob matrix condition when compared with the soil matrix condition. Three soils exhibited an increased value of peak compressive strength, when tested as a cob matrix and compared to the soil matrix only condition. Only the Bridgnorth and Halstow soil series failed to illustrate any marked change in the value of peak strength when utilised to form cob, with only the Crediton and Dunsford Soil Series exhibiting statistically significant increases. However, all the cob samples tested indicated that yield strength and, where applicable, peak strength, occurred at higher strains than those experienced by the soils when utilised as soil only cylinders. Consequently for soil series' illustrating no marked strength increase between cylinder types, this marked shift in the ability of these samples to achieve higher strain rates results in a decrease in the value of the Young's modulus, E, obtained. Table 5.9 indicates this decline in the value of E for the Tedburn, Halstow and Bridgnorth soil series when comparing soil cylinders to cob cylinders. However, the E value of the Crediton and Dunsford cob cylinders exceeds that of its soil-only counterpart due to the dramatic increase in stress realised at smaller strains for each of these soil series. Discussing the variation in the behaviour of these samples by reference to the changes in E, necessitates clarification of the parameter primarily influencing this change, stress or strain, as the primary influence appears to vary depending on the soil matrix. It is therefore more useful to focus a discussion about the individual changes to the parameters that define E when comparing the soil to the cob cylinders as opposed to the changes in the value of E itself. Chapter 6 discusses the influential factors that define the stress/ strain behaviour of a soil/cob matrix.

5.4 Results from Test Series 2: the unconfined/undrained compressive strength of soil and cob cylinders tested at manufacture.

Sections 4.4 and 4.3.3.2 describe the manufacture and procedure for the determination of the unconfined/undrained compressive strength values applicable to each of the five soil series, soil and cob cylinders, tested at the time of manufacture. In each instance, eight samples were produced and tested to determine the variation that may also be associated with these values. To ensure that variation is not a factor of the cylindrical sample manufacture technique, standardisation of the compactive effort used to produce the cylinders has resulted in the adoption of the 7-blow Proctor, as outlined in Section 4. 2.3.1.

Table 5.10 illustrates the effectiveness of a standardised compaction technique in achieving replication of the density of the cylinders produced for each test-group at the point of manufacture. Good homogenisation of the material matrix during manufacture, as highlighted in Section 4.2.3.1, is also supported by the results contained in Table 5.10 indicated by the small values of standard deviations in moisture content between test cylinders. Thus these values validate replication in the samples produced. In validating the replication of cylindrical sample groups, manufacture controls can be deemed as satisfactory. Sample manufacture data for the Halstow Soil Series cylinders within the each test-group may be found in Appendix 7.

During manufacture of the cob samples for the Test Series Two tests (see Section 4.4.) the initial manufacture moisture contents of the soil and cob cylinders was intentionally targeted at the moisture contents adopted for Test Series One. This was attempted in order to facilitate a direct comparison between the between the wet and dry strengths of soil cylinders and cob cylinders. However this does not accommodate soil sampling variations, permitting moisture content adjustments to ensure workability of mix and alignment of the manufactured cylinders as discussed in Chapter 4. Rehydration of the soil cylinders prior to the addition of straw to produce cob cylinders, was executed by targeting the manufacture moisture content of the soil cylinders to facilitate cross-comparison between soil and cob cylinders. Table 5.10 illustrates the success gained in achieving this.

Cylindrical sample group	Mean bulk density @ manufacture (kN/m³)	Mean moisture content @ manufacture (% by weight)	Mean bulk density @ test (kN/m³)	Mean moisture content @ test (% by weight)
Crediton soil cylinders	2166 ± 10.89	14.77 ± 0.15	2156 ± 31.82	14.77± 0.15
Crediton cob cylinders	2089 ± 22.10	14.78 ± 0.2	2081.7 ± 23.4	14.31± 0.27
Dunsford soil cylinders	2130 ± 7.52	17.39 ± 1.07	2131.6 ± 19.1	16.9 ± 1.30
Dunsford cob cylinders	2034.52 ± 7.36	17.90 + 0.74	2037.02 ± 4.92	17.28 ± 1.14
Tedburn soil cylinders	1889.42 ± 6.52	30.87 ± 0.35	1893.4 ± 10.38	29.41 ± 0.72
Tedburn cob cylinders	1857.6 ± 5.12	30.04 ± 0.27	1847.53 ± 8.36	29.13 ± 0.48
Halstow soil cylinders	1850.3 ± 7.2	33.55 ± .0.18	1845.86 ± 8.4	32.76 ± 0.27
Halstow cob cylinders	1811.6 ± 16.72	34.44 ± 0.30	1806.85 ± 16.94	31.64 ± 0.47
Bridgnorth soil cylinders	2209 ± 10.91	10.51 ± 0.05	2203.5 ± 7.4	10.23 ± 0.04
Bridgnorth cob cylinders	2042.8 ± 11.7	10.72 ± 0.23 (5 of 8)	2028.03 ± 11.6	10.13 ± 0.32 (5 of 8)

Table 5.10. The statistical means and deviations in the manufacture/ test densities and moisture contents for each sample group in Test Series 2 tests.

From Table 5.10 it should be noted that the average moisture contents for the Bridgnorth soil series at manufacture and test are obtained from only five of the eight samples tested. Due to partial collapse of these cylinders on handling, post-test, material was lost from the cylinder and only five in-tact cylinders remained from which to achieve accurate measurements. In order to assess the significance of the variations suggested in Table 5.10, and test the null hypothesise which assumes all cylinders to be exactly the same irrespective of Soil Series, moisture content, bulk density or cylinder group (soil or cob), an analysis of variance was executed on this data.

5.4.1 Test Series Two ANOVA

On comparing the soil cylinder/ cob cylinder condition for each soil series, moisture content and bulk density at manufacture and moisture content and bulk density at test were analysed to determine whether differences in these values within sample groups were significant. Four two-way ANOVA tests were run – one for each for each dependent measure (moisture content and bulk density at manufacture and moisture content and bulk density at test). For each two way ANOVA the independent variables were soil type and straw condition. The results of each two-way ANOVA were reported separately. The ANOVA tables for each analysis are reported in Tables 5.11, 5.12, 5.13 and 5.14.

For all four Two-way ANOVAs, there were main effects of soil type and of cylinder type. As expected, there were significant differences between values for all four dependent measures across soil series. There was also a main effect of cylinder type for all four dependent measures. Values for all four dependent measures were higher for the cob cylinders than for the soil cylinders. However, of most interest are the significant interactions. Tukey HSD tests were used as a means of follow-up analyses for these interactions.

Source	df and F value	MSe	p-value
Soil (S)	$F(4, 70) = 1925.00$	177.31	$p < 0.000001$
Cylinder type (C)	$F(1, 70) = 741.671$	177.31	$p < 0.000001$
(S) x (C)	$F(4, 70) = 59.90$	177.31	$p < 0.000001$

Table 5.11 – Results of Two-Way ANOVA, dependent measure Bulk Density at Manufacture, Test Series Two.

Source	df and F value	MSe	p-value
Soil (S)	$F(4, 67) = 15450.00$	0.09	$p < 0.000001$
Cylinder type (C)	$F(1, 67) = 44.66$	0.09	$p < 0.000001$
(S) x (C)	$F(4, 67) = 36.62$	0.09	$p < 0.000001$

Table 5.12 – Results of Two-Way ANOVA, dependent measure Moisture Content at Manufacture, Test Series Two.

Source	df and F value	MSe	p-value
Soil (S)	$F(4, 70) = 1681.83$	196.70	$p < 0.000001$
Cylinder type (C)	$F(1, 70) = 720.98$	196.70	$p < 0.000001$
(S) x (C)	$F(4, 70) = 60.45$	196.70	$p < 0.000001$

Table 5.13 – Results of Two-Way ANOVA, dependent measure Bulk Density at Test, Test Series Two.

Source	df and F value	MSe	p-value
Soil (S)	$F(4, 67) = 7500.34$	0.18	$p < 0.000001$
Cylinder type (C)	$F(1, 67) = 4.69$	0.18	$p < 0.05$
(S) x (C)	$F(4, 67) = 6.73$	0.18	$p < 0.001$

Table 5.14 – Results of Two-Way ANOVA, dependent measure Moisture Content at Test, Test Series Two.

Follow-up analyses for bulk density at manufacture showed significant differences between cylinder types for all soil series (all at $p < 0.001$). Follow-up analyses for moisture content at manufacture showed significant differences between cylinder types for only the Tedburn and Halstow Series (both at $p < 0.001$). Follow-up analyses for bulk density at test showed significant differences between cylinder types for all soil series (all at $p < 0.001$). Follow-up analyses for moisture content at test showed significant differences between cylinder types for only the Halstow Series ($p < 0.001$). For this series the mean moisture content at test was 32.76 % for the soil samples compared with a mean of 31.65 % for the cob samples.

The results of the analyses show that manufacture moisture contents of the Bridgenorth, Crediton and Dunsford series were deemed controlled between the soil and cob conditions. At test moisture contents they were even more controlled, with only the

Halstow Series showing a significant difference between the soil and cob conditions (although the effect size was rather small). For bulk density at manufacture difference between the soil and cob conditions were present for all soil series. Finally, for bulk density at test, differences were significant for all soil series, as expected.

The next stage in the analyses was to test whether there was a significant difference in compressive strength as a function of cylinder type. In order to test this, it was envisaged that a two-way ANOVA would be used where the independent variables were soil type and cylinder type, and the dependent measure as compressive strength. However, given the results of the two-way ANOVAs reported above for bulk density at manufacture and at test, and moisture content at manufacture and at test, it was deemed necessary to include bulk density at test as a covariate in the analysis. Although the Halstow Series had illustrated that its moisture content at test was not controlled, the size of the difference between the moisture contents at test comparing the soil and cob cylinders was small enough to omit this parameter from the analysis.

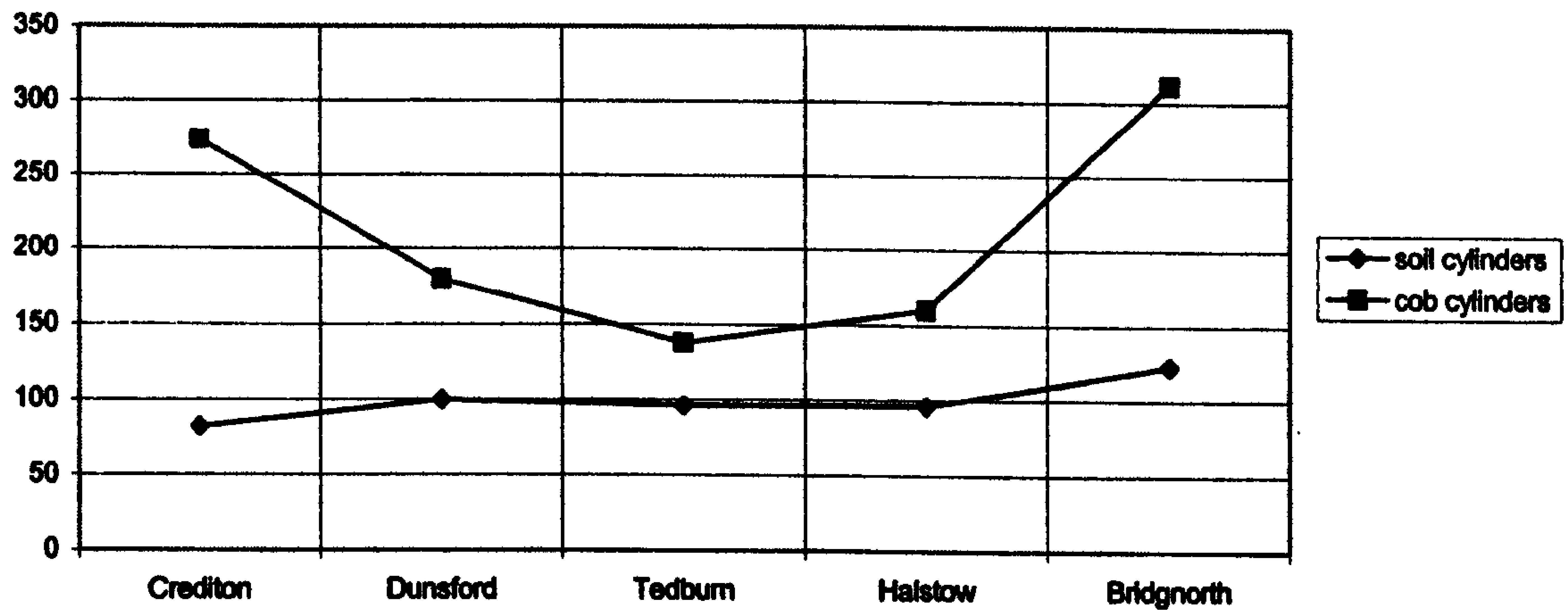
To summaries, a two-way ANCOVA was run to test the effect of soil series and cylinder type on the peak compressive strength values. The independent variables were soil series and cylinder type, the covariate was bulk density at test, and the dependent variable was compressive strength. The results of the two-way ANCOVA are displayed in Table 5.15.

Source	df and F value	MSe	p-value
Soil (S)	$F(4, 67) = 18.64$	465.89	$p < 0.000001$
Cylinder type (C)	$F(1, 67) = 47.46$	465.89	$p < 0.000001$
(S) x (C)	$F(4, 67) = 24.52$	465.89	$p < 0.000001$

Table 5.15 – Results of Two-Way ANCOVA, dependent measure Peak Compressive Strength at Test

Table 5.15 shows that there was significant main effect of soil series, as expected. Of most interest were the main effect of cylinder type and the interaction between soil series and cylinder type. Across soil series, cob cylinders had a mean peak compressive strength value of 211 kN/m^2 compared with a mean value of 100 kN/m^2 for the soil cylinders. The interaction between soil type and cylinder type was also significant. Follow-up analysis given the significant interaction found that the effect of cylinder type was significant for all soil types ($p < 0.001$), although these differences were more dramatic for some soil series compared to others. The mean values for this interaction are displayed in Table 5.2, and plotted in Figure 5.13 for each soil series and cylinder type.

Figure 5.13 Plot of means for Test Series 2, 2-way Interaction
$F(4,67) = 24.52$; $p<.0000$



This result gives further weight to the discussion concerning the role of straw within the cob matrix. These tests simulate the cob matrix in the initial stages of cob construction (as discussed in Chapter 1) and quantify the significant strength gains achieved through the addition of straw to particular soil matrixes. The significance and magnitude of these material strength increases have not previously been identified through research.

The results of each test group within this test series are plotted in the form of stress/strain graphs produced to illustrate the development of strength within each cylinder when tested at the point of manufacture (see Figures 5.14 to 5.23 inclusive). Unconfined compression testing is carried out up to the point where further testing will result in the structural deterioration of the sample on handling. In the case of the Bridgnorth Series three samples were subject to some deterioration post-test as a result of over-stressing.

5.4.2 The unconfined/undrained compressive strength of the Crediton Series soil and cob cylinders, tested at point of manufacture.

Consider the stress strain graphs for the Crediton soil and cob cylinders, Figures 5.14 and 5.15 respectively, and Table 5.2. The Crediton soil cylinders are shown to develop an approximate yield strength of 55kN/m^2 at around 2.75% strain which then peaks at 82kN/m^2 at approximately 5% strain. Alternatively the Crediton cob cylinders develop their full yield strength of 200 kN/m^2 at approximately 4.3% strain with an average peak stress of 274 kN/m^2 achieved at an approximate strain of 12.7%.

In contrast to the Crediton Test Series One results for the testing of air-dried cylinders, the addition of straw to the soil matrix to form cob, does not appear to influence the qualitative path which would be used to describe strength development over increasing strain. This remains common to both. Quantatively however, the addition of straw to this matrix is again reflected in the UCC testing of the respective soil and cob matrices of this soil series.

Figure 5.14 Crediton soil cylinders -Stress versus strain for all samples, tested at point of manufacture

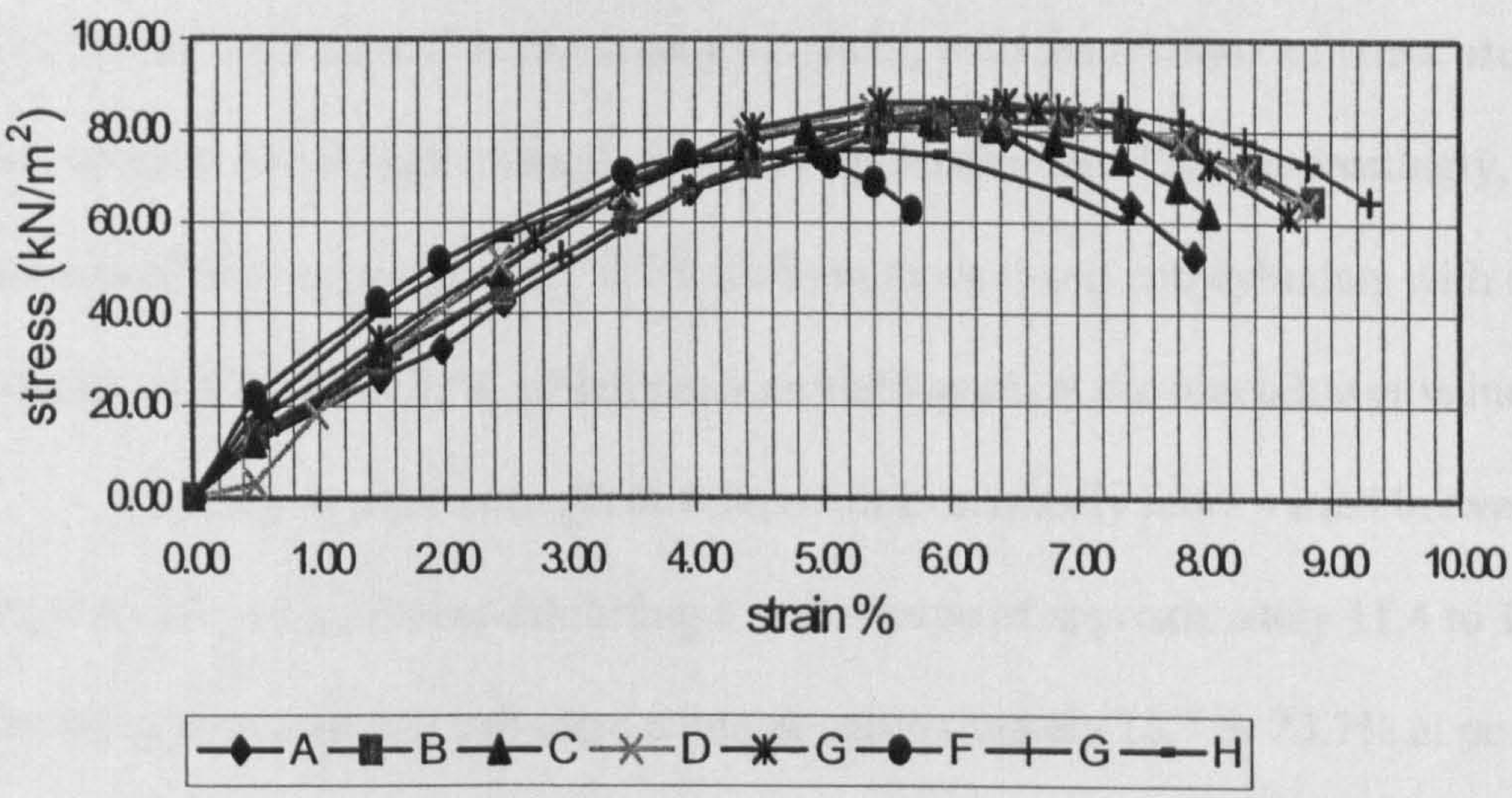
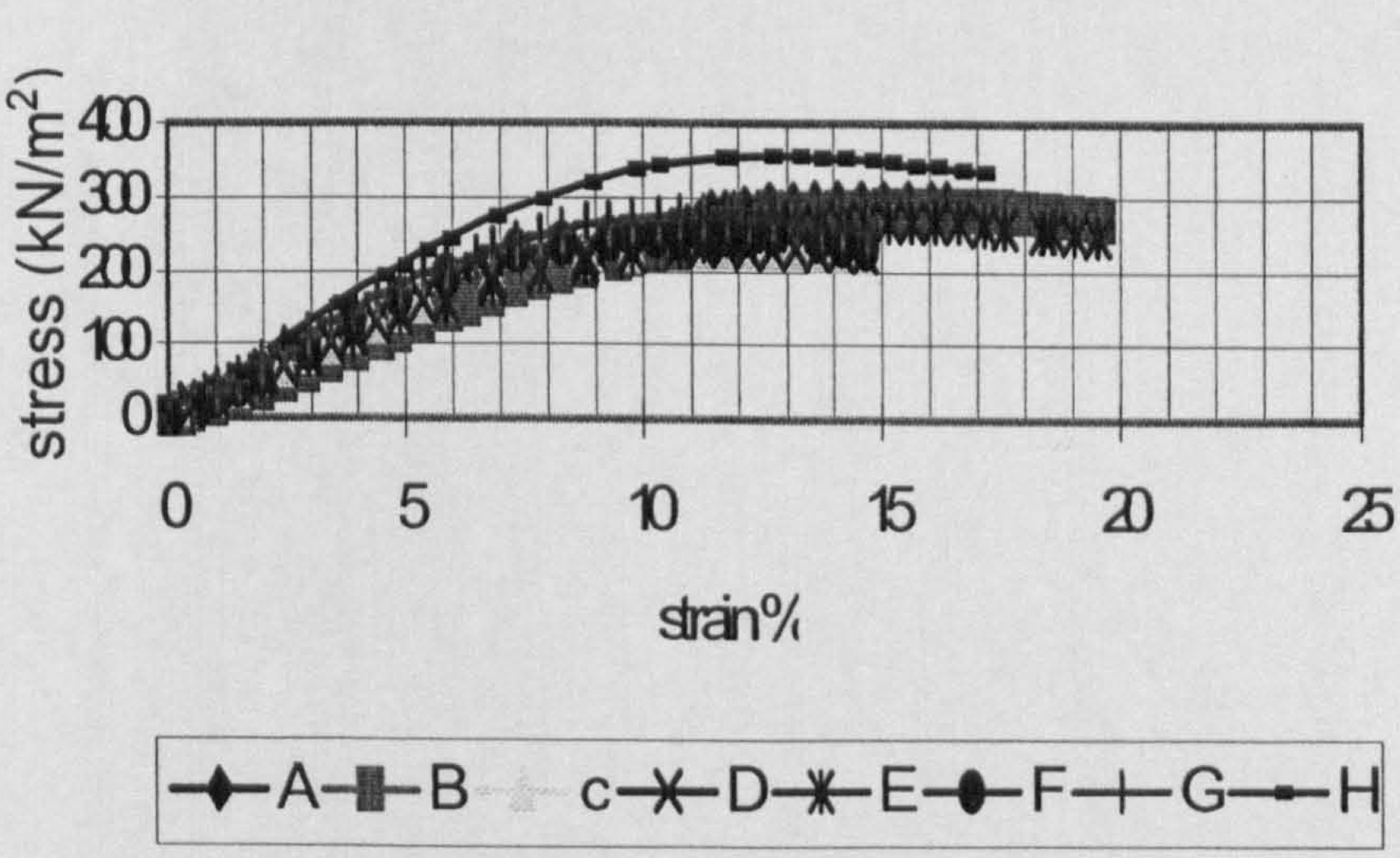


Figure 5.15 Crediton cob cylinders - Stress versus strain for all samples, tested at point of manufacture



5.4.3 The unconfined/undrained compressive strength of the Dunsford Series soil and cob cylinders, tested at point of manufacture.

Test Series Two results for the Dunsford Series soil and cob samples, are illustrated by the stress/strain graphs of Figures 5.16 and 5.17 respectively. These results together with those of Table 5.2 show the soil-straw matrix of the cob cylinders' to be decidedly stronger than that of its soil counterpart. Strength gains at yield, with the addition of straw are in the region of 60%, while peak strength gains are approximately 79%. Interestingly, yield strain remains similar at approximately 7.5% for both the soil and cob cylinders with the exception of soil cylinder 'b' which reaches yield strain at the much lower value of 0.25%.

Straining at peak strength development is markedly more varied between cylinder types with the soil cylinders exhibiting a strain value of approximately 11.4 to 17.7% at peak stress, while the cob cylinders strain at approximately 18.7 to 23.7% at peak stress. The cob cylinders are shown to continue straining with little decline in stress until testing ceased at around 30% strain.

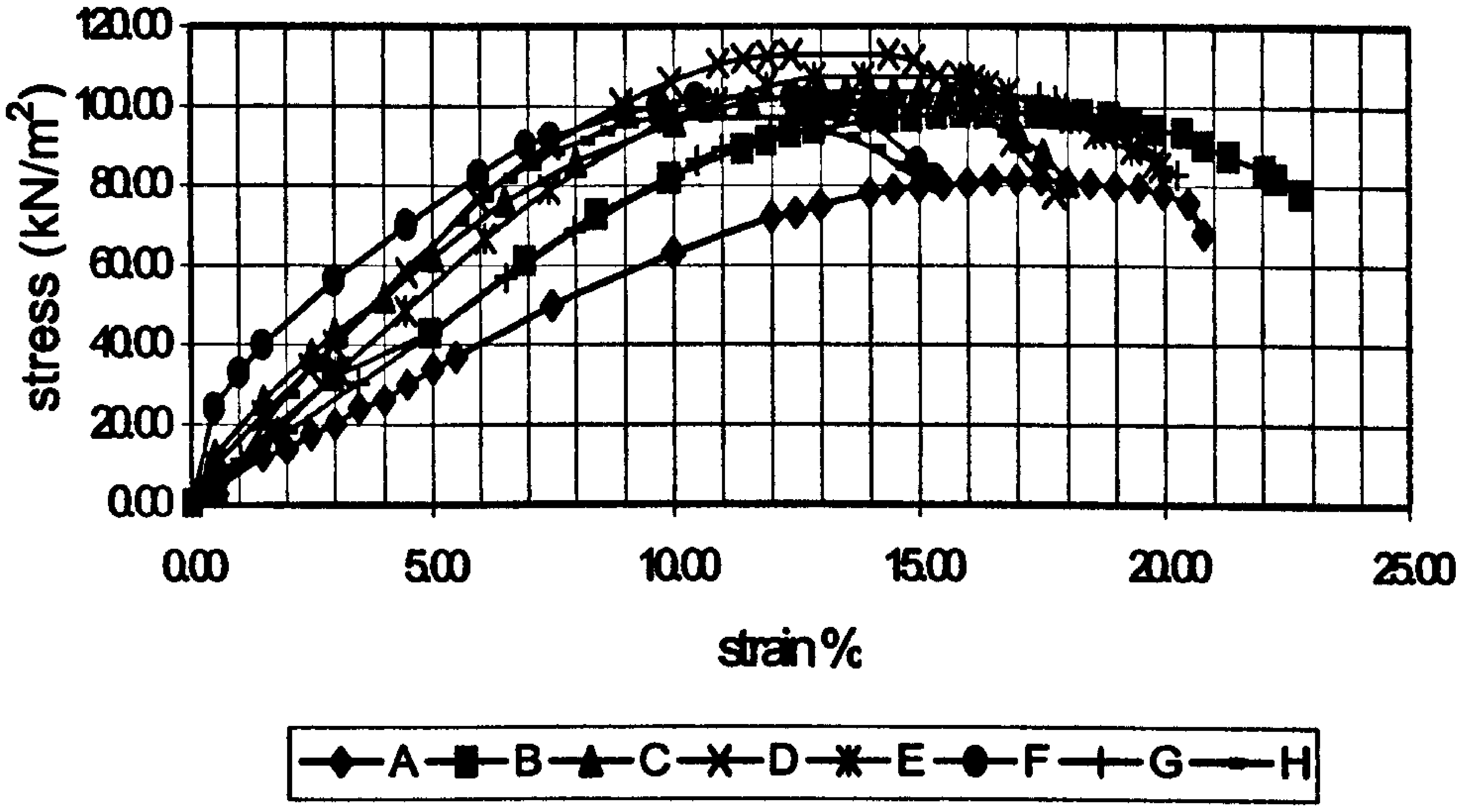


Figure 5.16 Dunsford soil cylinders - Stress versus strain graphs for all samples, tested at the point of manufacture.

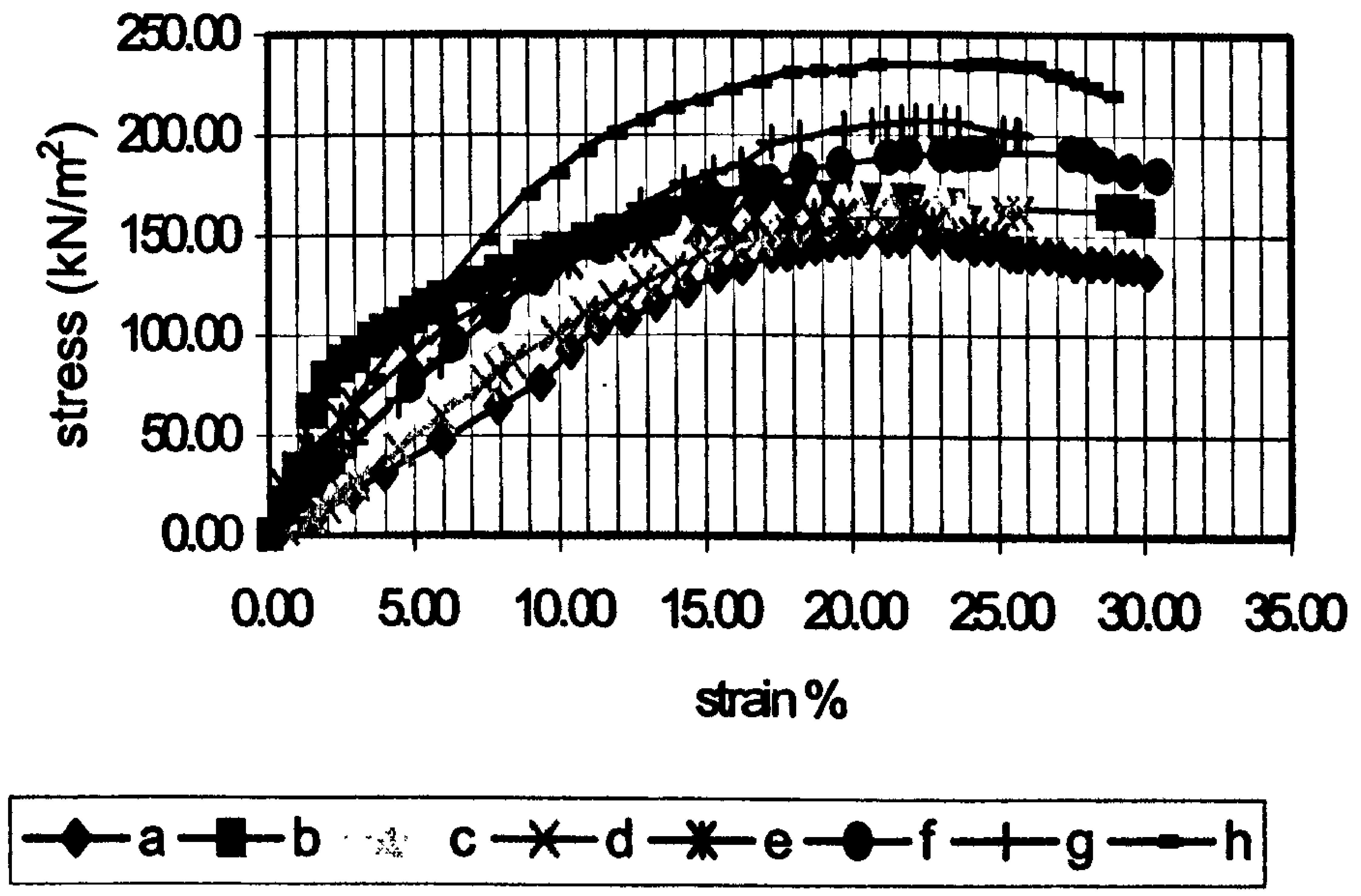


Figure 5.17 Dunsford cob cylinders- Stress versus strain graphs for all samples, tested at point of manufacture

5.4.4 The unconfined/undrained compressive strength of the Tedburn Series soil and cob cylinders, tested at point of manufacture.

Figure 5.18 illustrates the Tedburn Series soil cylinders stress/strain curve. The behaviour of sample 2 is clearly anomalous since it is not reflected by its cob counterpart. Generally, the graphs show samples, which yield at approximately 30kN/m^2, straining at 2.5%, and exhibit a peak stress of 96.4 kN/m^2 at 11-14% strain. The curvature of this graph at peak stress is such that the strength gains under increasing load are relatively large on approaching peak strength and likewise the decline in strength is relatively rapid once peak strength is achieved. Thus the strain range defining this transition period in the graph is between 3 to 5%. Yield strength lies between 16 to 50 kN/m^2 at strains ranging between 0.6 to 3.2%.

For the Tedburn cob samples, shown in Figure 5.19, the peak stress of 138kN/m^2 develops at particularly large strains (18.6 to33.3%) with cylinder sample 1 never actually attaining peak stress, but exhibiting the behaviour akin to the soil on the wet side of critical as defined in Section 5.2, Figure 5.1. Yield strengths for these cylinders are slightly above that achieved by the soil cylinders and show an approximate value of 24-65 kN/m^2, straining at 1.8 to 3.6%.

Figure 5.18 Tedburn soil cylinders - Stress versus strain for all samples, tested at point of manufacture

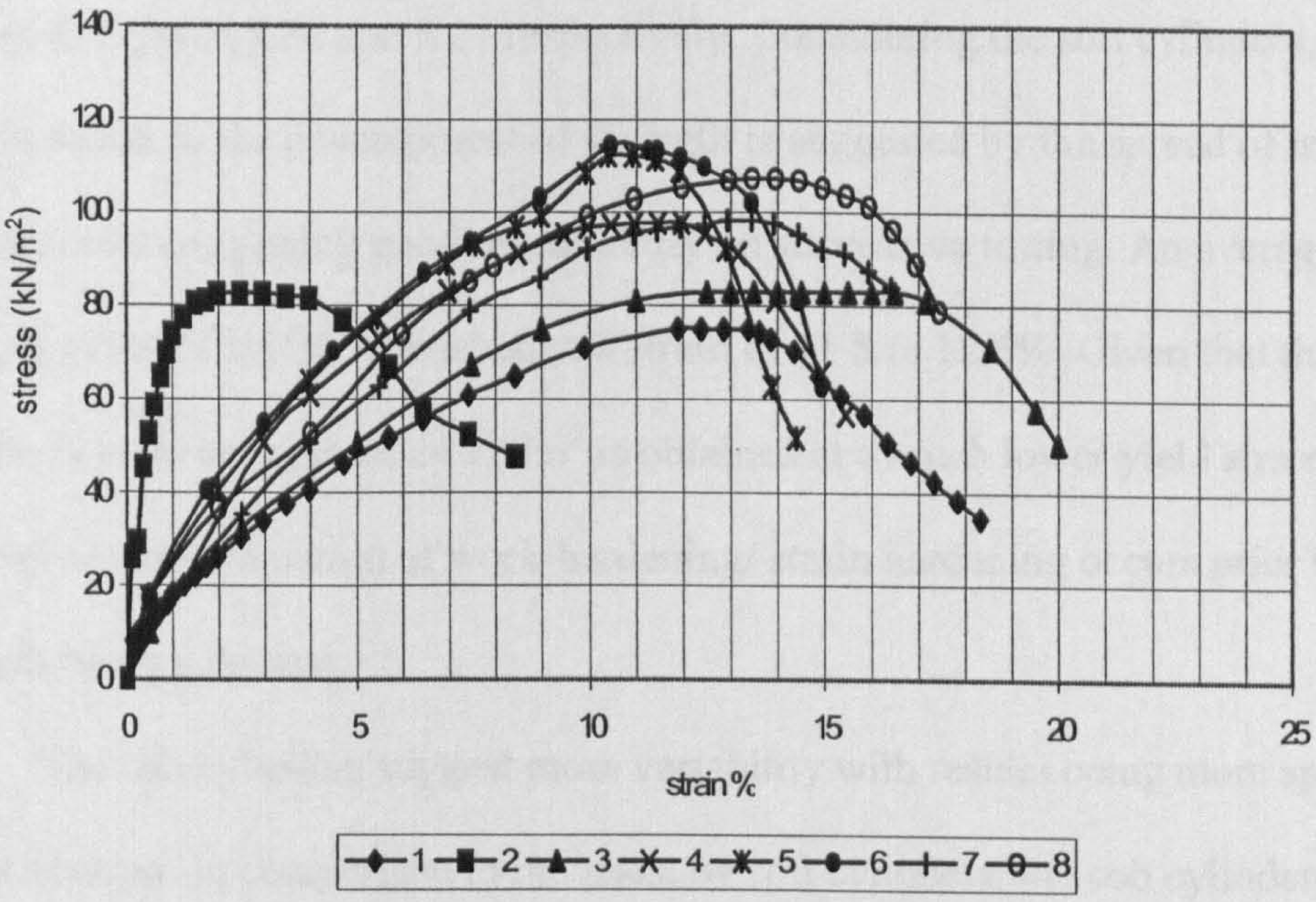
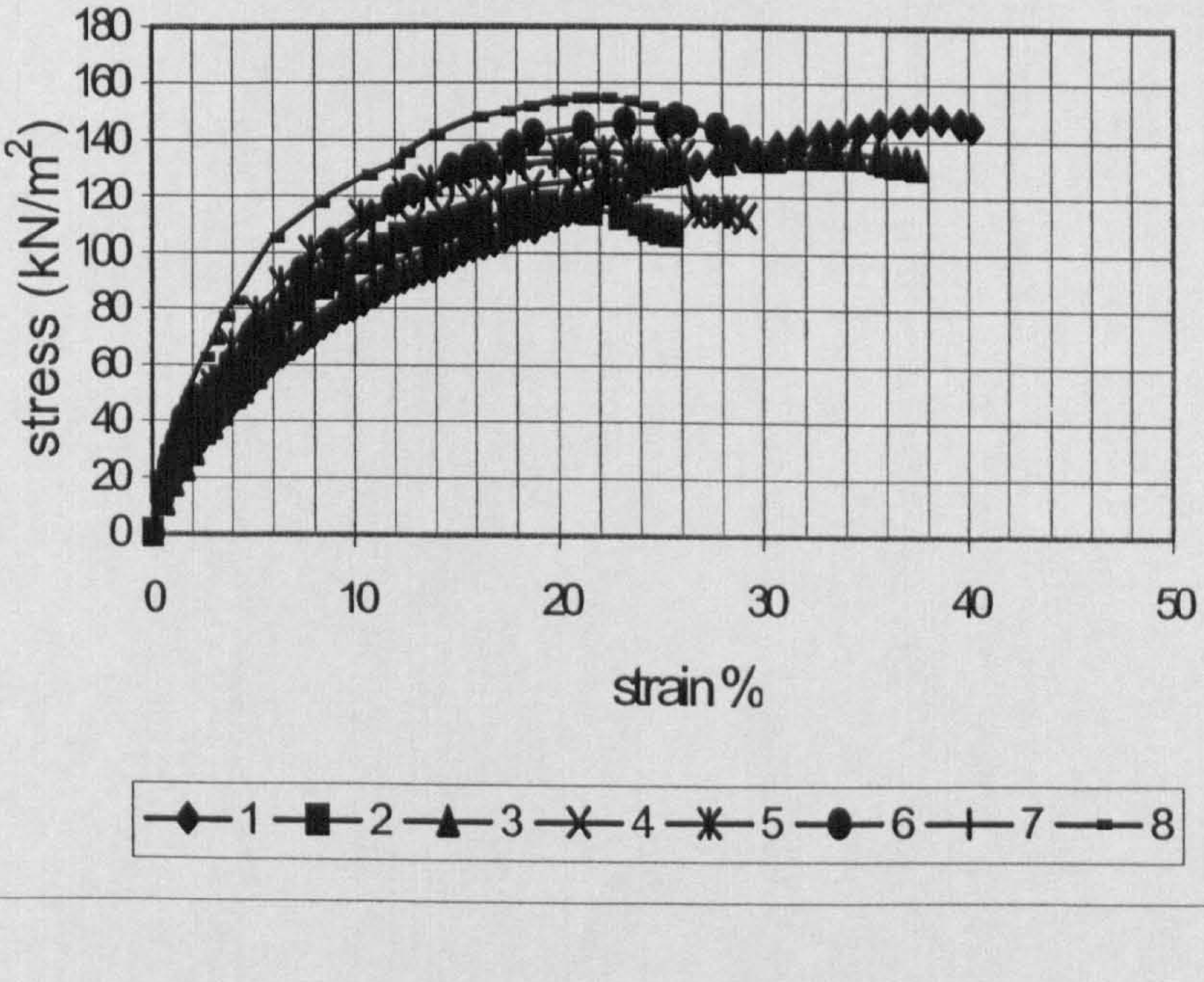


Figure 5.19 Tedburn cob cylinders -Stress versus strain graphs for all samples, tested at point of manufacture



5.4.5 The unconfined/undrained compressive strength of the Halstow Series soil and cob cylinders, tested at point of manufacture

The stress/strain development in the soil and cob cylinders for the Halstow Soil Series can be seen in Figures 5.20 and 5.21 respectively. Considering the soil cylinders, it appears that little variation in the development of strength is suggested by the spread of individual cylinder plots suggesting good repeatability on successive testing. An average peak UCC strength of 96.22 kN/m^2 is reached at a strain of 11.8 to 12.6%. Given that the soil cylinder's yield strength of 24 kN/m^2 is obtained at a much lower yield strain of 1.6% a relatively extensive period of work-hardening/ strain hardening occurs prior to peak strength being achieved.

The cob cylinders suggest more variability with results being more spread over the graphic output. In comparison to the Halstow soil cylinders, the cob cylinders exhibit a general increase in strength. However the peak strength is little distinguished amid a plateau of values of similar magnitude, of the order of 159kN/m^2, which occurs at about 20% strain. The yield strength of the cob cylinders is in the order of 30 to 60 kN/m^2 straining between 0.9 to 2.6% which suggests little variation from the yield strain values of the soil cylinder.

Figure 5.20 Halstow soil cylinders - Stress versus strain graphs for all samples, tested at point of manufacture

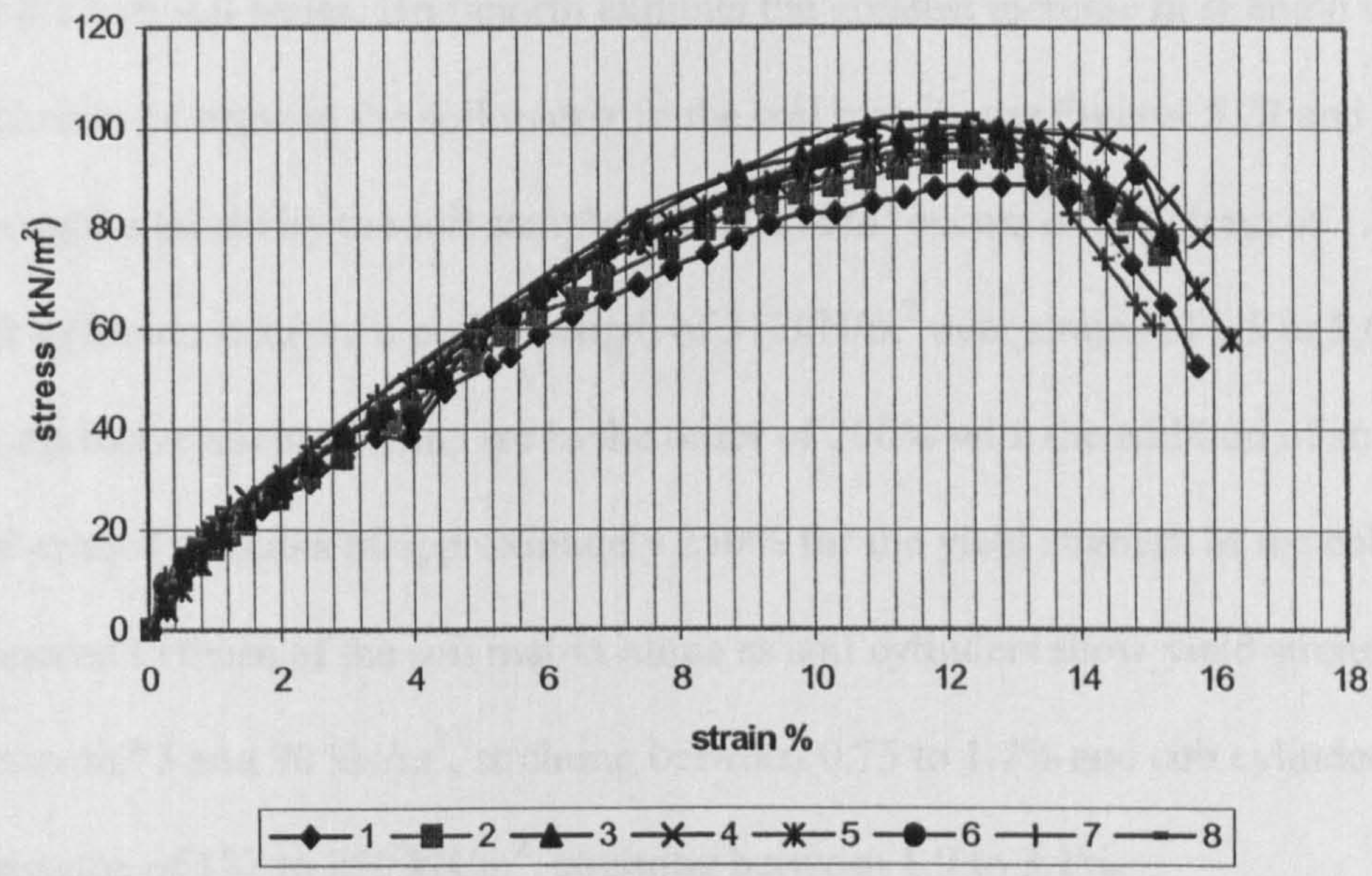
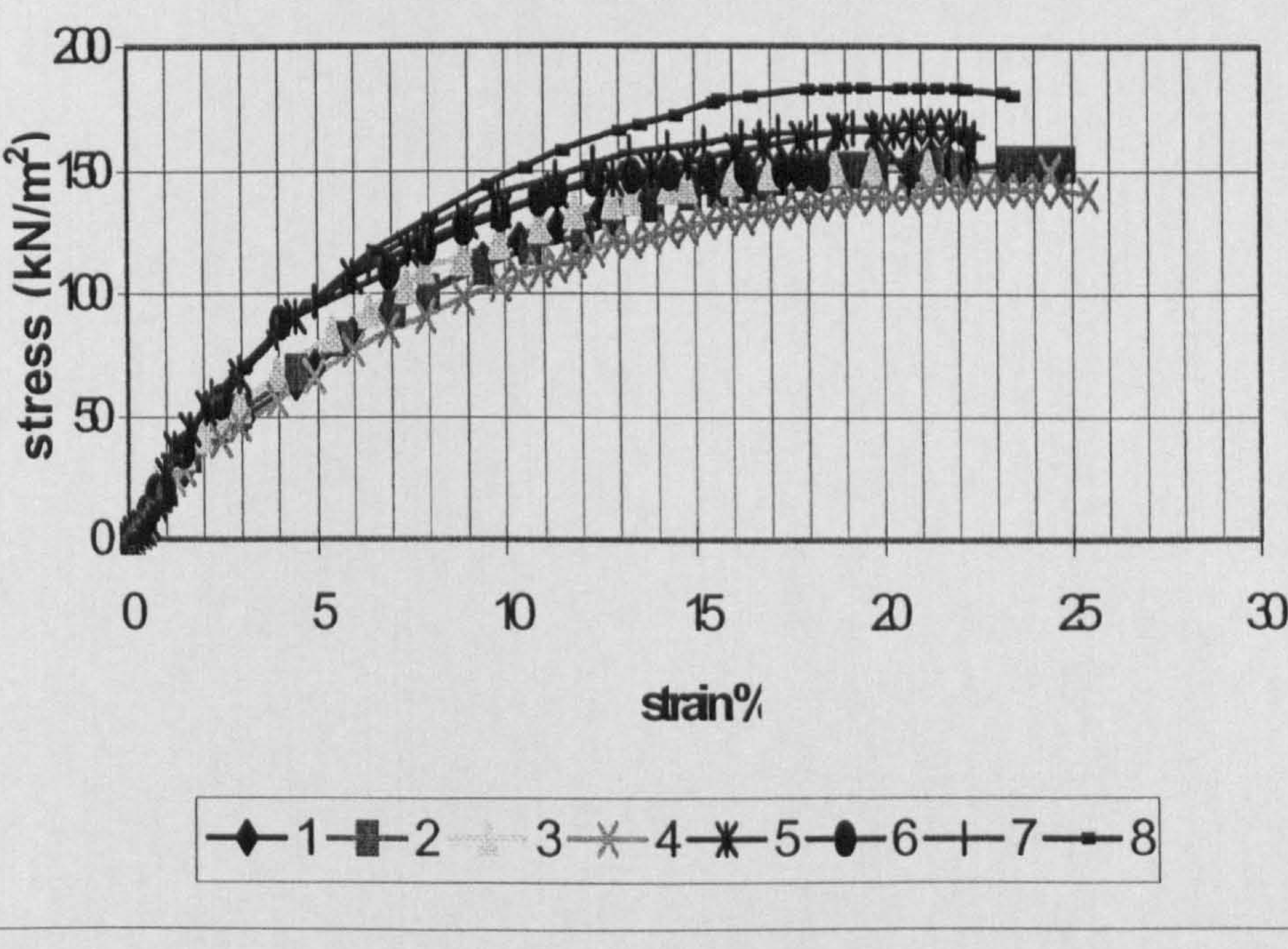


Figure 5.21 Halstow cob cylinders - Stress versus strain graphs for all samples, tested at manufature



5.4.6 The unconfined/undrained compressive strength of the Bridgnorth Series soil and cob cylinders, tested at point of manufacture

Of the five soil series, Bridgnorth exhibits the greatest increase in strength with the inclusion of straw in the soil matrix in the soil matrix, see Figures 5.22 and 5.23. The peak strength attained by the soil samples of 122kN/m^2 occurs over a strain of 1.5 to 2.7%; the cob cylinders achieve a peak strength of 312kN/m^2 over strains of 3.5 to 5.6%.Thus compressive strength gains are in the order of 200% with the addition of straw. These gains are echoed by gains of approximately 250% for the yield strength of the cob cylinders as opposed to those of the soil matrix alone as soil cylinders show yield strengths lying between 75 and 90 kN/m^2, straining between 0.75 to 1.7% and cob cylinders indicate yield strengths of 182 to 250 kN/m^2, straining between 1.9 to 3.2%.

Closer inspection of the stress/strain graphs suggests greater variability in the stress/strain behaviour of the soil samples when compared to the cob samples. Once again, the cob samples are shown to suggest the maintenance of peak stress over greater strain than that achieved by the soil samples.

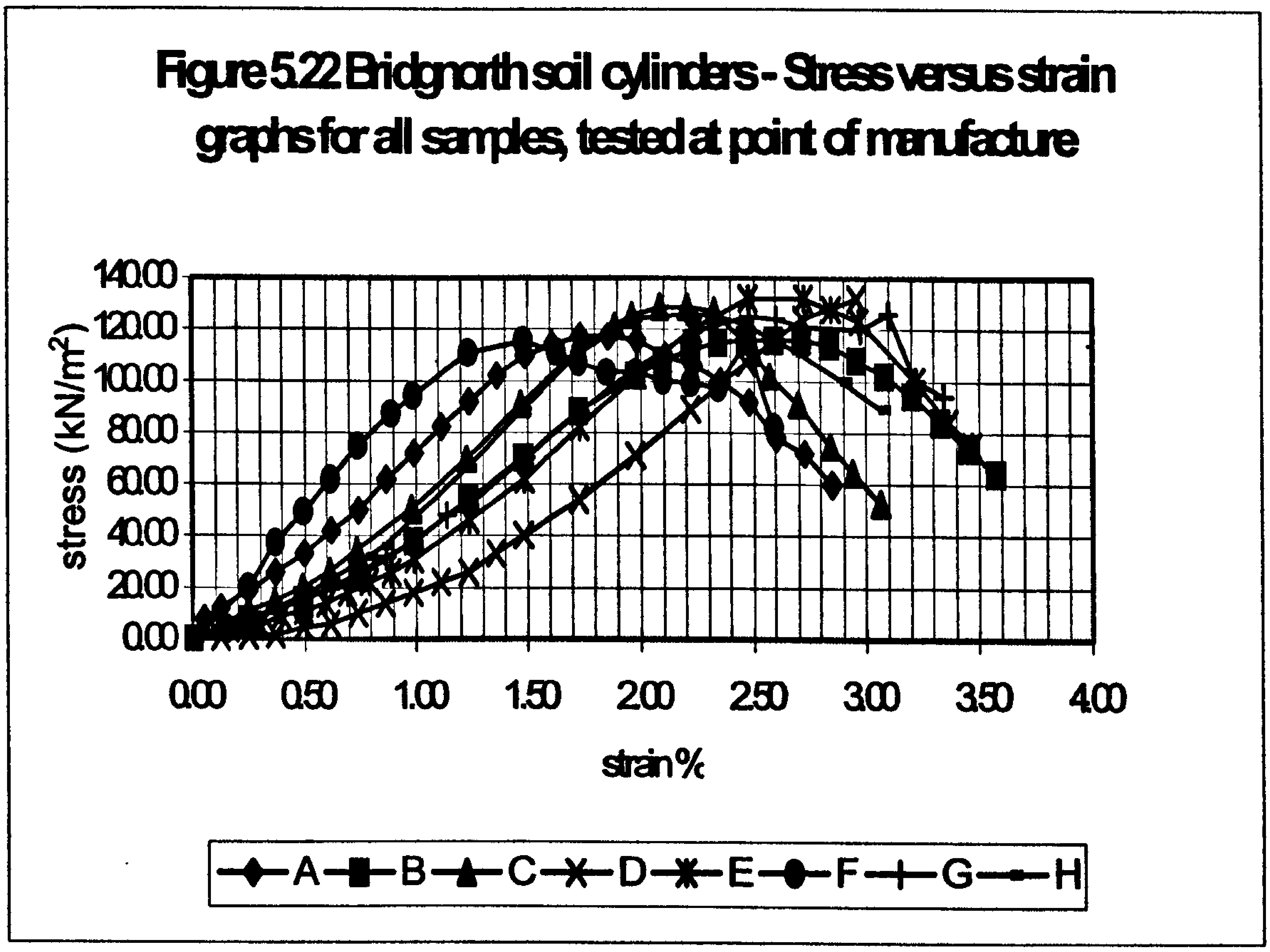


Figure 5.22 Bridgnorth soil cylinders - Stress versus strain graphs for all samples, tested at point of manufacture

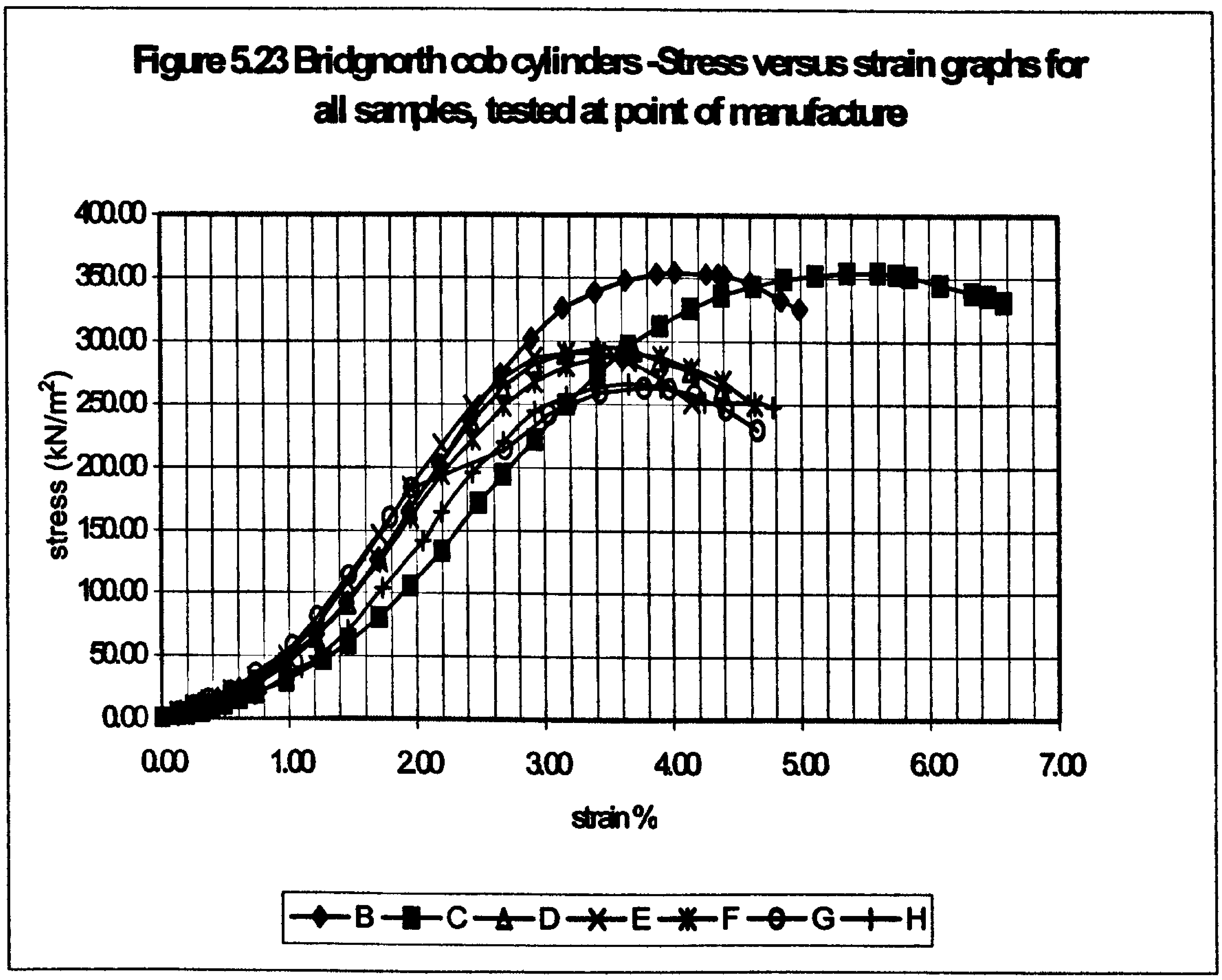


Figure 5.23 Bridgnorth cob cylinders -Stress versus strain graphs for all samples, tested at point of manufacture

5.4.7 Conclusions drawn from Test Series Two

Table 5.16 has been produced to summaries the findings from Test Series Two.

Soil Series and cylinder type	Average peak UCC stength and variability kN/m^2	Peak strain %	UCC Yield strength kN/m^2	Yield strain %	% increase in peak UCC utilising soil as cob	Indicative E val ue (kN/m^2)
Crediton –						
soil	81.89 ± 4.2	4.3 – 6.5	50 - 60	1.8 – 3.4 %		21.2
cob	274.09 ± 41	12.2 – 13	200	4.3%	234%	46.5
Dunsford –						
soil	100.76 ± 9.21	11.4 to 17.4	50	7.5		6.7
cob	179.84 ± 29.26	0.25 – 10	80	0.25 - 10	79%	15.7
Tedburn –						
soil	96.39 ± 14.82	12	16 - 50	0.6 – 3.2		17.4
cob	138.39 ± 11.82	24 - 65	280	1.8 – 3.6	43%	104
Halstow –						
soil	96.2 ± 4.51	12.2	24	1.6		15
cob	159.83 ± 11.9	20	30 – 60	0.9 – 2.6	67%	52.9
Bridgnorth –						
soil	122.87 ± 9.97	1.5 – 2.7	82	1.2		68.3
Cob	312.17 ± 4.01	3.5 – 5.6	225	2.5	155%	90

Table 5.16. Summary Table for Test Series Two

For the five soil series under investigation, all five soils were shown to have higher peak strengths in a cob matrix condition when compared with the soil matrix condition. Statistical analysis of these samples showed all strength gains to be significant on the addition of straw to all soil matrix. All soils exhibited an increased value of yield strength when tested as a cob matrix and compared to the soil matrix-only condition. Furthermore, all the cob samples tested indicated that yield strength and, where applicable, peak strength, occurred at higher strains than those experienced by the soils when utilised as soil only cylinders. This accounts for the increased values in the Young's modulus, E value, exhibited by all soil series on comparison of the results obtained for the soil and cob cylinders. The stress/strain graphs for the cob cylinders, exhibited a greater range of strain tolerated by the cob cylinders about peak strength, prior to work/strain softening, than those obtained for the soil cylinders was shown to be larger.

The inclusion of straw into the soil matrix is again shown to extend the period of work hardening of the wet cob matrix under the action of compressive load, as discussed for the Crediton air-dried cob cylinders in Section 5.3.6, by forcing the straw fibres into tension. However the ability of the straw to harness and maintain its tensile capacity is relative to the matrix and moisture condition of the matrix in which it operates as is apparent from the percentage increases in the peak strengths tabulated in Tabled 5.9 and Table 5.16 for the Test Series One and Test Series Two cylinders respectively. This is reflected in the E values given in these relative tables which illustrate a 60 to 90% drop when the samples are tested in the post-manufacture as opposed to the air-dried condition. This is discussed further in Chapter 6 on consideration of the role of moisture within a soil/straw matrix and its influence on strength.

5.5 Results from Test Series 3: the variation in the unconfined/undrained compressive strength of soil and cob cylinders over a range of moisture contents.

Figure 5.1 has shown the mode of strength development within a soil sample to be dependent on a critical moisture content value. The results from Test Series One and Two presented in Tables 5.9 and 5.16 respectively show that strength development within cob samples is moisture dependent. In view of this Test Series 3, described in Section 4.3.3.3, set out to investigate the engineering performance of the selected soils as structural materials concentrating on the significance of moisture content in the role of defining UCC strength and failure mode.

For this test series, samples were manufactured and then UCC tested over time to determine the variation in peak strength with moisture content for the particular soil series' soil cylinder and cob cylinder case. Graphs were produced showing the variation in peak compressive strength against moisture content (expressed as percentage by weight), see Figures 5.24 to 5.28 inclusive. The production of these graphs prompted the statistical application of regression techniques to define behaviour and this is presented in Section 5.5.1. Stress/strain graphs illustrating the stress path of all cylinders tested within each test-group variation are shown in Figures 5.29 to 5.38 inclusive. Figures 5.35 and 5.36 present the stress/strain graphs for the Halstow Series soil and cob cylinders respectively. To facilitate legibility, only eight of the sixteen cylinders manufactured for the series are illustrated. The stress/strain data for all sixteen cylinders is however presented in Appendix 6.

Manufacturing techniques are controlled and thus manufacturing data shows little variability from the mean. These data are presented in Appendix 5.

Figure 5.24 Crediton soil and cob cylinders- Variation of peak stress with moisture content

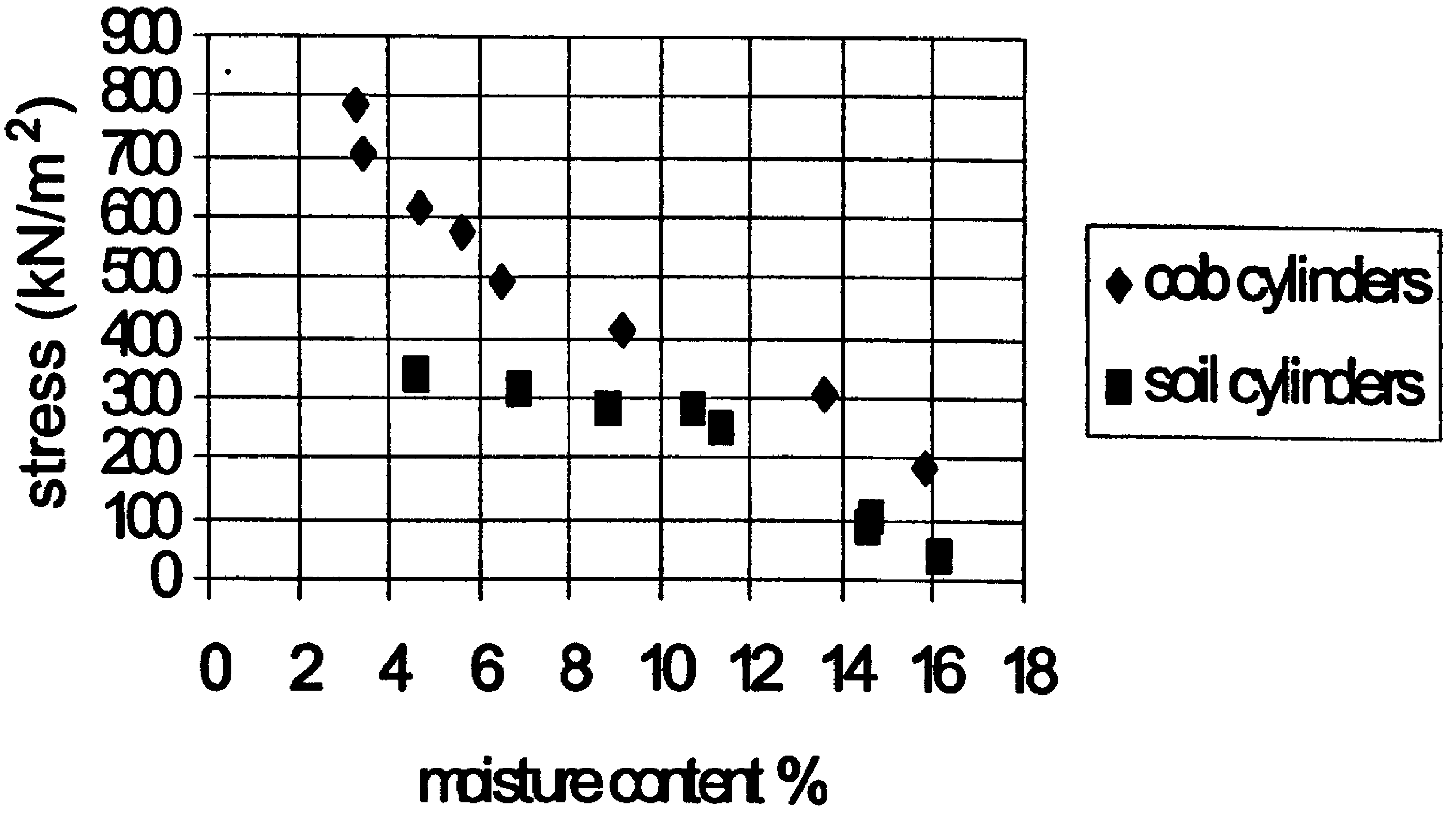
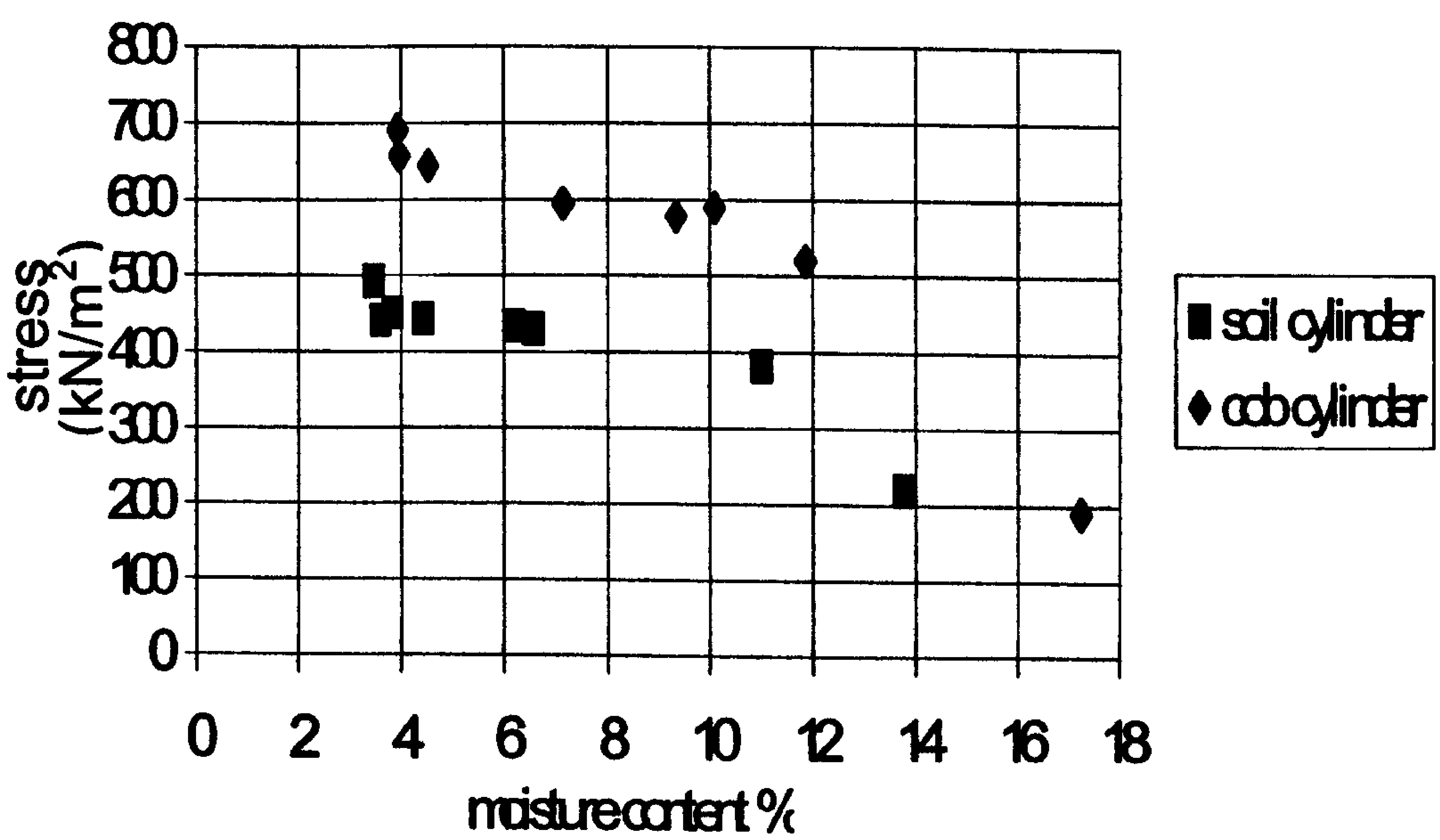


Figure 5.25 Dunsford soil and cob cylinders - Variation of peak stress with moisture content



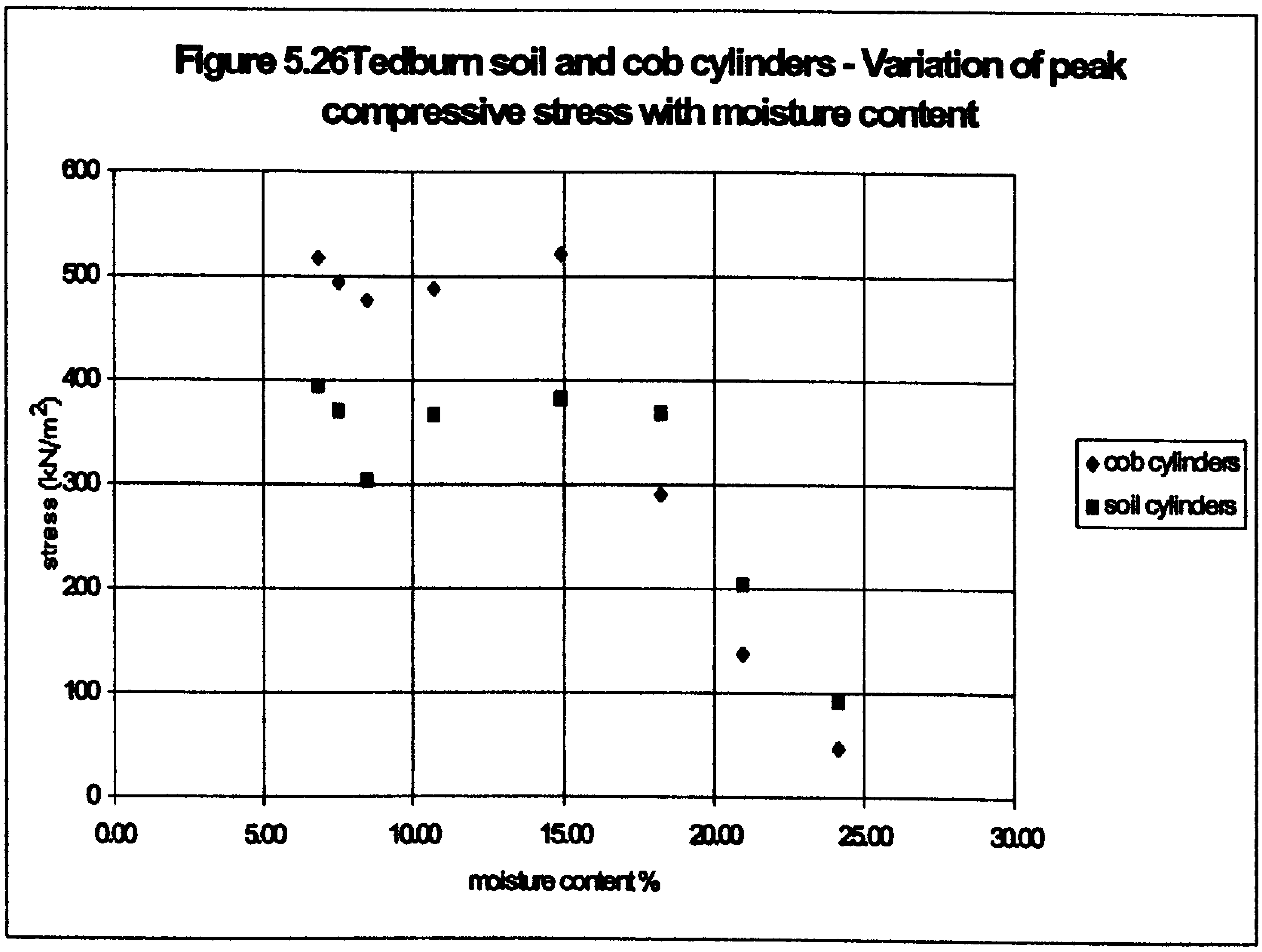


Figure 5.26 Tedburn soil and cob cylinders - Variation of peak compressive stress with moisture content

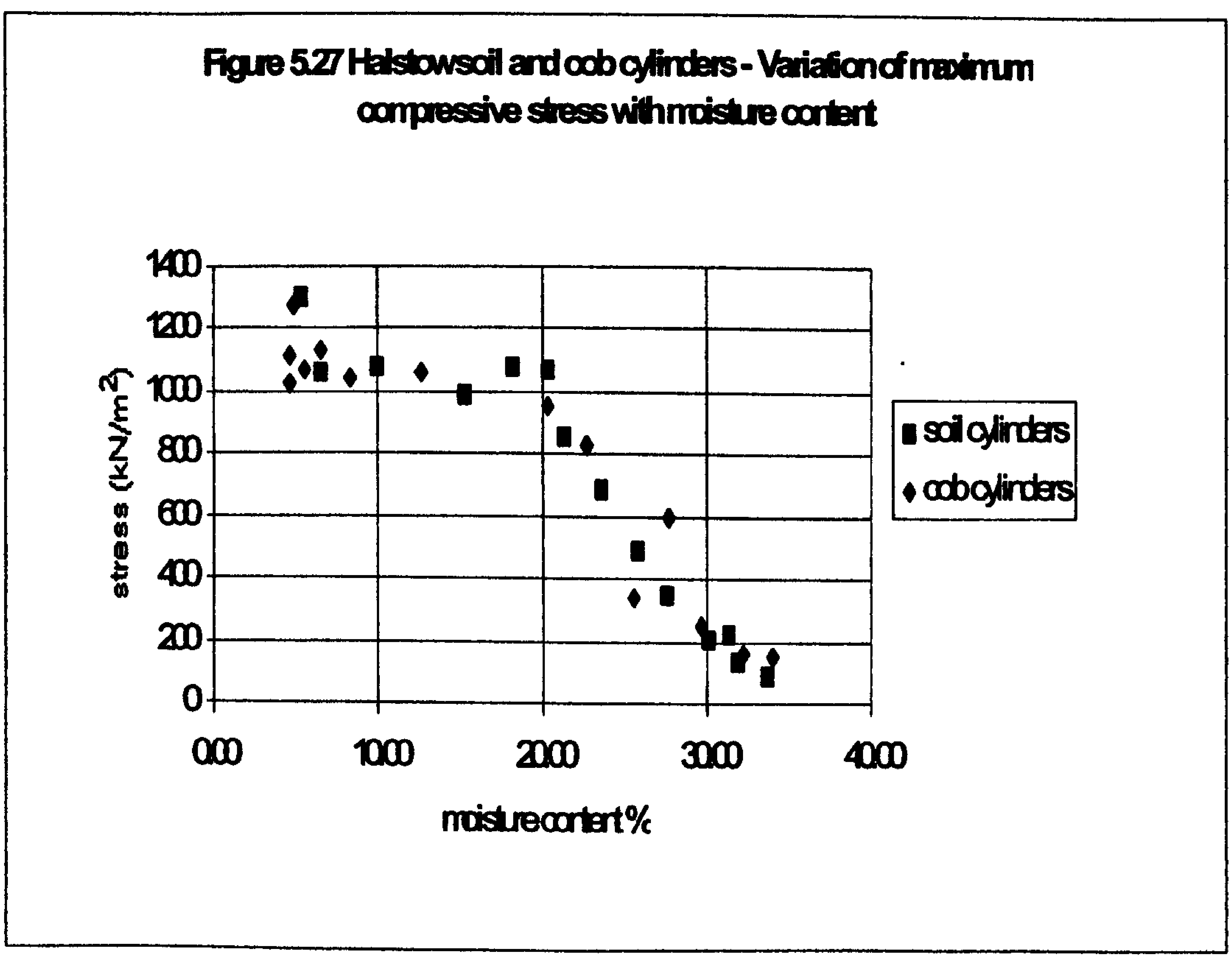


Figure 5.27 Halstow soil and cob cylinders - Variation of maximum compressive stress with moisture content

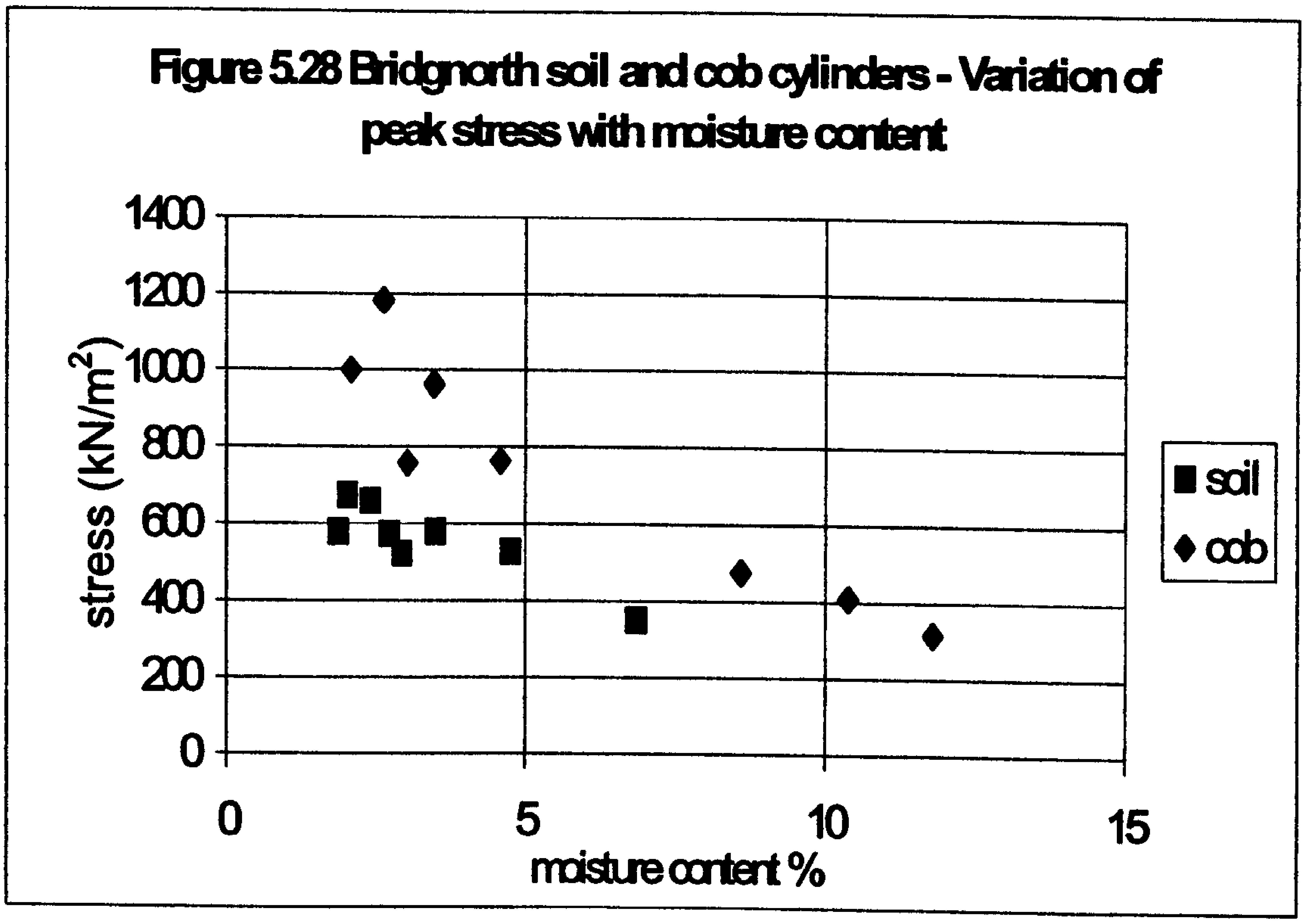


Figure 5.28 Bridgnorth soil and cob cylinders - Variation of peak stress with moisture content
1400
1200
1000
800
600
400
200
0
stress (kN/m²)
0
5
10
15
moisture content %
soil
cob

5.5.1 Test Series 3 Regression Results

On plotting the graphs of moisture content and compressive strength for the soil cylinders and cob cylinders for each soil series, displayed in Figures 5.24 to 5.28, the relationships appeared to show consistency in the functions they exhibit.

The function depicted is indicative of a cubic quadratic function. In order to establish whether this quadratic function provided an adequate fit to the data, regression analyses were performed on the data for soil and cob cylinders for each soil series individually, in order to calculate the degree of fit.

The type of regression adopted was multiple regression, with compressive strength as the dependent variable and moisture content at test, moisture content at test squared, and moisture content at test cubed, as the independent variables. Multiple regression is often assumed to be associated with linear variables alone. However, it is the regression surface that is linear, and not the relationship between the predictor and predicted variables. The results for each regression analysis are displayed in Tables 5.17-5.26.

Variable	B	SE B	β	SE β	t(4)	p-level
Mtest	-9.99	83.28	-0.35	2.89	-0.12	0.91
$(Mtest)^2$	1.31	8.65	0.97	6.40	0.15	0.89
$(Mtest)^3$	-0.12	0.28	-1.61	3.61	-0.45	0.68

$R^2 = 0.967$, Adjusted $R^2 = 0.941$, $p < 0.002$, Std. error of estimate = 28.284, Intercept = 368.17

Table 5.17. Regression results for Crediton soil cylinders

Variable	B	SE B	β	SE β	t(4)	p-level
Mtest	-225.66	47.29	-5.26	1.10	-4.77	0.009
$(Mtest)^2$	19.91	5.71	8.86	2.53	3.49	0.025
$(Mtest)^3$	-0.64	0.21	-4.63	1.49	-3.12	0.036

$R^2 = 0.990$, Adjusted $R^2 = 0.983$, $p < 0.0005$, Std. error of estimate = 26.68, Intercept = 1307.57

Table 5.18. Regression results for Crediton cob cylinders

Variable	B	SE B	β	SE β	t(4)	p-level
Mtest	-102.95	45.47	-4.72	2.09	-2.26	0.09
$(Mtest)^2$	14.30	5.96	11.12	4.64	2.40	0.07
$(Mtest)^3$	-0.67	0.24	-7.46	2.63	-2.84	0.05

$R^2 = 0.975$, Adjusted $R^2 = 0.957$, $p < 0.005$, Std. error of estimate = 17.31, Intercept = 680.03

Table 5.19. Regression results for Dunsford soil cylinders

Variable	B	SE B	β	SE β	t(4)	p-level
Mtest	-100.28	42.79	-2.94	1.25	-2.34	0.001
$(Mtest)^2$	10.86	4.65	6.53	2.80	2.33	0.079
$(Mtest)^3$	-0.44	0.15	-4.70	1.60	-2.93	0.043

$R^2 = 0.993$, Adjusted $R^2 = 0.987$, $p < 0.0005$, Std. error of estimate = 17.85, Intercept = 923.33

Table 5.20. Regression results for Dunsford cob cylinders

Variable	B	SE B	β	SE β	t(4)	p-level
Mtest	-160.59	68.47	-7.24	3.09	-2.35	0.079
$(Mtest)^2$	20.10	7.32	18.16	6.61	2.75	0.052
$(Mtest)^3$	-0.78	0.24	-11.91	3.66	-3.26	0.031

$R^2 = 0.935$, Adjusted $R^2 = 0.887$, $p < 0.01$, Std. error of estimate = 36.41, Intercept = 742.96

Table 5.21. Regression results for Tedburn soil cylinders

Variable	B	SE B	β	SE β	t(4)	p-level
Mtest	127.00	115.89	4.44	4.05	1.10	0.33
$(Mtest)^2$	-8.30	7.97	-8.81	8.46	-1.04	0.36
$(Mtest)^3$	0.13	0.17	3.50	4.53	0.77	0.48

$R^2 = 0.945$, Adjusted $R^2 = 0.903$, $p < 0.01$, Std. error of estimate = 58.71, Intercept = -43.48

Table 5.22. Regression results for Tedburn cob cylinders

Variable	B	SE B	β	SE β	t(11)	p-level
Mtest	69.63	59.47	1.51	1.29	1.17	0.27
$(Mtest)^2$	-4.40	3.37	-3.78	2.89	-1.31	0.22
$(Mtest)^3$	0.05	0.06	1.35	1.67	0.81	0.44

$R^2 = 0.947$, Adjusted $R^2 = 0.933$, $p < 0.0001$, Std. error of estimate = 111.53, Intercept = 894.32

Table 5.23. Regression results for Halstow soil cylinders

Variable	B	SE B	ß	SE ß	t(11)	p-level
Mtest	54.42	99.17	1.41	2.57	0.55	0.60
$(Mtest)^2$	-5.07	5.82	-4.81	5.51	-0.87	0.40
$(Mtest)^3$	0.08	0.10	2.55	3.08	0.83	0.43

$R^2 = 0.840$, Adjusted $R^2 = 0.792$, $p < 0.0005$, Std. error of estimate = 201.16,
Intercept = 963.13

Table 5.24. Regression results for Halstow cob cylinders

Variable	B	SE B	ß	SE ß	t(4)	p-level
Mtest	-211.46	391.80	-3.52	6.53	-0.54	0.62
$(Mtest)^2$	48.43	100.47	7.08	14.68	0.48	0.65
$(Mtest)^3$	-4.24	7.83	-4.54	8.38	-0.54	0.62

$R^2 = 0.822$, Adjusted $R^2 = 0.689$, $p < 0.06$, Std. error of estimate = 56.00,
Intercept = 889.38

Table 5.25. Regression results for Bridgnorth soil cylinders

Variable	B	SE B	ß	SE ß	t(4)	p-level
Mtest	-175.37	306.48	-2.17	3.79	-0.57	0.60
$(Mtest)^2$	10.85	48.00	1.85	8.19	0.23	0.83
$(Mtest)^3$	-0.31	2.27	-0.62	4.58	-0.14	0.90

$R^2 = 0.880$, Adjusted $R^2 = 0.791$, $p < 0.05$, Std. error of estimate = 142.20,
Intercept = 1384.30

Table 5.26. Regression results for Bridgnorth cob cylinders

The results indicate that both sample groups for the Crediton, Dunsford, Tedburn, and Halstow Soil Series were significantly matched to a cubic quadratic function. The results for the Bromsgrove Soil Series, are similarily) for the cob sample group however the soil samples show marginal significance significant ($p < 0.006$) but effectively fit the overall pattern of the data.

5.5.2 Discussion of Test Series Three results

Considering Figures 5.24 to 5.28, for four of the five cob cylinder test-groups, it would appear that higher values of compressive stress are achieved by cob cylinders, across the whole range of moisture contents, from relatively wet to air-dry. The Crediton soil and cob cylinders, Figure 5.24, aptly illustrate this trend.

The effect of straw addition to the Dunsford and Tedburn soil matrixes would appear to illustrate peak strength gains through the range of moisture contents tested, see Figures 5.25 and 5.26. Both relationships may be defined by cubic quadratic equations as has already been shown in Section 5.5.1. However the specific form of these functions alters little between the soil to cob condition, suggesting that the output function is merely translated to illustrate the strength gains. This suggests the dominance of the soil matrix in defining the material's response to load application.

The Halstow soil series is the only series not to show a distinctive improvement in the compressive strength carrying capacity of its cob matrix as opposed to that of its soil matrix. In fact the graph of UCC versus moisture content for the Halstow soil and cob cylinders are virtually inter-changeable, see Figure 5.27. Once again, it may be suggested that the soil matrix remains dominant in defining the macro-response to the applied loads. This suggestion is supported by Figures 5.35 and 5.36 which illustrate the stress/ strain paths over a range of moisture contents taken by the soil and cob cylinders respectively. Here it would appear that the addition of straw to the soil matrix is notable only in that it appears to have no obvious effect.

In Figure 5.28, the increase in the peak UCC for the Bridgnorth cob cylinders with decreasing moisture content is again mirrored by the Bridgnorth soil cylinders, although at lower stress values.

Figure 5.29 Crediton soil cylinders - stress/strain graphs for Test Series 3

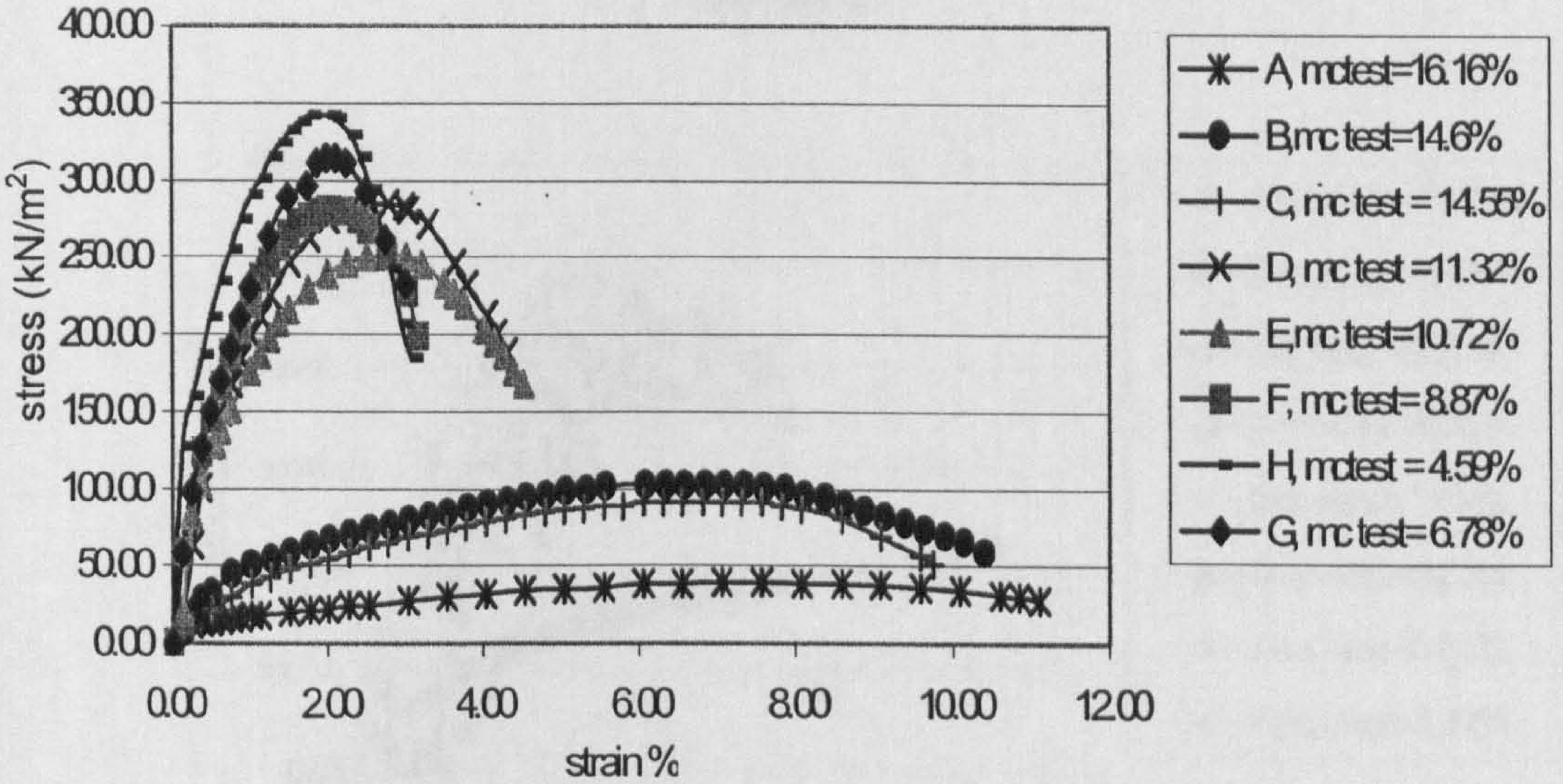


Figure 5.30 Crediton cob cylinders - stress/strain graphs for Test Series 3

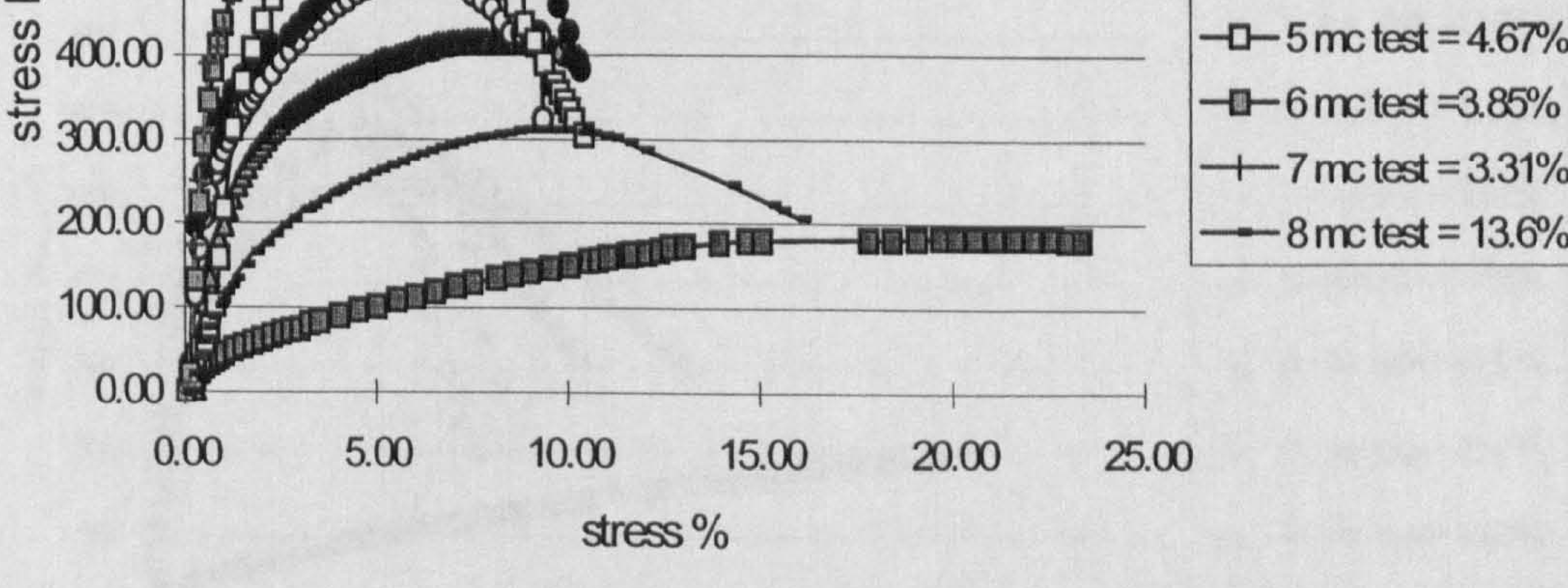


Figure 5.31 Dunsford soil cylinders - stress/strain graphs for Test Series 3

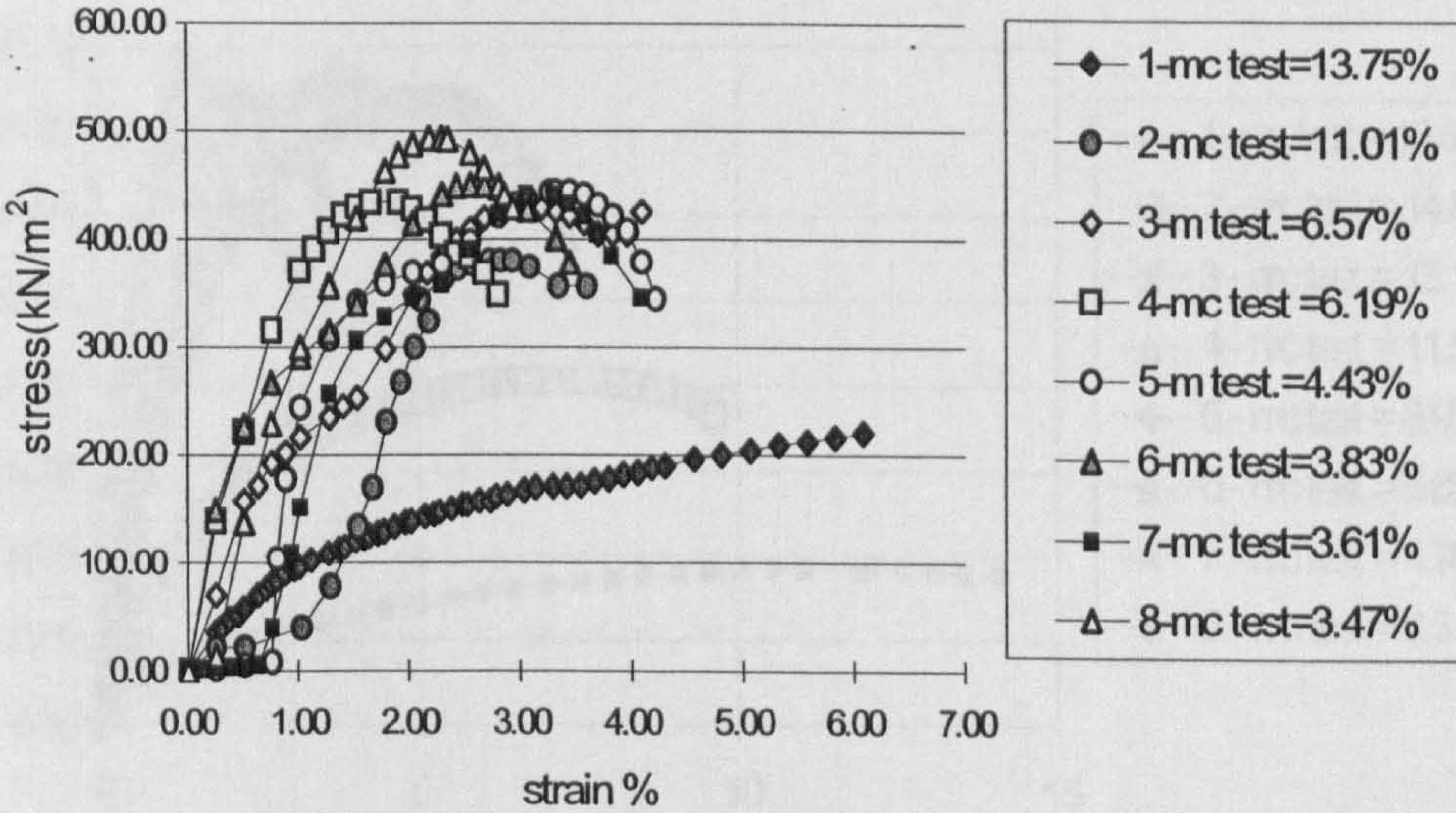
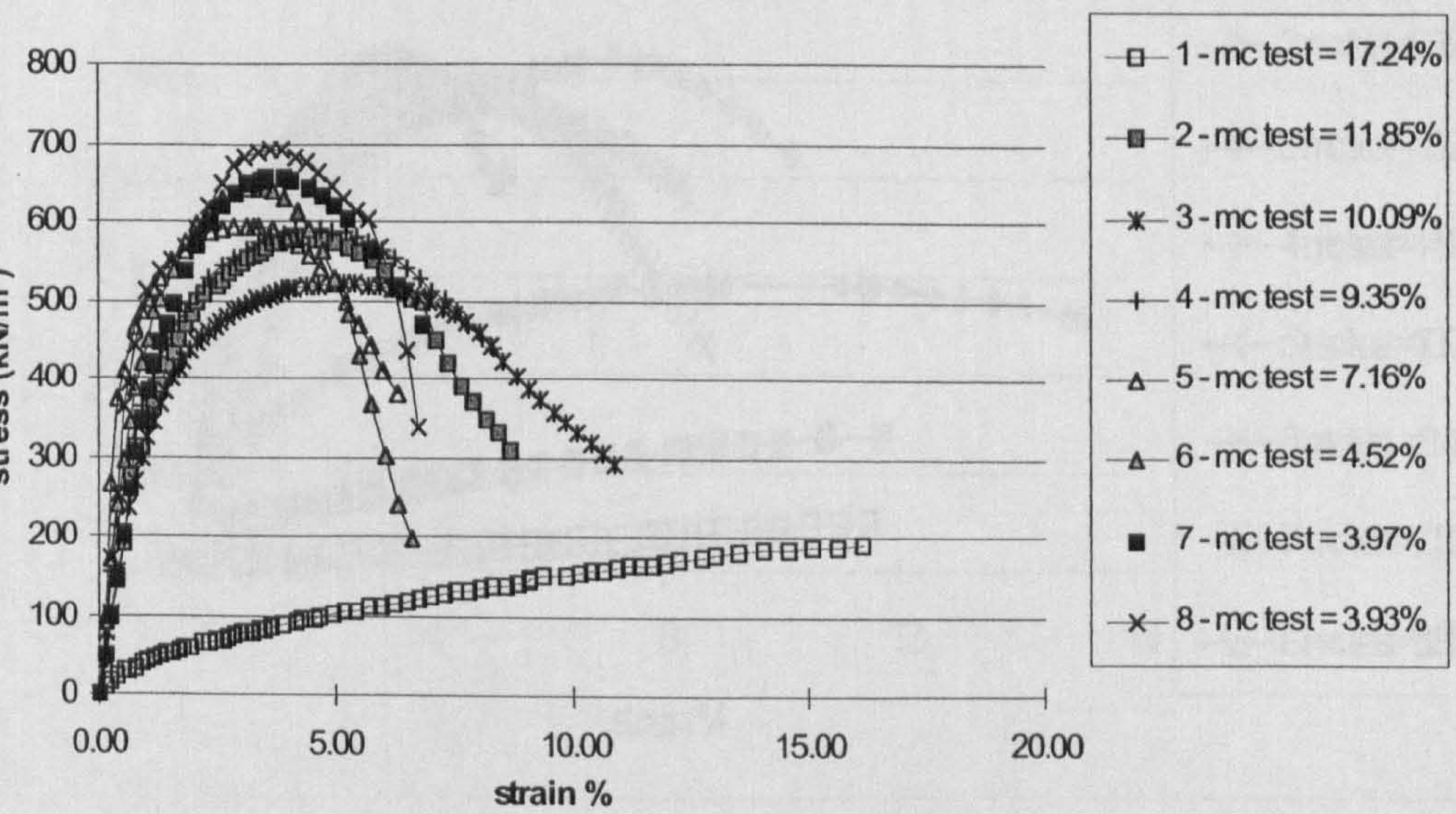


Figure 5.32 Dunsford cob cylinders - stress/strain graphs for Test Series 3



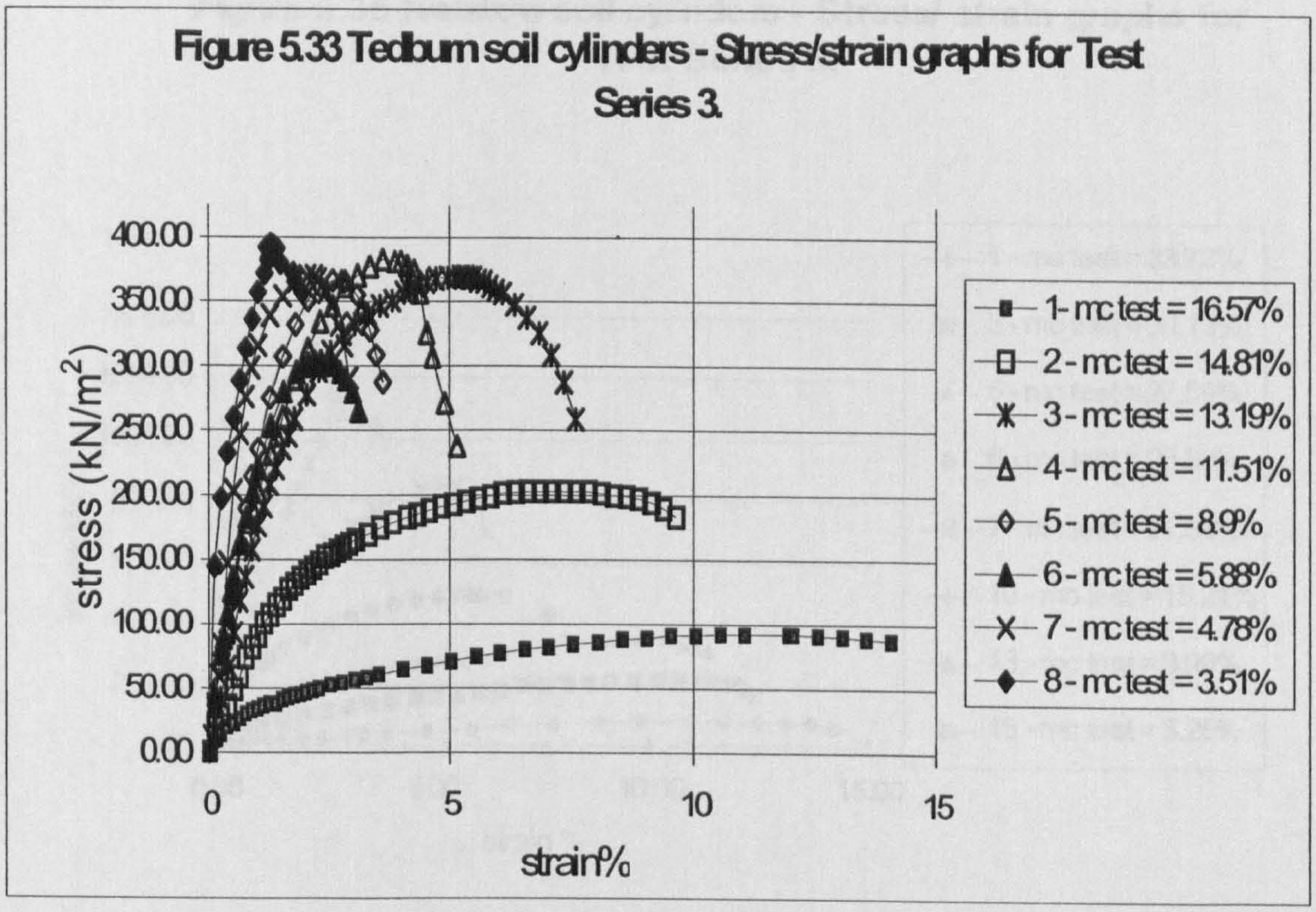


Figure 5.33 Tedburn soil cylinders - Stress/strain graphs for Test Series 3.
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
stress (kN/m2)
0
5
10
15
strain%
1- mc test = 16.57%
2 - mc test = 14.81%
3 - mc test = 13.19%
4 - mc test = 11.51%
5 - mc test = 8.9%
6 - mc test = 5.88%
7 - mc test = 4.78%
8 - mc test = 3.51%

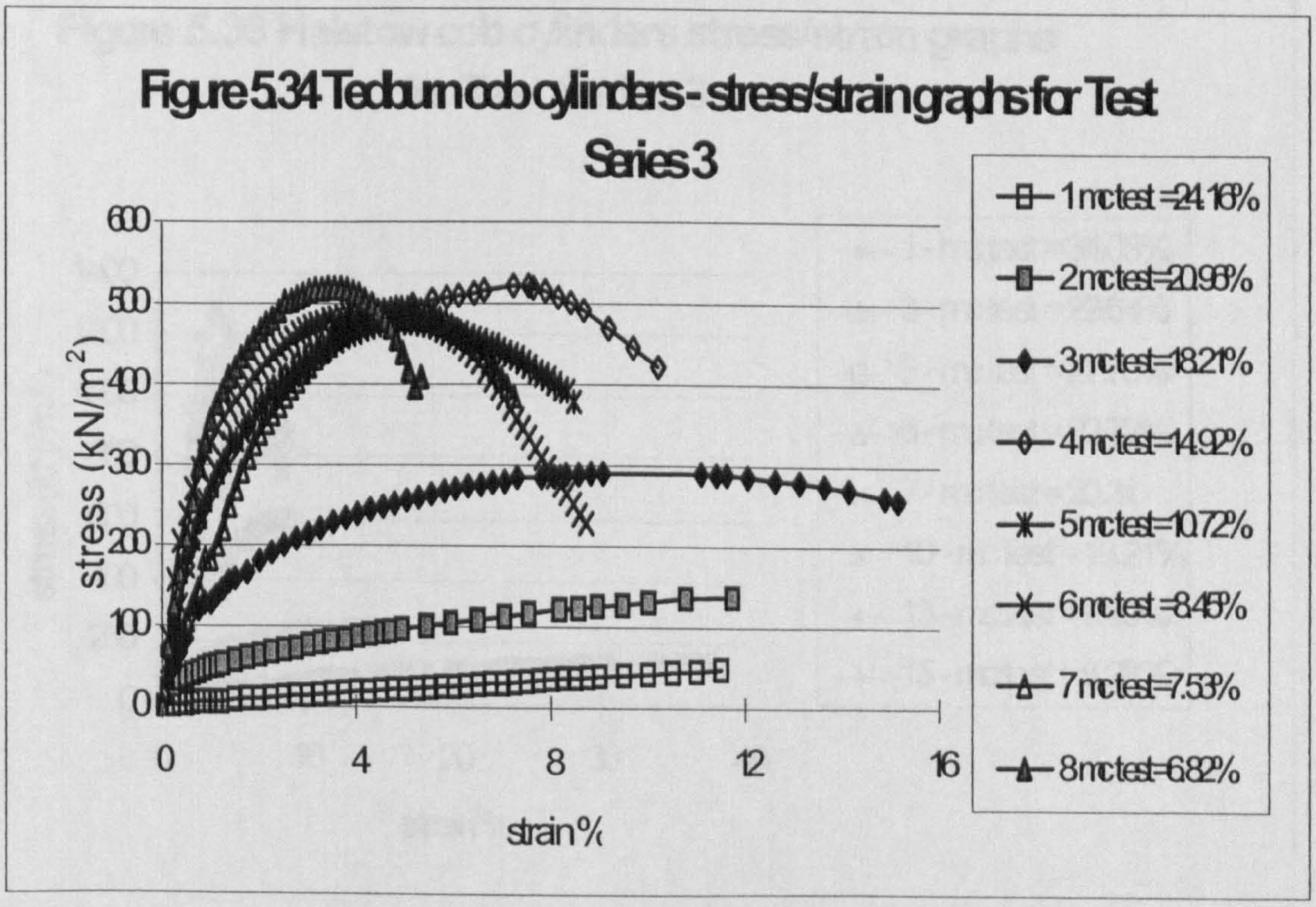


Figure 5.34 Tedburn cob cylinders - stress/strain graphs for Test Series 3
600
500
400
300
200
100
0
stress (kN/m2)
0
4
8
12
16
strain%
1mctest=24.16%
2mctest=20.96%
3mctest=18.21%
4mctest=14.92%
5mctest=10.72%
6mctest=8.45%
7mctest=7.53%
8mctest=6.82%

Figure 5.35 Halstow soil cylinders - Stress/ strain graphs for Test Series 3.

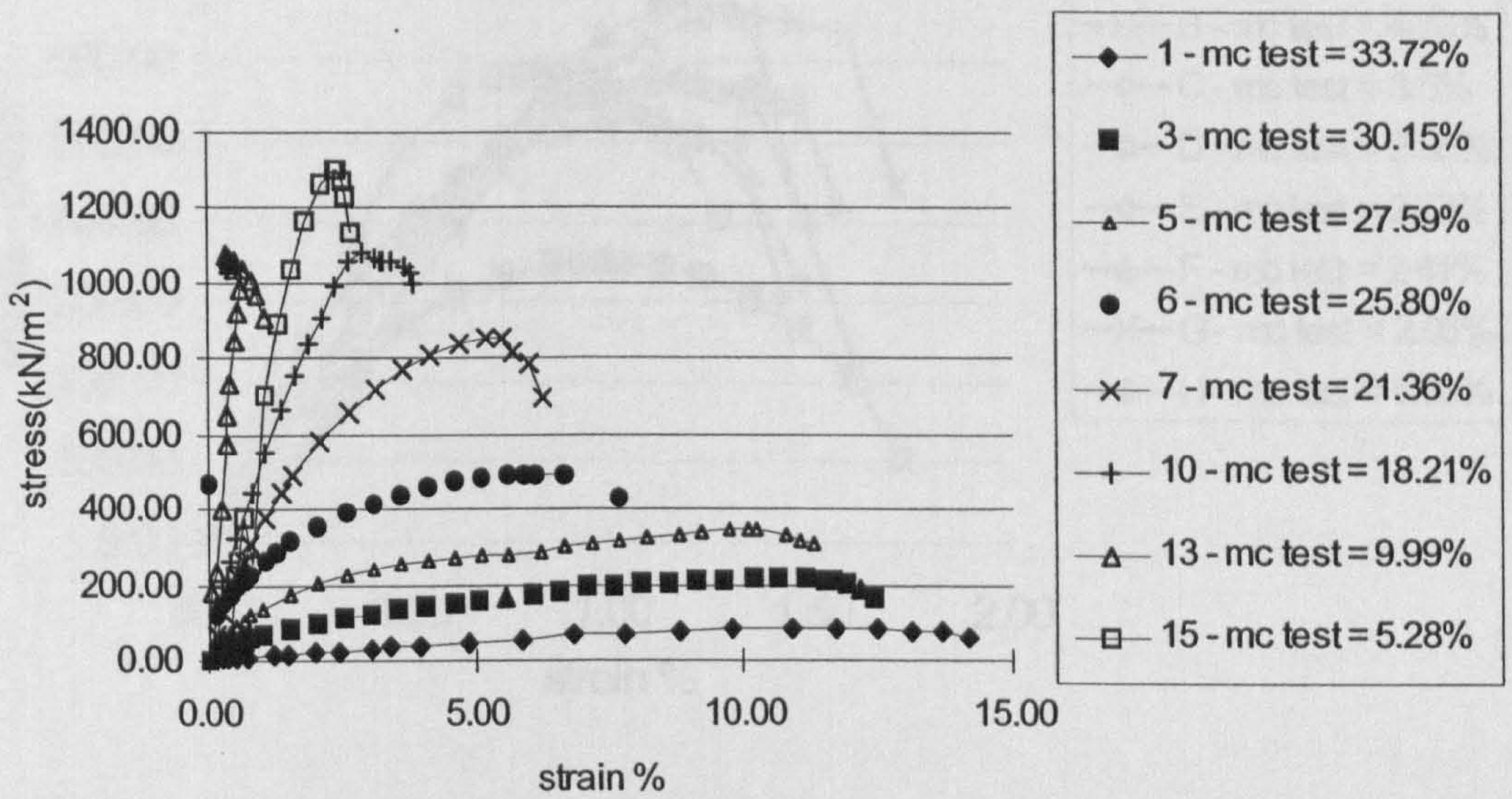


Figure 5.36 Halstow cob cylinders stress/strain graphs for Test Series 3

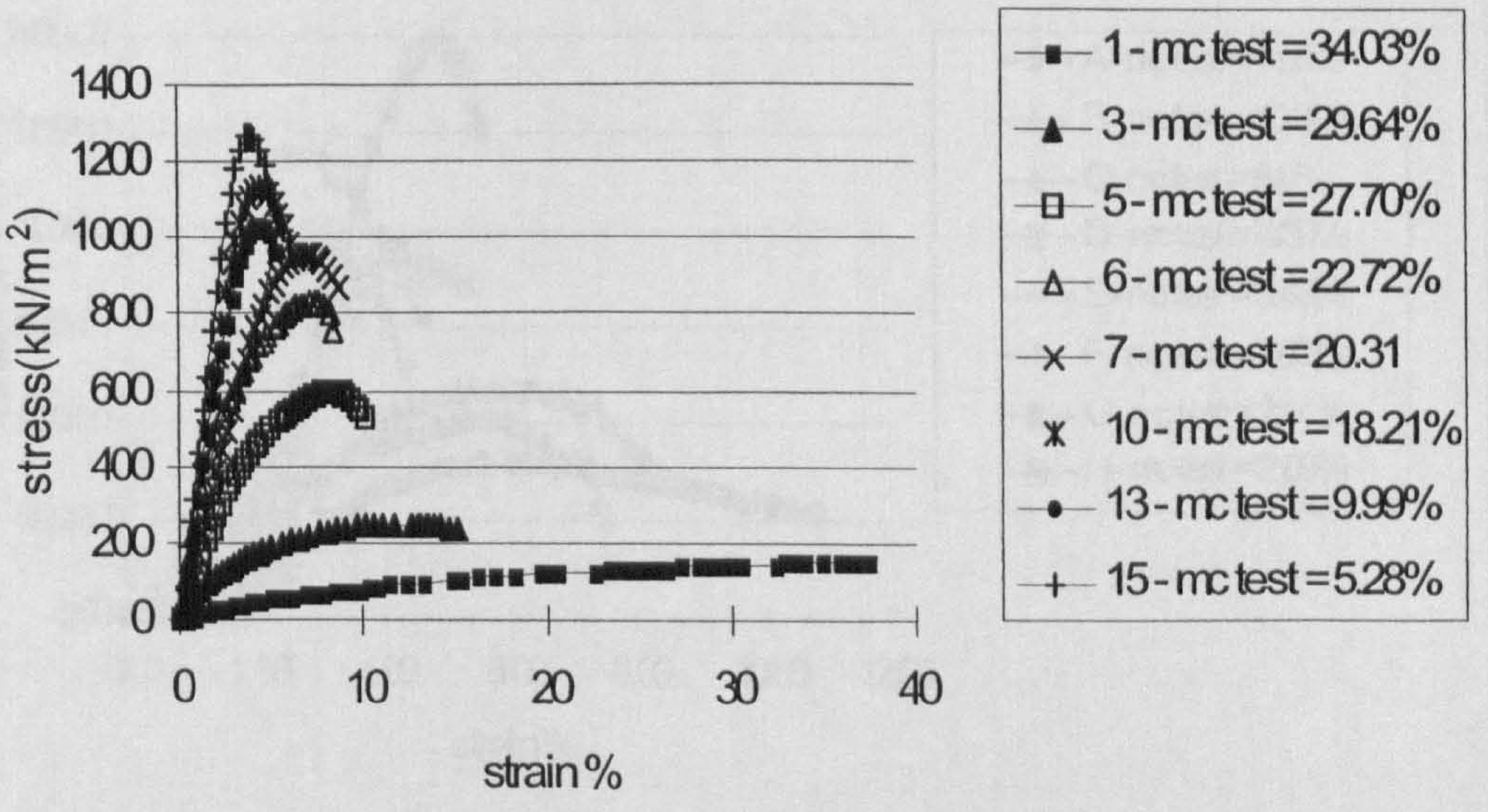


Figure 5.37 Bridgnorth soil cylinders - Stress/ strain graphs for Test Series 3

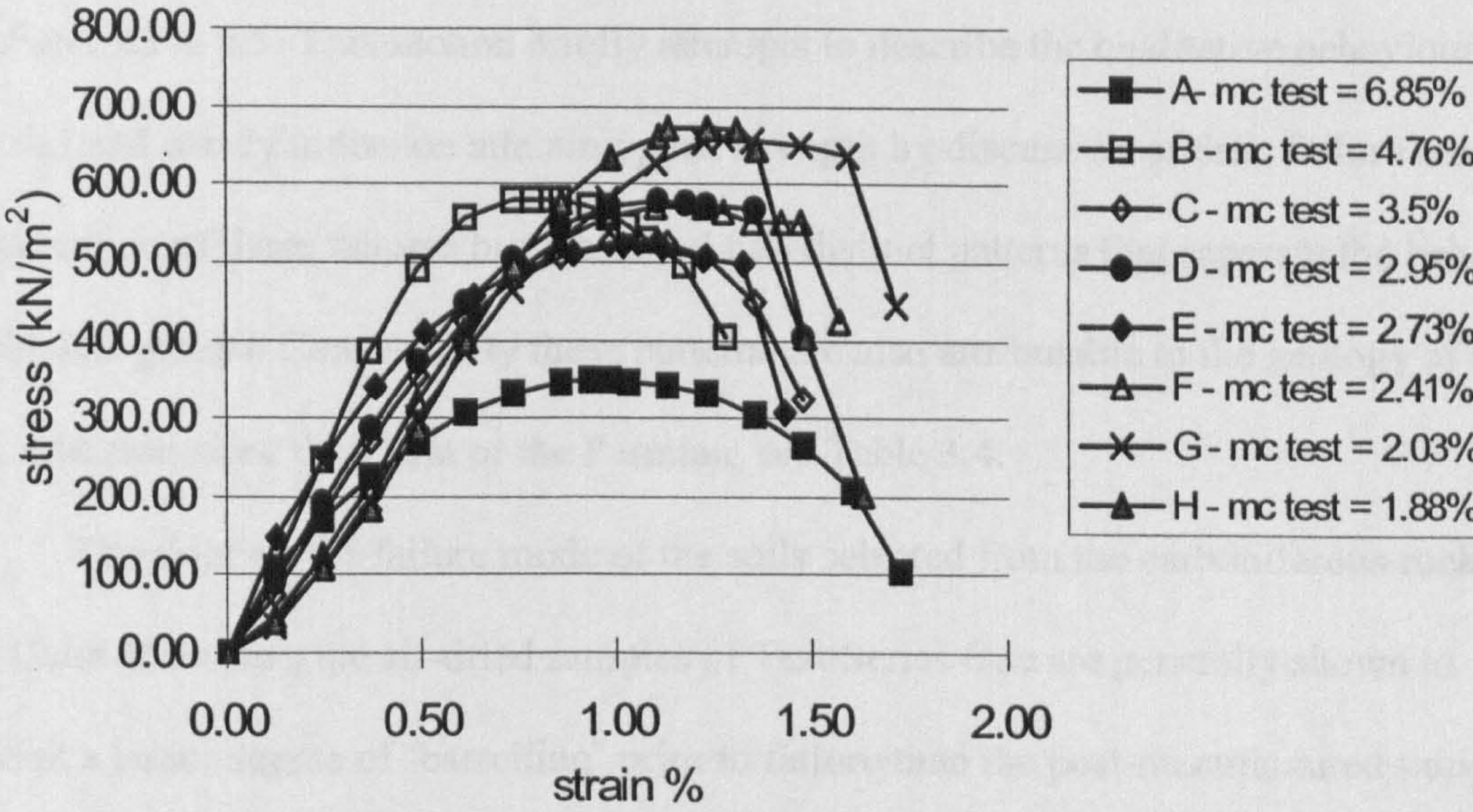
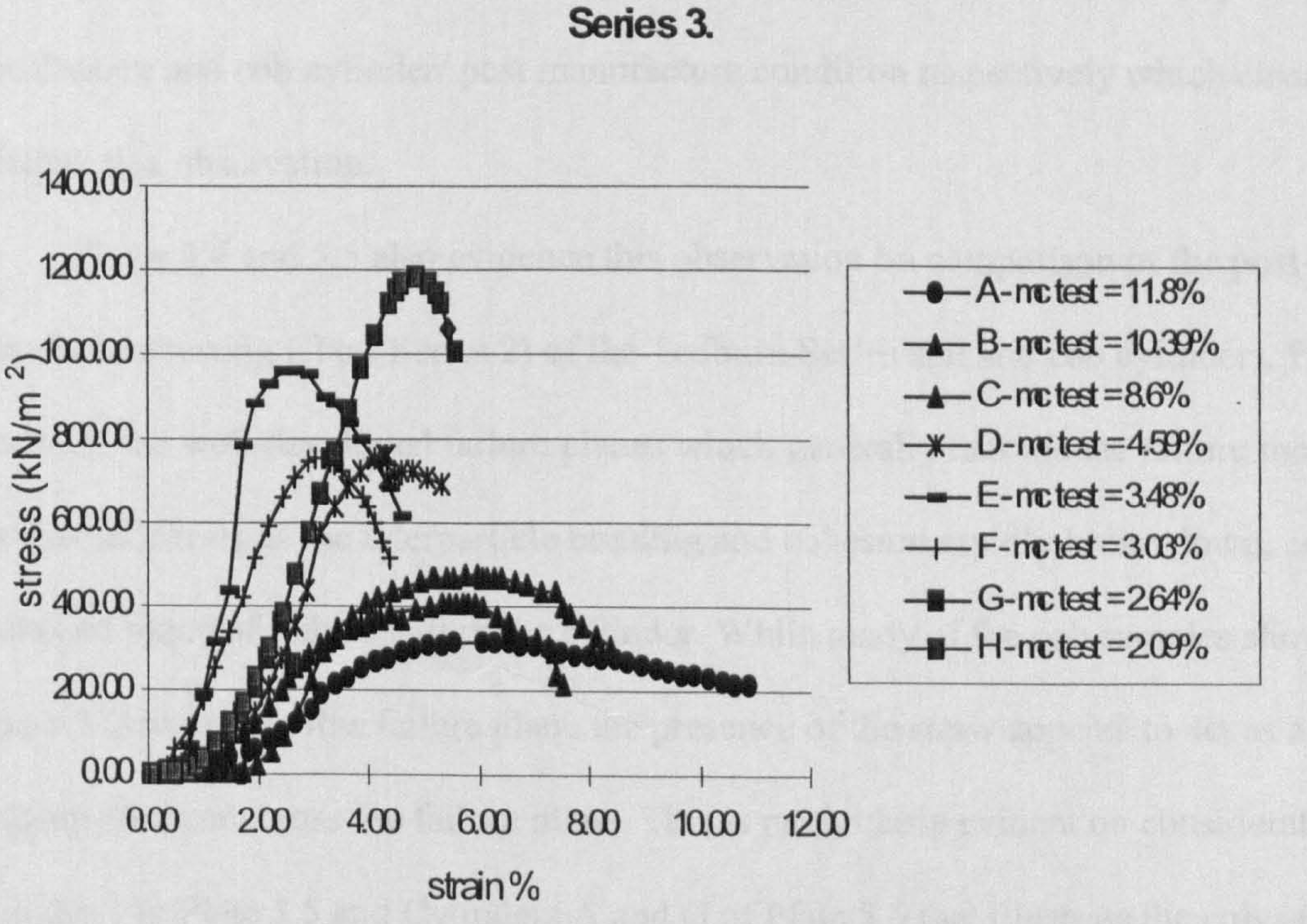


Figure 5.38 Bridgnorth cob cylinders - Stress/strain graphs for Test Series 3.



5.6 Modes of cylinder failure

The results quantifying the behaviour of soil and cob cylinders in terms of the development of their peak strength, produced for Test Series 1 to 3 inclusive, have been presented in Sections 5.3 to 5.5. This section briefly attempts to describe the qualitative behaviour of the soil and cob cylinders on attaining peak strength by discussion of their failure mode. Observation of these failures has identified two distinct patterns that separate the behaviour of the soil groups. Conveniently these patterns are also attributable to the geology of the soil selection sites, the Culm or the Permian, see Table 3.4.

Considering the failure mode of the soils selected from the carboniferous rocks of the Culm Measures, the air-dried samples of Test Series One are generally shown to exhibit a lesser degree of 'barrelling' prior to failure than the post-manufactured samples tested in Test Series Two. Furthermore the cob cylinders tended to 'barrel' more than the soil cylinders, under the increased straining and work-hardening experienced by these cylinders over that of the soil only counter-part. Plates 5.1 to 5.3 show the deformation of the Halstow Series samples tested in the soil cylinder/air-dried, soil cylinder/ post manufacture and cob cylinder/ post manufacture condition respectively which clearly illustrate this observation.

Plates 5.4 and 5.5 also evidence this observation on comparison of the post-manufacture testing (Test Series 2) of the Tedburn Series soil and cob cylinders. Plate 5.4 illustrates the well-developed failure planes which generally marked the failure mode from Test Series 2 tests as the interparticle bonding and cohesion rapidly broke-down, creating a weakened plane of failure within the cylinder. While many of the cob samples shown in Plate 5.5 also exhibit this failure plane the presence of the straw appears to act as a bridging element across the failure plane. This is particularly evident on consideration of Cylinder 1 in Plate 5.5 and Cylinders A and G of Plate 5.6 that illustrate the cob samples from the Dunsford Series of Test Series 2.

The cob samples of the Crediton Series (derived from the rocks of the Permian sandstones) of Test Series 2 (see Plate 5.7) also appear to show some straw-bridging across the failure planes of these cob cylinders. However cylinders 1, 5, 7 and 8 also indicate that failure is not restricted to the formation of one distinct plane. Plate 5.8 showing the post-test deformation of the soil samples of Test Series 2 illustrates wide-spread break-down of interparticle bonds of the Crediton soil cylinders which appear to coalesce and promote failure of these samples through inter-connection of the failure planes. This behaviour of these Permian cylinders is also depicted in Plate 5.9, illustrating the post-test deformation of the Bridgnorth soil cylinders from Test Series 1. Here, the inability of this Permian soil to tolerate lateral stressing once interparticle bonds at the cylinders' surface began to form, resulted in the dramatic collapse of these cylinders at failure.

Interparticle bonds, the relation between the soil matrix, moisture content and the presence of the straw is further discussed in Chapter 6.

Plate 5.1 Halstow soil cylinders from Test Series 1, post-test

Plate 5.2 Halstow soil cylinders from Test Series 2, post-test

Plate 5.3 Halstow cob cylinders from Test Series 2, post-test

Plate 5.4 Tedburn soil cylinders from Test Series 1, post-test

Plate 5.5 Tedburn cob cylinders from Test Series 2, post-test

Plate 5.6 Dunsford cob cylinders from Test Series 2, post-test

Plate 5.7 Crediton cob cylinders from Test Series 2, post-test

Plate 5.8 Crediton soil cylinders from Test Series 2, post-test

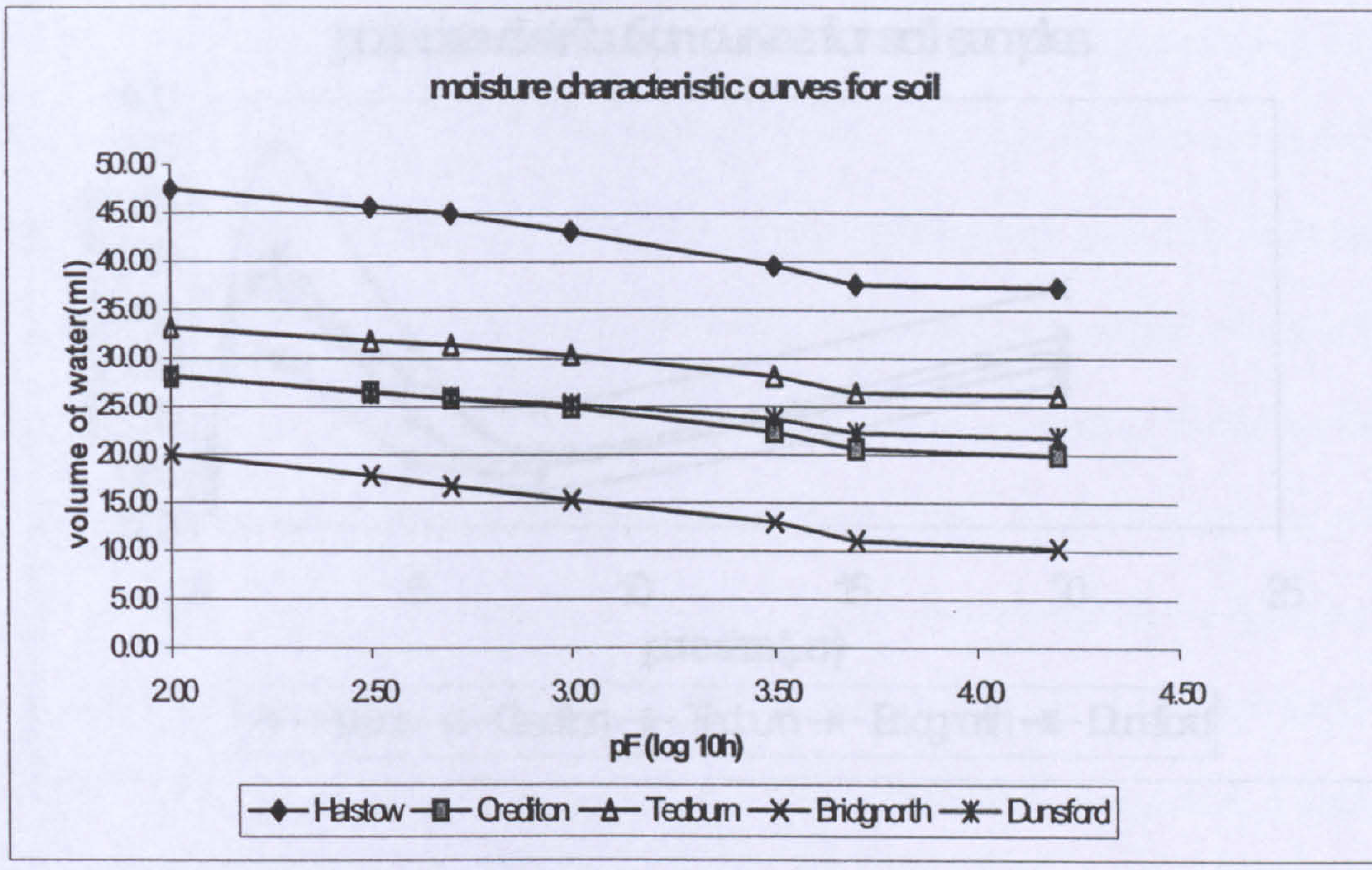
Plate 5.9 Bridgnorth soil cylinders from Test Series 1, post-test

5.7 Results from Test Series 4: determination of pore size distribution curves for the soil and cob matrix of each selected soil series.

Section 4.5 outlines the adoption of the pressure membrane apparatus to obtain information concerning the moisture content held by micropores within the soil cylinder/cob cylinder soil/water system for each soil series. The results presented are in accordance with the method adopted by the Soil Survey of England and Wales (see Hall et al (1977)). Table 5.16 illustrates the basic calculated parameters determined from this work and highlights the increased pore space associated with cob cylinders as opposed to soil cylinders. Figure 5.39 and 5.40 show the moisture characteristic curves and the pore size distribution curves for both the soil and cob samples. All monitoring data associated with this work are presented in Appendix 7.

Soil Sample	Sample type	Particle density, Dp (kg/m^3)	Dry weight (kg)	Bulk Density, Dbt (kg/m^3) dry wgt./ orig'l vol	Total Pore space %, Tt 100*(1-Dbt/ Dp)
Crediton	soil	2860	0.42370	1791.3	37.4
Dunsford (cuttings)	soil	2705	0.50119	1779.5	34.2
Halstow	soil	2770	0.34146	1435	48.2
Tedburn	soil	2730	0.42646	1534.2	43.8
Bridgnorth	soil	2745	0.55777	1784.5	35.0
Crediton	cob	2860	0.35488	1648.5	42.4
Dunsford (cuttings)	cob	2705	0.37228	1622.6	40.0
Tedburn	cob	2730	0.41175	1433.4	47.5
Halstow	cob	2770	0.34146	1197.5	56.8
Bridgnorth	cob	2745	0.46593	1545.8	43.7

Table 5.27 Basic sample parameters from pressure membrane testing



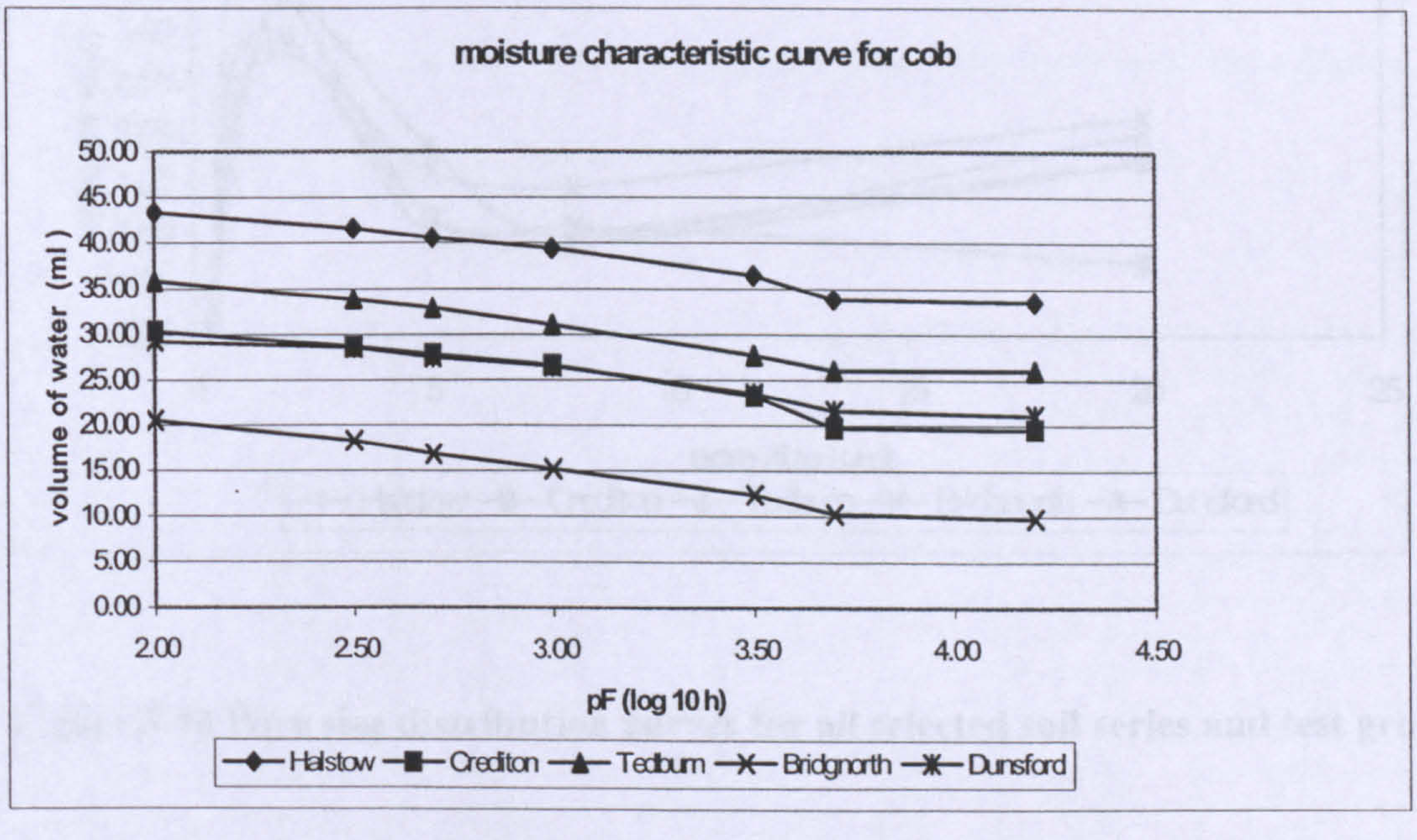


Figure 5.39 Moisture characteristic curves for all selected soil series and test groups

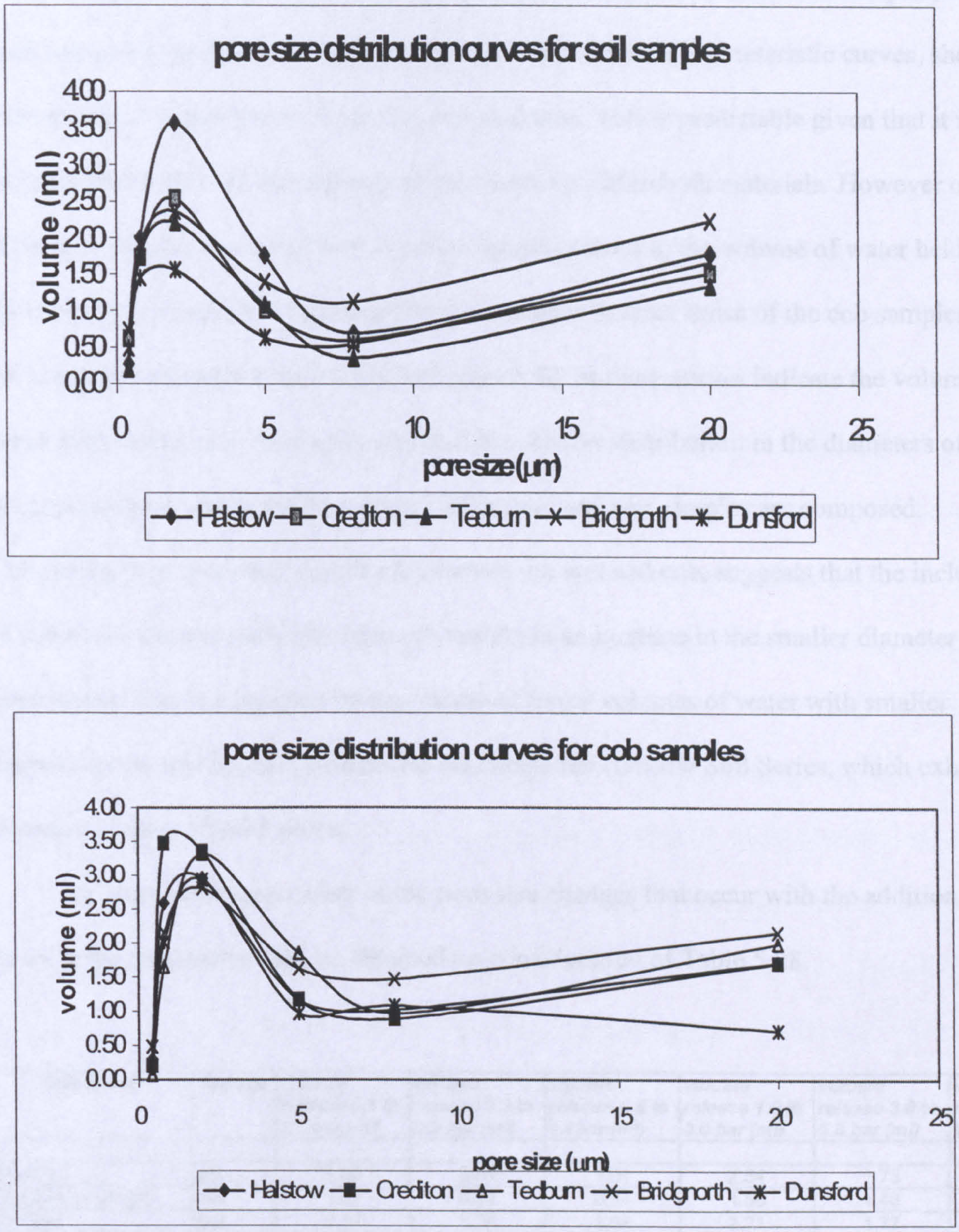


Figure 5.40 Pore size distribution curves for all selected soil series and test groups

Figure 5.40 indicates the volumes of water held by the soil and cob samples, under each successive pressure head. Observation of both moisture characteristic curves, show little variation in function between the curves drawn. This is predictable given that it is the soil itself that will hold the majority of the moisture within both materials. However one difference that may be noted between these graphs relates to the volume of water held at similar pressures which is larger for the soil samples than for those of the cob samples. This may be explained by reference to Figure 5.40 as these curves indicate the volume of water held within each micropore and thus the relative distribution in the diameters of the micropores from which the pore spaces of the soil and cob samples are composed. Comparing these pore size distribution curves, for soil and cob, suggests that the inclusion of straw into the soil matrix to form cob results in an increase in the smaller diameter micropores. This is suggested by the release of larger volumes of water with smaller diameter pores and appears pertinent to all except the Halstow Soil Series, which exhibits a decrease in these smaller pores.

A more accurate account of the pore size changes that occur with the addition of straw to the cob matrix may be obtained on consideration of Table 5.28.

Soil series	*Sample*	*volume release 0.1 to 0.3 bar (ml)*	*volume release 0.3 to 0.5 bar (ml)*	*volume release 0.5 to 1.0bar (ml)*	*volume release 1.0 to 3.0 bar (ml)*	*volume release 3.0 to 5.0 bar (ml)*	*volume release 5.0 to 15.0 bar (ml)*
Crediton	soil	1.52	0.61	1.01	2.54	1.73	0.62
Dunsford (cuttings)	soil	1.67	0.54	0.64	1.56	1.45	0.49
Tedburn	soil	1.34	0.35	1.08	2.21	1.77	0.20
Halstow	soil	1.80	0.69	1.76	3.57	1.99	0.28
Bridgnorth	soil	2.24	1.13	1.40	2.35	1.92	0.73
Crediton	cob	1.71	0.88	1.17	3.36	3.47	0.21
Dunsford (cuttings)	cob	0.71	1.08	0.97	2.94	2.00	0.48
Tedburn	cob	1.99	0.96	1.85	3.32	1.65	0.07
Halstow	cob	1.72	1.02	1.16	2.96	2.59	0.29
Bridgnorth	cob	2.16	1.44	1.63	2.81	2.15	0.48
Mean pore diameter μm		*20*	*8*	*5*	*2*	*0.8*	*0.40*

Table 5.28 Water volumes held by mean pore diameters

This table presents the water volumes associated with pore diameters for the soil and cob samples. The volumes shown in bold, indicate an increase in volumes recorded for the cob samples when compared with those recorded for the soil samples, for the same pore diameter. These volume increases may imply an increase in the number of specific pore sizes unless the inclusion of straw into the soil matrix is also affecting the throat size of the pores, preventing drainage at lower applied pressures. While two thirds of the tabulated volumes are shown to increase when the soil is mixed with straw to form cob, the cob volumes associated with the smallest pore size considered, 0.4 μm, is suggestive of the contrary.

Further observation of these graphs also indicates that the continuity across the range of pore sizes investigated in this test, is more evenly displayed by the cob samples than those of the soil samples. The volume of water released by pores of approximately 8μm is shown to be greater for the cob samples than for the soil samples. Thus greater 'connectivity' between pores is achieved on addition of straw to the soil matrix. It is this connectivity which may explain the lower volume of water retention exhibited by the moisture characteristic curves shown in Figure 5.39. Chapter 6, Section 6.3, offers further discussion concerning the retention of water in a soil/cob fabric.

5.7.1 Conclusion to Test Series 4

The inclusion of straw in a soil matrix appears to result in an increase in the volume of micropores contributing to the total voidage of a given cob. Increasing the micropore volume at the expense of the macropore volume is initially suggestive of a process of material densification. However, the discussion presented in Chapter 6, proffers a more probable reason for these changes in the material and structural matrix.

5.8 Summary and Conclusions

The soils selected for this investigation have been air-dried and unconfined compression tested when formed into soil and cob cylinders. The inclusion of straw into the soil to form the cob matrix resulted in yield strength increases for all soil and peak strength increases for three soils. Statistical analysis has shown that only two of the soil series tested (namely the Dunsford and Crediton Soil Series) exhibited a significant increase in peak strength. Furthermore, these peak strength were obtained at higher strains.

Utilising the same test methodology, all selected soils where then unconfined compression tested as soil and cob cylinders in a wet/ immediate post manufacture state. The statistical results for these tests showed that all soils sampled significantly increased their peak strength capacity when utilised in a cob matrix compared with that of a soil matrix. Once again, these peak strengths were obtained at higher strains.

Consideration of peak strengths and moisture contents has shown moisture content to be a potential predictor of compressive strength. Statistical analysis supported the validity of defining the increase in unconfined compressive strength with decreasing moisture content by means of a cubic quadratic function specific to a given soil series and soil/cob cylinder condition. All soil series, with the exception of the Halstow Series, indicated increasing values in UCC strength when utilised as cob cylinders compared to soil cylinders. The Halstow Soil Series showed little variation in UCC strength when utilised as either soil or cob over a range of moisture contents.

Investigations into the changes in the structural matrix of the soil and cob samples, utilising the pressure membrane apparatus, has highlighted fabric changes resulting from the inclusion of straw into the soil matrix which suggests an increase in the micropore volume within cob when compared to its soil-only counterpart. All selected soil samples indicated an increase in pore volume with the Crediton and Dunsford soil series showing a notable increase in the smaller-sized (8μm) micropores while the Halstow Soil Series intimated a decline in the volume of these pores. Continuity and thus connectivity between

pore sizes was also shown to increase with the inclusion of straw into the soil matrix. Chapter 6 considers the implications of these changes in the material matrix when utilising soils in cob construction.

Chapter 6. Discussion of results

6.1 Introduction

A test programme has been defined for soils utilised in cob construction and is outlined in Chapter Four. The programme investigated the air-dried unconfined compressive strength, the manufacture unconfined compressive strength, and the unconfined compressive strength over a range of moisture contents, of simulated cob and soil samples. Further to this, a study was presented which facilitates the classification of the structural matrix of these samples in terms of their porosity, as an extension to the traditional material classification addressed in Chapter Three. Five soils, namely Crediton, Dunsford, Tedburn, Halstow and Bridgnorth, were selected for this study, under the criteria defined in Chapter Three, and were subjected to the test programme. The post-test results are briefly outlined below in Table 6.1; circled ticks denote statistically significant UCC strength gains when the selected soils were tested as cobs.

Soil series	Peak air-dry strength greater for cob than soil	Yield air-dry strength greater for cob than soil	Peak wet strength greater for cob than soil	Yield wet strength greater for cob than soil	Predictive UCC with varying mc greater for cob than soil	Pore volume increases 0.8μm to 8μm when utilised as cob
Crediton	(■)	■	(■)	■	■	■
Dunsford	(■)	■	(■)	■	■	■
Tedburn	■	■	(■)	■	■	■
Halstow			(■)	■		■
Bridgnorth	(■)		(■)	■	■	■

Table 6.1 Indicative results from Test Series 1 to 4.

(Note: Circled results are statistically significant)

The discussion that follows begins to link the results from these test areas together. Pore size distributions are discussed and associated with water retention in soils. The water retention characteristics of the soil and cob samples used in this study are then considered. Clarifying the water retention mechanisms within the soil and cob samples, informs discussion concerning the effects of moisture content on the unconfined compressive strength characteristics. Particular attention is given to the material classification characteristics of the selected soils and the role of straw within the soil matrix when utilised as cob.

6.2 The effects of drying on the UCC strength of the soil/cob matrix

The effects of drying soils on their associated unconfined compressive strength values has been investigated by Joshi et al (1994) over the temperature range of 110 to 700 degrees centigrade. These temperatures result in the dehydroxylation of clay soils (the removal of structural water from the clay minerals within a soil) and consequently influence the UCC values obtained. Drying soils below 110 degrees centigrade promotes dehydration in soils, removing only the free water, pore water and the mechanical water held by the clays. However, the forces retaining pore and mechanical water vary over the period of drying and are believed by the author to be significant to the development of UCC strength within the soil and cob cylinders tested. Water retention is therefore considered below.

6.2.1. Mechanical water in clays

Day (1966), ibid. Joshi et al. (1994), define mechanical water as the water from between the silicate layers of different clays. Section 3.3.3.1 has already discussed the water held between these silicate layers, referring to it as absorbed water. The absorbed water within a clay mineral and the other water structures that may be found about clay particles are illustrated in Figure 6.1.

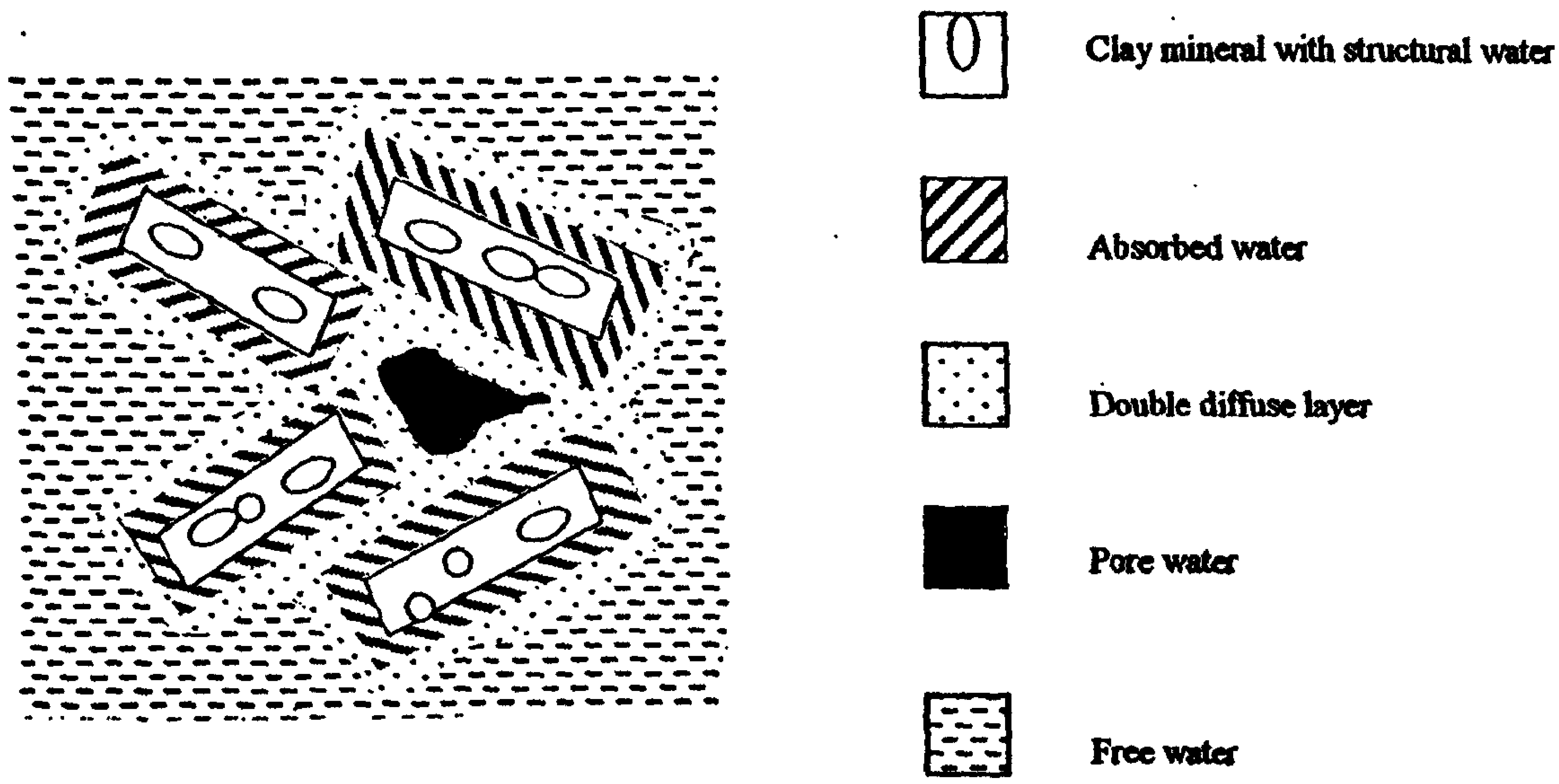


Figure 6.1 Classification of water structures about clay minerals

Redefining mechanical water as the non-structural water structures particular to clays, mechanical water comprises absorbed water and the water contained within the diffuse double layer. The double diffuse layer shown in Figure 6.2 comprises an electric double layer and a region of thermal diffusion. The electric double layer occurs as the result of cations in solution, aligning themselves immediately adjacent to the predominantly negative surface charge of the clay minerals. However there is also a thermal diffusive force which tends to drive cations out of this area of high concentration which is counterbalanced by the coulombic forces of attraction. The resulting arrangement of ions about a clay mineral surface is shown in Figure 6.2.

Arnold (1978), White (1979) and Sposito (1984), offer a fuller commentary on this model, also known as the Guoy-Chapman model, after the investigators who independently proposed the theory. The forces controlling the thickness of the diffuse double layer decrease as the distance from the surface of the clay mineral increases until the water is no longer bound within the double layer but retains the property of free water. Consequently

Selby (1993) suggests that the water bound within the double layer is more viscous in nature. Landon (1991) concedes to this opinion when discussing the retention of water in unsaturated soils.

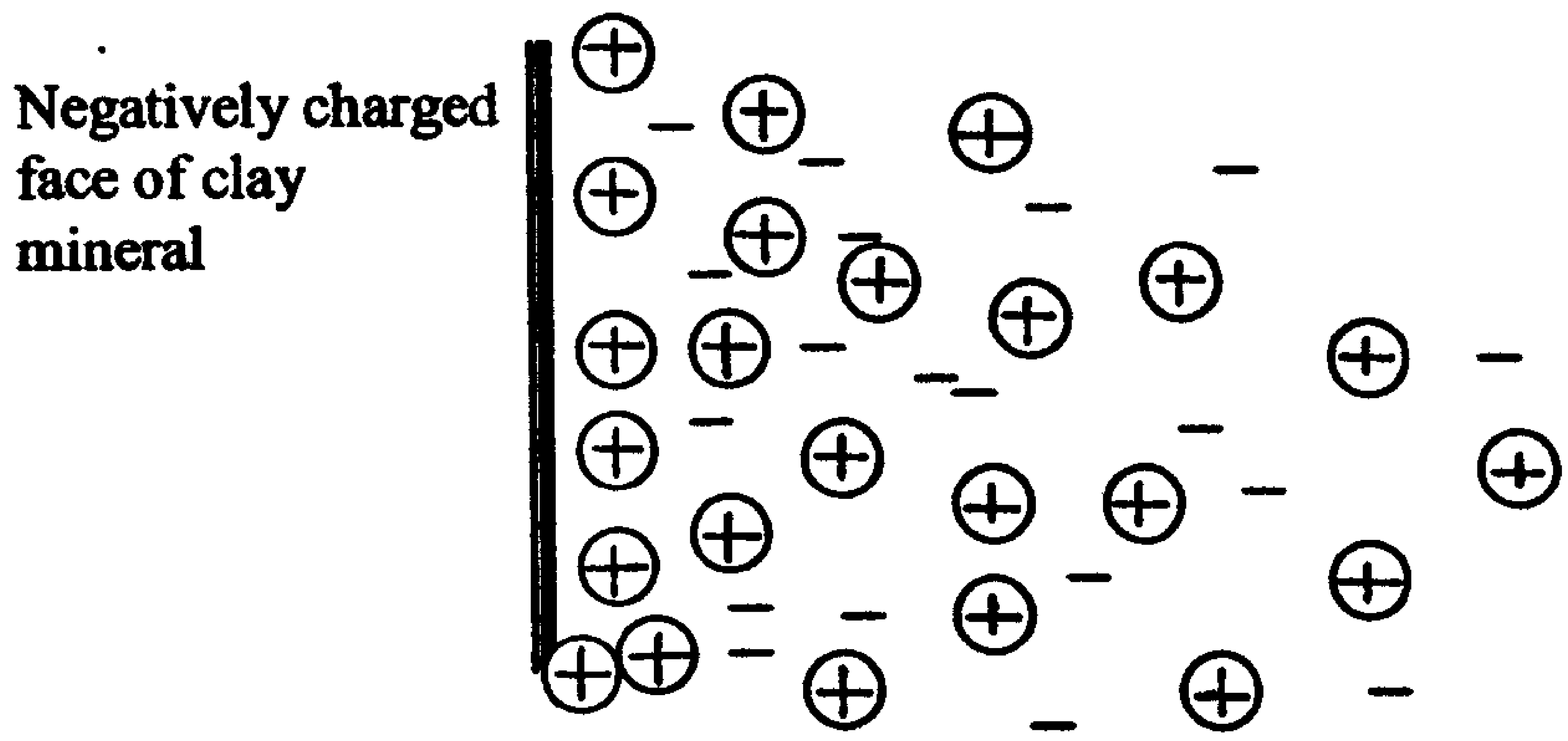


Figure 6.2 Guoy Chapman diffuse double layer

6.2.2 The retention of water in unsaturated soils

According to Landon (1991), the majority of water held by unsaturated soils occurs in thin films on soil particle or pore surfaces, where its physical properties differ from that of the bulk liquid which would fill the larger pores. The retention of water on clay particles is discussed in Section 6.2.1. However, particle or pore surfaces that are sufficiently close together may also retain water in discrete rings (Fountaine, 1954). This later form of retention is due to surface tension forces (Road Research, 1952). Keen (1931) offers a succinct analysis of the development of these forces with decreasing moisture content, and the following description is based on Keen's discussion.

For a saturated soil the air-water boundary has zero pressure deficiency. The removal of water induces a pressure deficiency between atmospheric pressure and the lower pressure of the water retained in the soil. The magnitude of this pressure differential is reflected in the radii of the menisci formed in the surface pores. These surface pores connect to narrower pores within the soil matrix via constricted channels. Once the meniscus reaches this constriction, pressure-instability forces water to displace into the smaller pore space. The meniscus continues to advance inward as more water is removed and water is displaced into smaller diameter pores. Thus a reduction in moisture content is accompanied by increased suction. However, as the removal of water progresses the retention of water becomes less linked to matrix structure and more specifically linked to clay surface chemistry, as discussed previously.

6.2.3 Water retention in a soil and cob matrix

Figure 6.3 re-presents the moisture characteristic curves produced in Figure 5.27 showing comparative plots for soil and cob samples for each soil series. Initial observation of these plots is focused on the higher retention volumes suggested by four out of five (the Halstow Soil Series being the exception) of the cob samples at the larger pressures. Reference to Appendix G will show that these soils were compacted at slightly higher moisture contents and thus the initial retention of larger water volume is unsurprising. However, Figure 6.3 illustrates sharper declines in the water volumes retained within the cob samples between pressure applications equivalent to 3.0pF to 3.5pF. This is echoed by the increased volumes held by pores within the cob samples of the Crediton, Dunsford, Tedburn and Bridgnorth Series, illustrated by the pore size distribution curves shown in Figure 5.40. Obviously the cob samples possess a commonality that remains singular to these samples and is not shared by the soil samples. This is also suggested from the decline in water retention shown for these cob samples occurring about a similar range of applied pressure for these particular retention curves. The commonality shared by these samples is that of straw inclusion within the matrix.

The addition of straw to the soil matrix to form cob, eventually, over the course of drying, results in an increase in void space within a defined volume of cob when compared to a similar volume of soil, for a given soil series. The reason for this is primarily due to the shrinkage of the straw during drying which results in the appearance of a fine line of

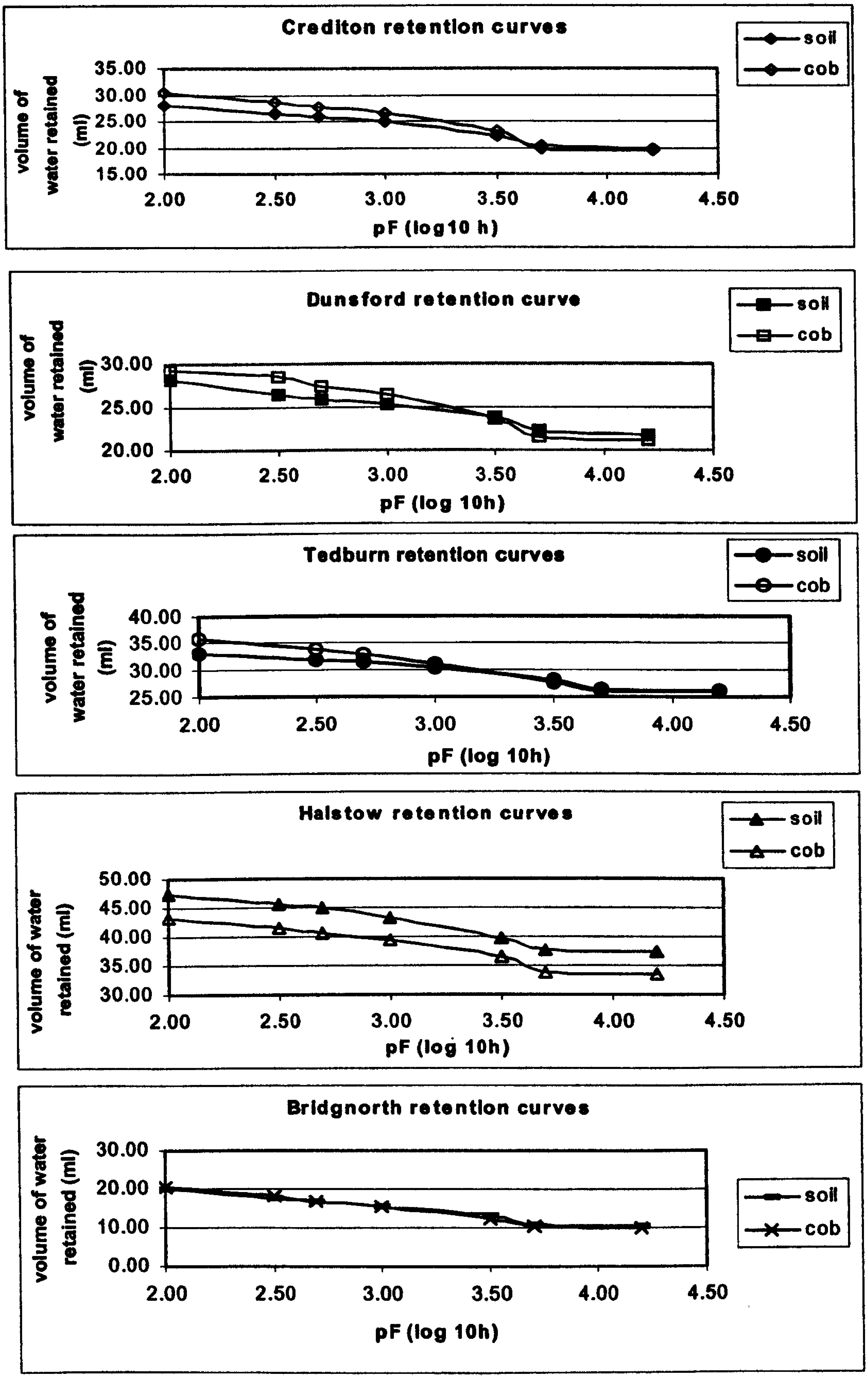


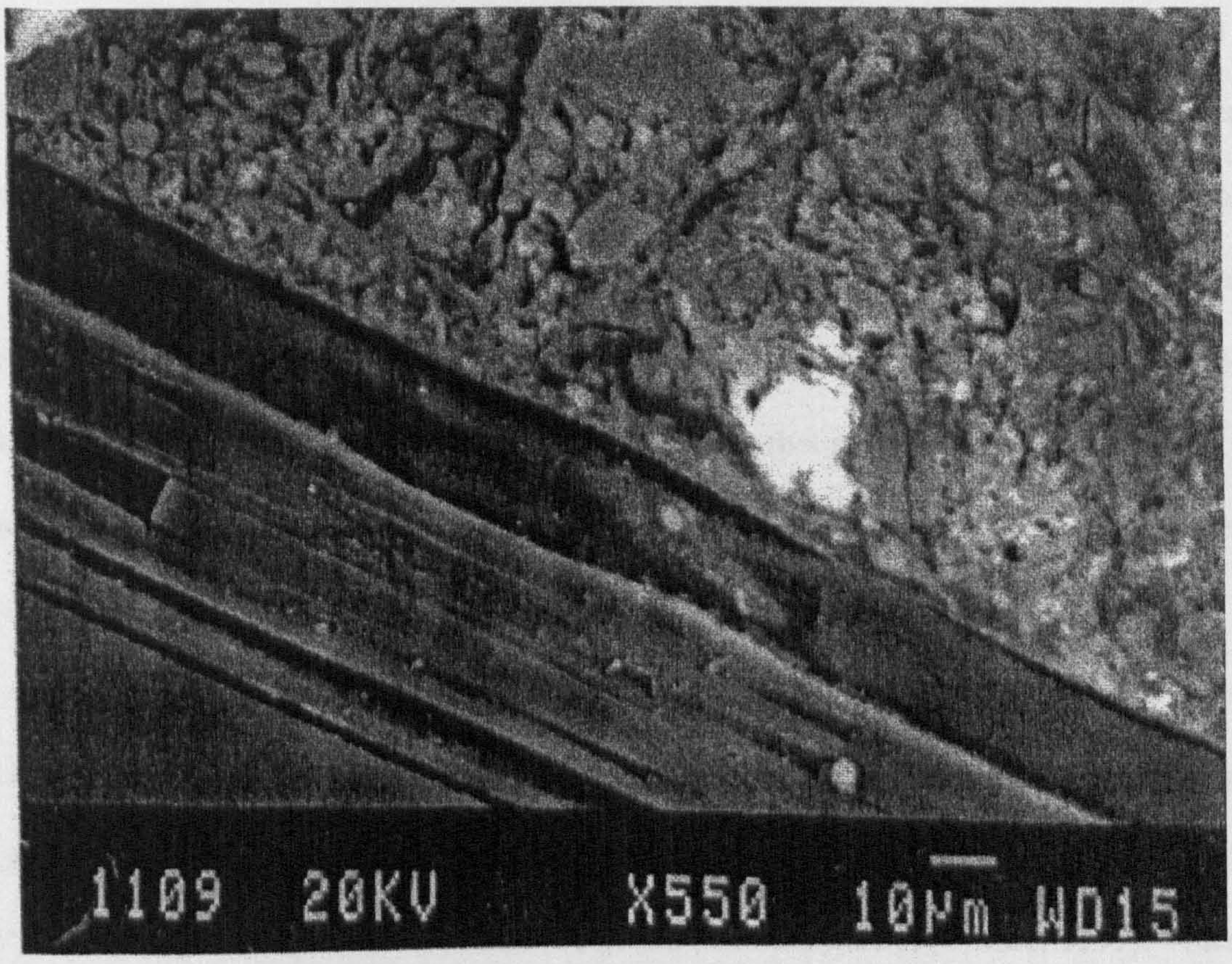
Figure 6.3 Moisture characteristic curves for soil/cob samples for each soil series

voids, along the length of the fibre (Castro et al, 1981; Ghavami, 1999; Lilholt et al., 2000). The occurrence of this void line is affirmed by an electron micograph taken of a Crediton cob sample, showing the interface between the straw and soil (see Plate 6.1). Utilising the scale shown on the micrograph the void line may be shown to be approximately 2μm wide. Returning to Table 5.17 the water volumes released at pore sizes 2-0.8 μm for each soil series, are shown to increase on comparing the soil and cob samples.

After 15 bars, water availability depends on clay content (Hall et al., 1977), assuming the applicability of this test to field soils investigated for the purpose of agricultural interest. However this investigation into Devon cob utilises destructed soils, compacted to produce an alternative material. The orientation of clays have been shown to influence the pore size distribution and strength of soils (Al-Jalili, 1976). Consequently, issues remain concerning the alignment of clays about the fibre inclusions and their affect on strength. The significance of particle orientation to strength is discussed later in this chapter.

6.3 Moisture, matrix and UCC strength

Test Series Three has illustrated, via means of Figures 5.24 to 5.28 inclusive, the variation in UCC strength when the moisture content at test is varied for both the soil and cob samples. The generalised form of this relationship is common to both the soil and cob samples and is shown in Figure 6.4. The relationship appears to be definable by three phases of strength development, phases A to C. It is suggested that the mechanisms controlling strength development at this stage are similarly definable and are discussed below. While straw inclusion into the soil matrix does not appear to influence these mechanisms (as the three phases of strength development are exhibited by both the soil and the cob cylinders) it does appear to exert considerable influence on the peak strength values attained. Alternatively the inclusion of straw into the soil matrix has no influence at all. These differing phenomenological responses are considered below.



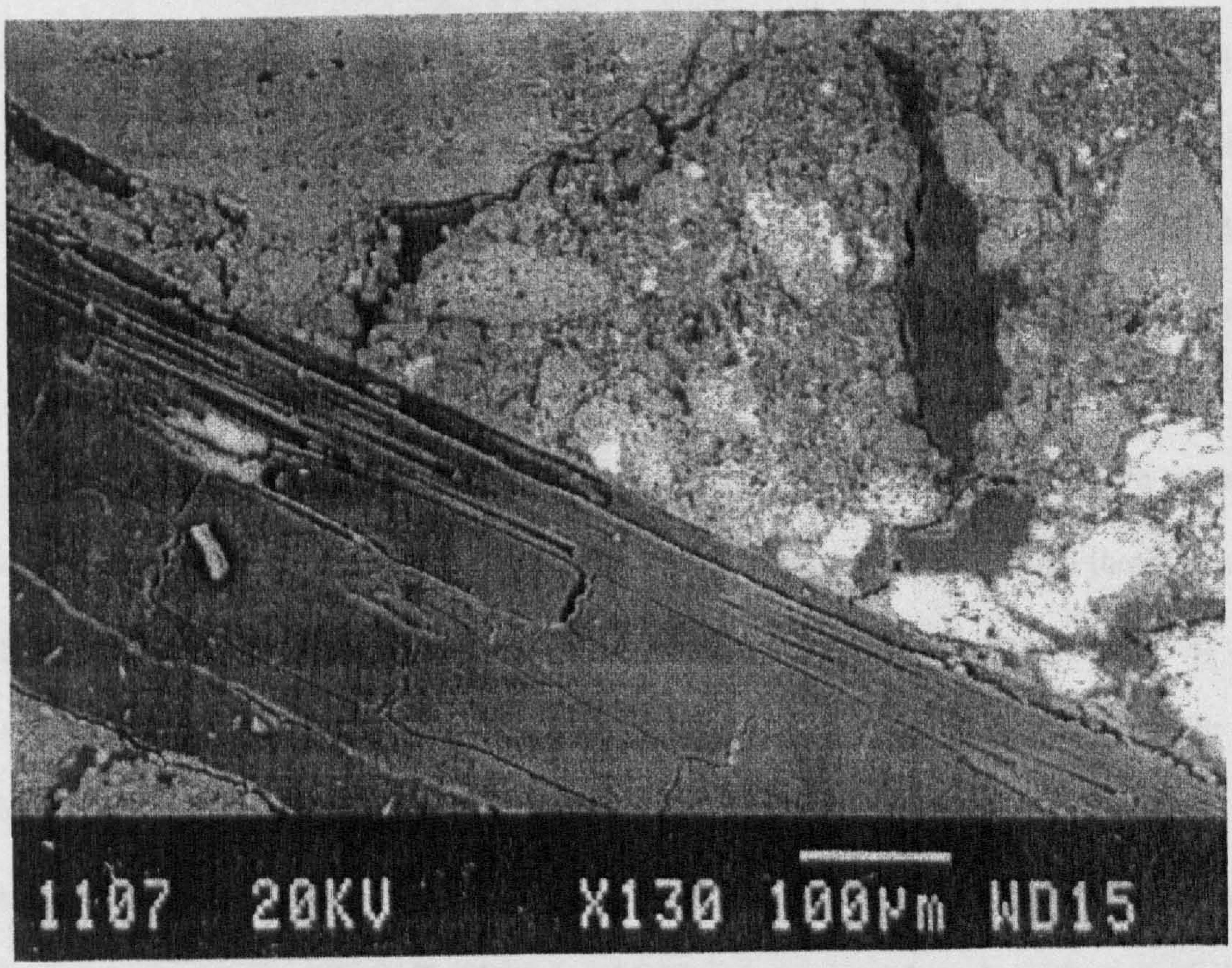


Plate 6.1 Micrographs of Crediton Cob sample

6.3.1 The forces governing UCC strength of a soil/cob matrix.

Figure 6.4 illustrates the generalised relationship that exists between moisture content and UCC strength in a soil or cob matrix. Three phases of strength development are suggested and highlighted in Figure 6.4 as phases A to C, in order of decreasing moisture content.

Phase A defines the development of strength in the moist, post manufacture period of the soil/cob samples. Post manufacture, the samples are not fully saturated but the low energy status (soil-water potential) of the soil ensures that surface tension is not high. Thus on application of the compressive load, particles are easily mobilised at relatively small strains (see Figures 5.28 to 5.27). To do this, surface friction at particle level must be overcome. Obviously a clay particle surrounded by an extensive double layer achieves greater separation from other particles (a situation perpetuated by the forces of interparticle repulsion arising from the osmotic activity in the diffuse double layer; Warkentin & Yong, 1962), contributing little to the frictional resistance of the matrix (Moore, 1991). Thus the percentage distribution of the non-clay particles together with their shape characteristics (angularity, asperities) becomes potentially relevant to defining peak strength within this phase. Once mobilised, particles rotate over each other re-positioning themselves in voids under the action of the increasing load, effectively densifying/work-hardening under this load to realise peak strength. Phase A shall therefore be re-defined as the dilatant frictional phase.

The peak strengths obtained during the second phase, phase B, are shown to rise steadily with decreasing moisture content. During this phase, it is suggested that tension surface forces dominate. These forces increase during the period of drying as the soil water potential steadily increases, resulting in the apparent cohesion of the matrix. Thus the ability of the structural matrix to carry load, over the range of moisture contents that defines this phase, is dominated by the micropore structure within the material. Adequate specification of compactive effort becomes highly consequential to phase B strength development, as compaction is known to increase the micropore and mesopore volume

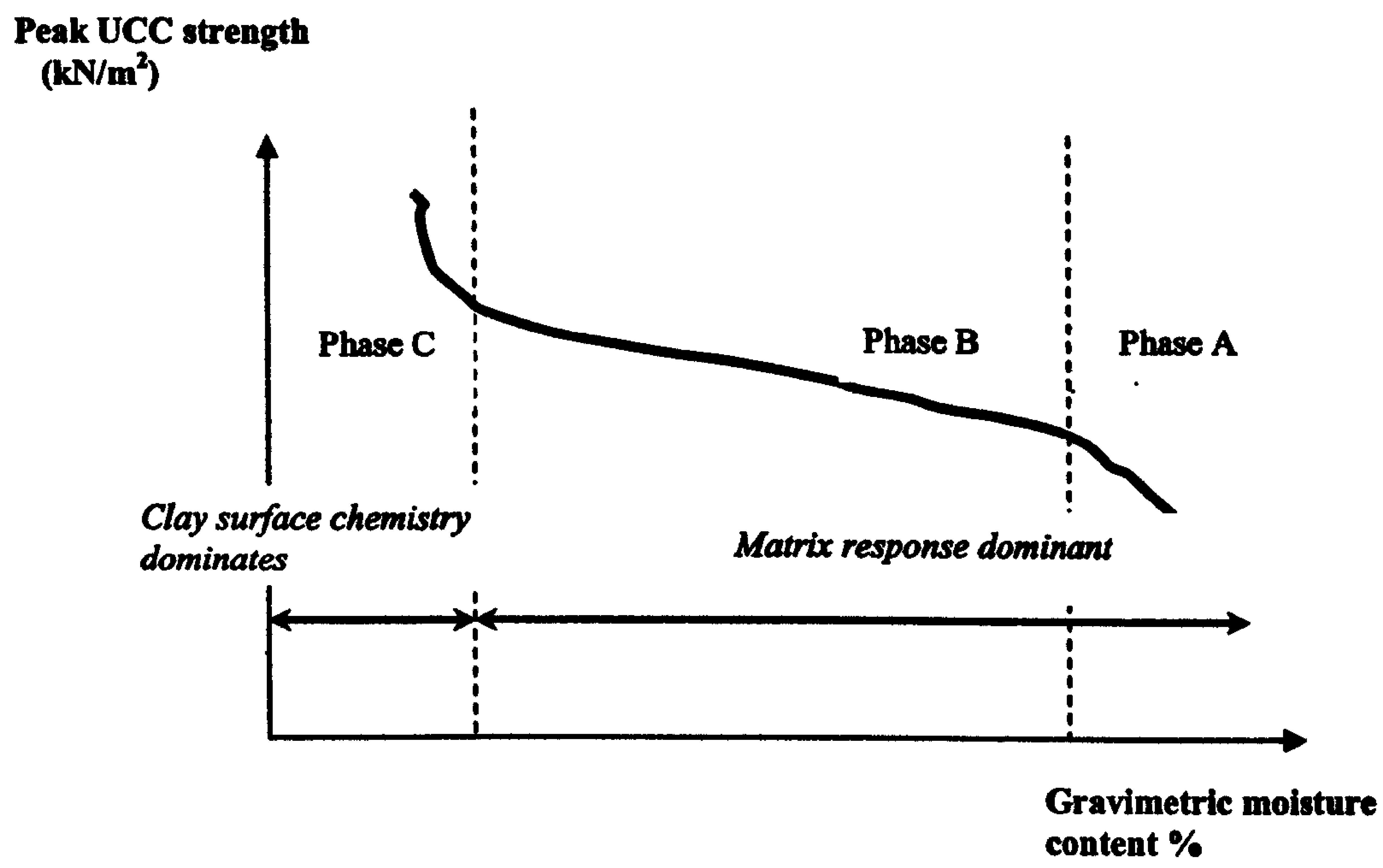


Figure 6.4 The mechanisms controlling the peak UCC strength of soil/ cob

relative to the macorpore volume of a given soil (Sridharan et al., 1971; Langdon, 1991). Furthermore the surface texture of rough aggregates is also known to be influential to the frequency distribution of micropores (Langdon, 1991). Henceforth this phase shall be redefined as the micro-dilatant phase.

Finally, during phase C, as moisture contents approach equilibrium under air-dried conditions, the significance of the structure of the material matrix is less relevant to a discussion concerning the mechanisms governing peak strength, than the clay water chemistry. The clay water chemistry within a given matrix will determine the contribution of the clay to frictional and cohesive strength. This contribution defines behaviour in this the non-dilatant phase.

6.3.1.1 Cohesion in clays

Moore (1991) attributes the cohesion of clays to the ionic and hydrogen bonding (chemical bonding) between clay particles and the hydrogen bonds between mineral layers. *Hydrogen bonding* between mineral layers occurs due to the distortion of charge distribution within a water molecule which results in a permanent dipole (see Figure 6.5). The side to which the hydrogen atoms are attached is electropositive while the opposite side is electronegative. This polarity in charge distribution permits water molecules to adhere to clays as the electropositive side aligns itself adjacent to the negatively charged clay faces to satisfy the charge deficit. Meanwhile the negative pole must satisfy its own charge deficit by cohering itself to the positive pole of another water molecule via hydrogen bonding.

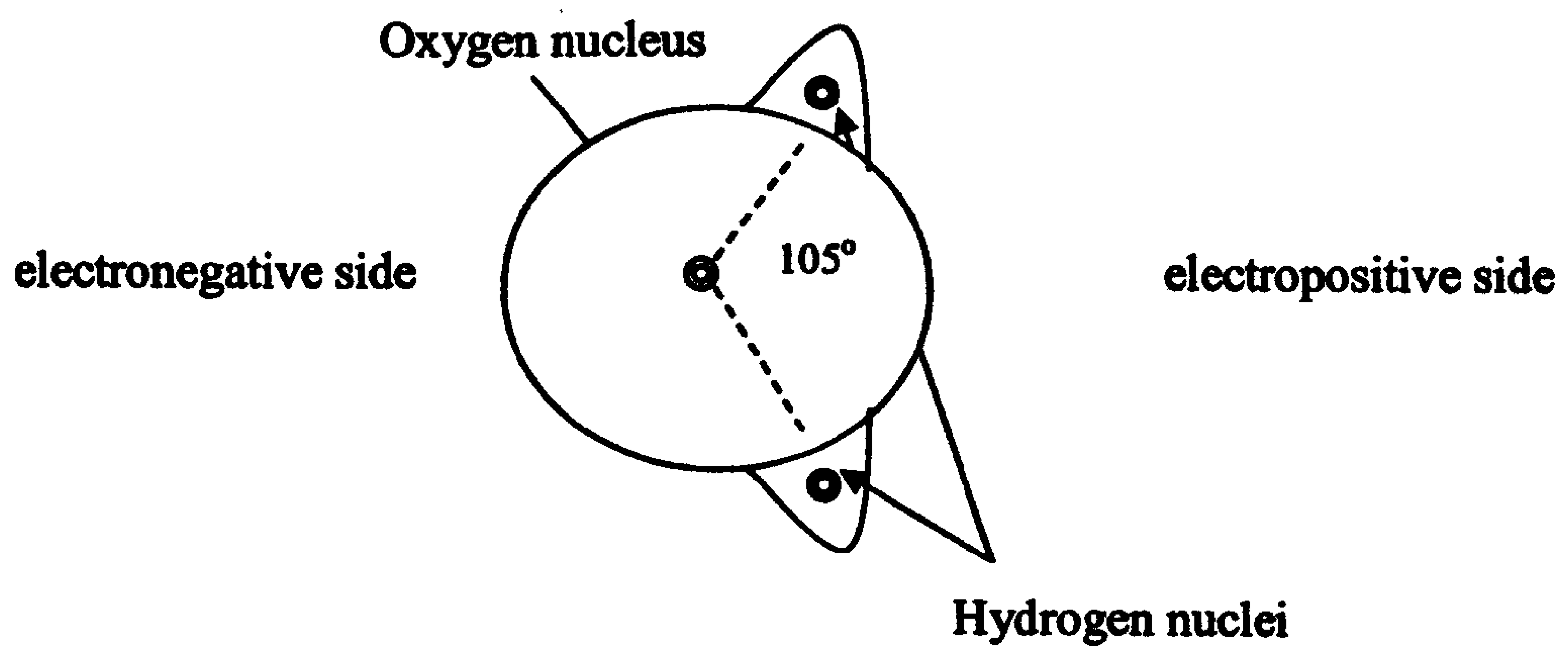


Figure 6.5 A two-dimensional representation of a water molecule

Ionic bonding may define the strong bonding of positive ions to negative mineral faces within the structure of the clay mineral or the electrostatic forces that result from the interactions between positive ions (cations) within the clay water and the negatively charged anions. Figure 6.6 illustrates the cohesion between two clay particles due to electrostatic ionic bonding between a clay water cation and an orientated water molecule. The strength of these bonds is shown to increase with increasing concentration of ions within the absorbed water (Selby, 1993). Thus the removal of water on drying results in less dilution of these ions and therefore increasing bond strength.

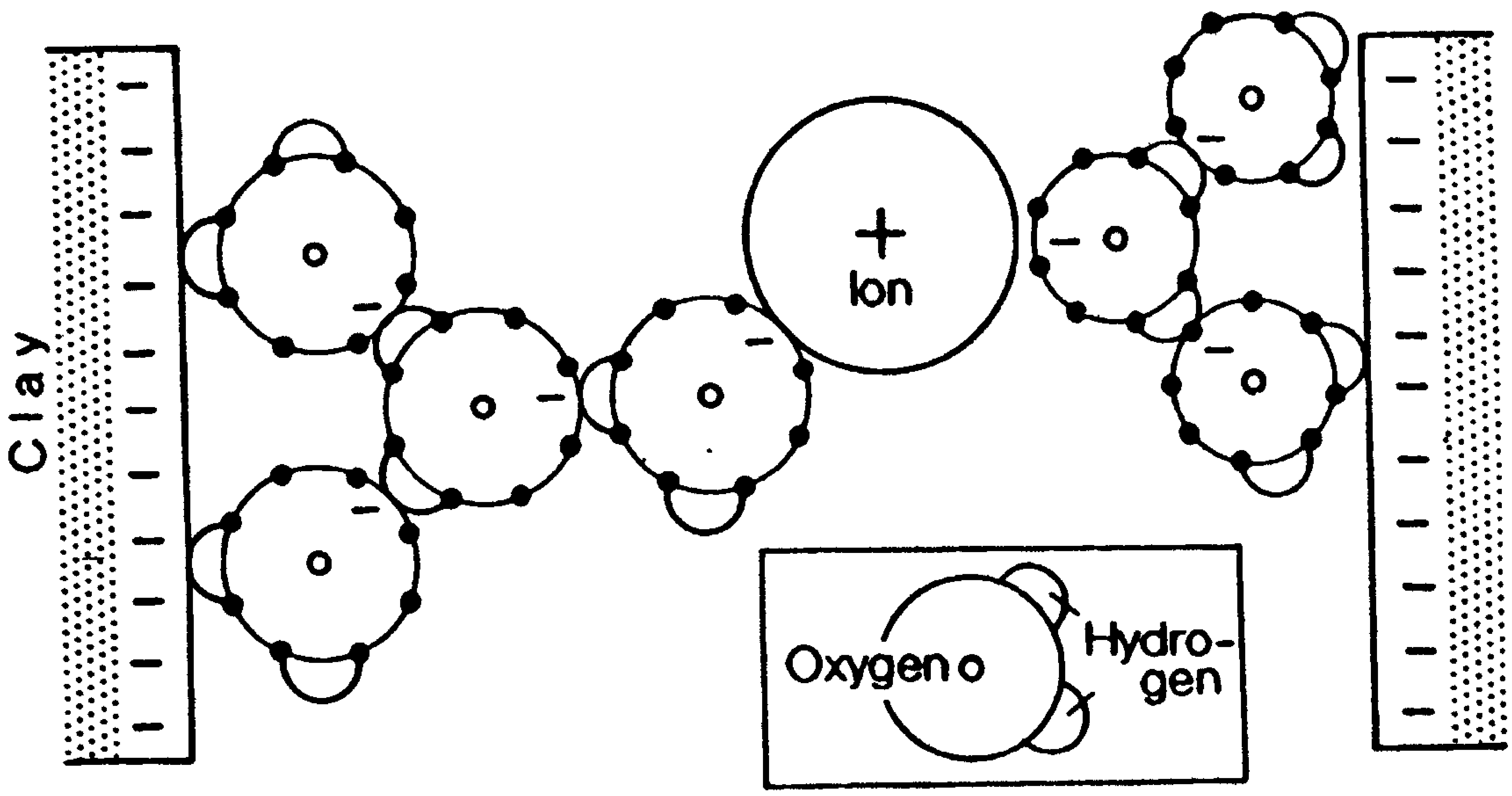


Figure 6.6 Ionic bonding in a clay-water system, from Selby (1993)

Secondary electrostatic bonding may also contribute to strength. Secondary bonding arises due to the need for clays to satisfy their electron charge. The predominantly negative basal clay face may neutralise its charge by bonding to the positive edge of a neighbouring clay crystal. Large numbers of clays bonded in this way have real impact on the clay fabric that may be described as being flocculated. Alternatively, neighbouring clay crystals may orientate themselves edge to edge or face to face. Thus, interparticle forces (forces of attraction or repulsion, discussed below) determine particle arrangements and are potentially influential to shear strength (Warkentin and Yong, 1962). The parallel orientation of clays has been shown to define the particle arrangement of clays along a shear plane (Muhunthan, 1991). Compaction is also shown to influence particle arrangement and therefore strength (Hilf, 1975; Al-Jalili, 1976).

6.3.1.2 Friction forces in clays

The friction contribution of clays may be considered in physio-chemical terms of clay particle adherence. When two clays are brought into contact under stress the area of contact will yield. Due to the close proximity of the contact areas the exchangeable ions will distribute into the interparticle space and adhesion occurs due to forces of electostatic attraction (coulombic attraction) and Van der Waal's forces (Rosenqvist, 1961).

Van der Waal's forces are the name for the forces of attraction that occur between uncharged molecules. These forces occur because of permanent molecular polarity (as in the case of water) or temporary molecular polarity. Temporary molecular polarity occurs due to instantaneous electron movements within the atomic shells creating a charge imbalance across the molecule. In response an instantaneous dipole is induced in adjacent molecules which gives rise to net attraction. According to Yong and Warkentin (1975), adhesion is responsible for shear resistance and must be overcome before particles mobilise and slide. Van der Waals forces of attraction are pertinent to clay spacings less than 15A (Rosenqvist, 1961; Yong and Warkentin, 1975). Clay spacings in excess of 15A gives rise to particle repulsion. The interparticle forces of attraction and repulsion in clays are influenced by exchangeable cations and soil pH (Sridharan et al., 1988).

Moore (1991) discusses the contribution of clay mineral surface area to friction and concludes that particles of larger surface area have a greater contribution to the friction resistance of the matrix. Furthermore friction is increased by reducing the thickness of the diffuse double layer, as may be experienced by a drying clay matrix.

6.3.1.3 Bond strengths in soils

Table 6.2 illustrates the bond strengths attributable to a soil/cob matrix.

From the discussion presented above, surface tension forces, ionic electrostatic forces and Van der Waals forces are all shown to increase with a drying clay-water matrix. While section 6.3.1 has discussed the influence of surface tension forces during phase B, the micro-dilatant phase of Figure 6.4, the rise in peak compressive strength obtained within the non-dilatant phase C, is potentially indicative of the dominance of the ionic electrostatic interactions occuring within the ion-rich absorbed claywater, typified by low water content matrices.

Types of bond	Strength of soil system (kN/m^2)
Chemical, intermolecular ionic, covalent and hydrogen	$10^4 - 10^5$
Van der Waals, interaction of polar molecules	< 10
Ionic electrostatic, interactions between charged clay surfaces and cations.	< 1000
Coulombic electrostatic, forces of attraction and repulsion of charged surface particles	1-10
Magnetic forces of ferromagnesian minerals	0.1 – 1
Apparent cohesion from surface tension in water films	<400

Table 6.2 Bond strength in soils, Vyalov (1986) ibid. Selby (1993).

6.3.2 Assessing the impact of straw within a soil matrix on the UCC strength capacity

The discussion above regarding the forces influencing the behaviour of the soil and cob sample- matrices, remains generic for both materials. However, the inclusion of straw into the soil matrix to form cob has produced some significant strength gains as highlighted in Section 6.1. The following discussion will rationalise the behaviour of the soil/ straw composite that is cob, in order to identify its contribution to dry and wet UCC strength.

On UCC testing during the post-manufacture state (*wet testing*), it is suggested that the tensile capacity of the straw within the cob cylinders will be mobilised predominantly via frictional interaction with the larger matrix particles. The potential of straw to distribute the stress from a crack tip to a straw fibre and utilise its tensile capacity, as highlighted by Greer (1996) and described in Section 2.3, is the primary reason that the UCC strength of a cob matrix exceeds that of its soil counterpart. However to enable this to occur, the ends of the straw must remain embedded within the matrix (see Figure 2.1, fibre 2). At this stage the instantaneous utilisation of the tensile capacity of the straw is accompanied by progressive work-hardening of the soil matrix in its 'wet' state. Since work-hardening promotes the densification of the matrix structure via an increase in particle contact, the straw/soil contact within a cob sample will also increase permitting further load application with increasing strain. With contact improved, and the fibres held in tension, loads exceeding those of the soil-only matrix may be applied as the tensile straw bands restrict movement and permit loading.

In essence this situation is similar to that experienced by a soil in a confined triaxial test, sheathed in a water-proof membrane. As the axial load is increased, lateral tension is induced in the test-cylinder and as the cylinder barrels, the membrane is forced into tension. In this situation it is advantageous to minimise the stiffness of the membrane in order to prevent the tensile capacity of the membrane from influencing the outcome of the compression test. In the case of the cob matrix, optimisation of the tensile capacity of the straw and its influence on the determination of UCC strength capacity is desirable.

Consider now the role of straw inclusion on UCC strength of air-dried cob cylinders (*dry tests*). At this stage of partial saturation, it is important to note that the straw is not bonded within the cob matrix but exists embedded in the soil, separated from the clay matrix by a fine void space along the length of the fibre (as established in Section 6.2.3). This void space is therefore analogous to a tube. Crack propagation is not, therefore, curtailed by the dissipation of energies during the debonding of the straw from the cob matrix as has been reported (Greer, 1996), but is curtailed by the dissipation of energies about the circumferential area of the internal void space. The bonds that have to be overcome are still those that define the non-dilatant phase of soil-strength, as defined above.

On surmounting the bond strength of the clays in the non-dilatant phase, further load may be applied due to the reinforcing nature of the straw transversing the failure plane (see Figure 6.7).

Figure 6.7 illustrates the potential of the straw to maintain the structure of the cylinder, permitting the continued application of load until further straining disrupts the integrity of the sample under test. It is important to note that on cessation of testing of air-

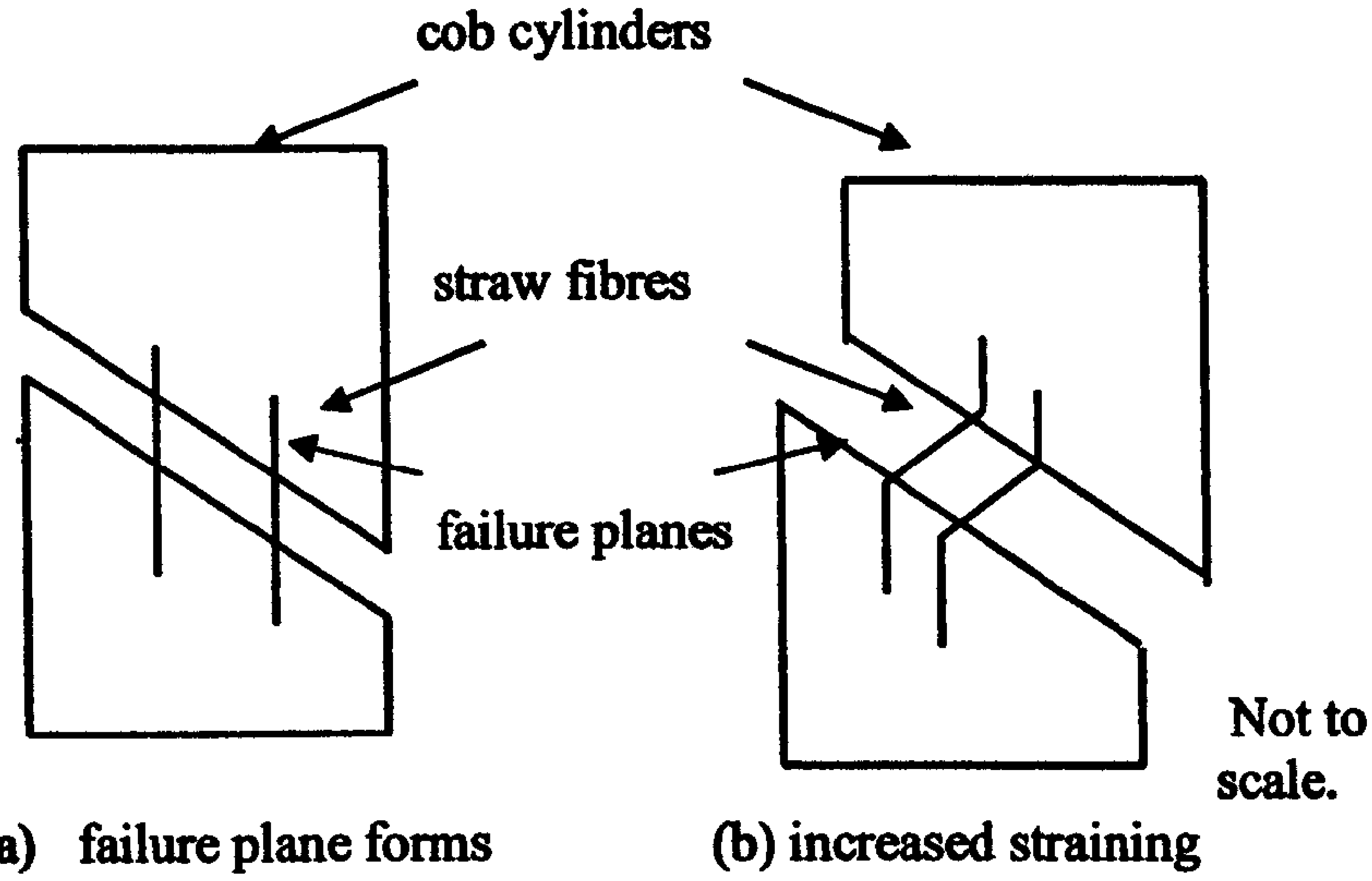


Figure 6.7 Representation of two straw fibres transversing the failure plane of an air-dried cob cylinder.

dried samples no straw fibre was shown to have broken as may have occurred for a fibre composite with strong matrix to fibre cohesion (Kelly and Macmillan, 1985). In the absence of bonding, it is postulated that the fibres are held within the matrix by frictional forces. Thus pull-out strength, fibre embedment, and the number of fibres transversing the shear plane become relevant to the discussion of fibre/matrix interaction. Implicit in this is the notion of tortuosity. Unlike the representation shown in Figure 6.7 (a), straw fibres are randomly aligned within a cob matrix, thus the tortuosity of their pathway to achieve pull-out must be represented in any definitive model presented. Morel et al (2000) have attempted to model, with some success, the behaviour of sisal reinforcement within a soil matrix adopting the kinematic assumption of fibre breakage across the shear plane. This assumption is not valid for the behaviour of the cob matrices investigated. The discussion that follows considers the specific matrices of the sampled soils in light of the ideas presented above.

6.3.3 Moisture, selected soil matrices and UCC strength

The previous section has discussed the mechanisms associated with UCC strength development within a soil/cob matrix, tested over decreasing moisture. The UCC strength development of the Crediton, Dunsford, Tedburn, Halstow and Bridgnorth soil/cob matrices as illustrated in Figures 5.24 to 5.28, are now re-addressed in light of this discussion, and in consideration of their classification data as presented in Chapter 3.

On consideration of the Crediton Soil Series, Figure 5.24, the significant strength gains exhibited by this series for Test Series One and Two, appears to be pertinent to all phases of strength development along the drying curve. In not reaching the same degree of air-drying attained by the cob cylinders, predictive values may be found for the soil cylinders, utilising the regression equations established during Test Series Three. At a moisture content of 3.31% (the lowest test moisture content for the cob samples) the predictive UCC strength of a soil sample is 345.1kN/m^2. Clearly the strength gains illustrated by the Crediton cob samples appear to be increasing on drying. Given that the particle matrixes adopted in Test Series Three are the same for the cob as the soil tests, thus particle distributions and mineralogy between test series remains the same, the only potential difference is the arrangement of the fabric of the clay about the straw fibres. For the strength gains suggested, the clay fabric about the fibres is most likely to exhibit flocculation since this particle arrangement has been shown to improve strength capacity (Al-Jalili, 1987). The flocculation of kaolinitic soils has been shown to increase strength (Warkentin and Yong, 1962). However, consideration of Table 3.5 shows the low percentage fine fraction associated with the Crediton Soil Series and it is surprising that such low fractions produce such a marked strength increase in this phase of strength development. While the 'activity' (the A_S and A_{CB} values) of this fraction may potentially negate the percentage size fraction in relative terms, the values shown in Table 3.9 are unlikely to reflect the UCC strength increases shown.

The contribution of the straw to the UCC strength of the cob matrix over a descending range of moisture contents, would appear, on observation of Figures 5.25 and 5.26, for the Dunsford and Tedburn Soil Series cylinders, to behave in a consistent manner from the dilatant to non-dilatant phases of strength development. Here the mechanical effect of fibre inclusion does not appear to affect the mechanical behaviour of the soil matrix. Instead the addition of straw within the soil matrices of these soil series produces an output suggesting these soils are influenced by an external force (see Figures 5.25 and 5.26).

Considering the relative particle distributions of these fractions, the Dunsford Soil Series is shown to posses a fine fraction of approximately 35% while the Tedburn Soil Series has a fine fraction of 51% (see Table 3.5). For the Dunsford Soil Series, Skempton's 'Activity' A_S is 2.4 while the 'blue activity' A_{CB} is 10.5. The Tedburn Soil Series shows Skempton's 'Activity' A_S is 0.79 while the 'blue activity' A_{CB} is 4.23. The trend of these values is consistent between these soils and both suggest that potentially the physico-chemical reactions for the Dunsford Soil Series are greater than those of the clays within the Tedburn Soil Series. The greater strength capacity of the Dunsford Soil Series may therefore be attributable to this activity, despite the lower percentage fines associated with this soil. The fact that the relationship between these two sets of activity values may not be defined in relative terms may not be relevant, considering that natural soils are not known to conform to the linear law of mixtures (Sivapullaiah, 1985; Sridharan et al., 1988).

The activity values of the Halstow Soil Series are such that A_S is 0.72 while A_{CB} is 4.36. From Table 3.5 the predominance of clay and silt within this matrix becomes apparent and an immediate conclusion may be that the composition of the soil matrix , the clay-water chemistry, interparticle exchange reactions and clay mineralogy (properties collectively refered to as the physico-chemical properties of clays) will dominate the behaviour of this matrix at 1% straw inclusion. This conclusion is supported by the apparent insignificance of the presence of straw, within the cob matrix of the Halstow Soil

Series, on the mechanical behaviour of the soil (see Figure 5.27). Furthermore, the Test Series One (*air-dried*) results for Halstow Soil Series illustrated no significant strength variation occurred on adding straw to the soil matrix. This later result is surprising, given that this lack of variation accompanied a significant reduction in the comparative densities of the test soil cylinder densities, to those of the cob cylinders for this soil series. Higher density suggests higher numbers of particle to particle contact reducing localised compressive stresses and the development of lateral tensile stresses. A point occurs where control of the developing tensile stresses is critical to preventing dislocation that will reduce the particle to particle contact and negate the benefits of structural density. The addition of 1.0% straw within the soil matrix appears to balance the needs of the matrix to maintain its integrity by mobilisation of the tensile capacity of the straw thus enabling it to realise its UCC strength capacity.

The average peak UCC strength of the air-dried cob samples for the Halstow Soil Series lies only just above that of the Bridgnorth Series (at 1185kN/m^2 and 1188kN/m^2 respectively). However the matrices of these soil types are considerably different with the coarse fractions dominating that of the Bridgnorth series as opposed to the fine fractions of the Halstow series (see Table 3.5). Considering Figure 5.28, the frictional characteristics of the coarse fraction of the Bridgnorth Series appear to easily mobilise the tensile capacity of the straw over the dilatant and micro-dilatant phases. Strength development in the non-dilatant phase is similar to that exhibited by the Crediton Soil Series discussed above. The activity of this series is such that A_S is 6.96 while A_{CB} is 10.66. These values are slightly lower than those of the Crediton Soil Series but greater than those of the other soils sampled. Consider Table 3.7, and the relative percentages of minerals capable of cation exchange reactions (31% for Bridgnorth and 58% for Crediton). The lower activity of the Bridgnorth Soil Series may be explained in that activity values are calculated from the fraction of clay sized particles. This is not necessarily the same as the value of the clay fraction. If the physio-chemical activity of the clays together with the fabric of the cob matrix dominates behaviour in this phase then the strength development of the Crediton Soil Series may be expected to exhibit similar gains to that of the Bridgnorth Soil Series when the soil is utilised as cob. Comparison of Figures 5.24 and 5.28 may suggest this.

6.4 Conclusions

The pressure membrane apparatus has been utilised to investigate the micro-structure of the cob matrix and has facilitated the discussion concerning voidage within an earth/straw fibre composite. This in turn has clarified the role of the straw within the cob matrix as providing tension reinforcement during crack propagation. A three phase model of strength development during the drying of a cob matrix has been proposed. The function of the model shows a good fit with the data collected for all the soils sampled. Each phase of strength development is described in terms of the forces applicable to a drying cob matrix but further micro-scopic studies into the fully air-dried cob-state are required to support the validity of the discussion presented. These later sentiments are echoed in Chapter 7 and proposals are made to extend the investigation accordingly.

Chapter 7. Conclusions drawn from this investigation

7.1 Summary

Earthen building techniques have been adopted throughout the World (Houben, 1994). A particular technique known as cob construction has historically been utilised within the county of Devon, England. Chapter One, described this form of construction and discussed the developmental programme which aims to re-establish cob as a contemporary construction material.

Chapter Two identified the climate which has forced the need to re-address construction methods in today's society. It discussed the re-prioritising of issues pertinent to the construction industry, focusing upon the potential role of earthen building technology as an expanding area within a framework of re-assessed building technologies. Contemporary research on earthen construction techniques was presented and assessed in light of its particular relevance to cob construction from whence recommendations have been made to inform the test programme outlined in this investigation. The literature pertinent to cob construction is currently shown to lack adequate specification and documentation of a considered and coherent test methodology for Devon cob that accommodates the determination of material variability as an explicit output of its methodology. The existing research into Devon cob is confined by material selection, with all work utilising material sourced from one particular area of Devon. By adopting this material as an example of generic Devon cob, erroneous extrapolations have been suggested concerning the beneficial contribution of straw reinforcement to UCC strength within the cob matrix. This thesis has re-addressed this issue by selecting a variety of historically utilised cob, soil matrices, UCC testing them via a rigorous and pre-determined test program and illustrating that the role of straw reinforcement within the cob matrix is soil matrix dependent. These data are then used to inform a provisional test methodology specification for cob.

The selection of the soil matrices investigated was discussed in Chapter Three. Selection criteria were influenced by the descriptive and quantitative data presented by the relevant Soil Survey to bias sampling towards naturally weathered sequences of soil formation to ascertain potential material or structural relationships between soil types. Utilisation of the Soil Survey to this end proved less fruitful than had been imagined due to the limitations of the information presented, particularly concerning the quantitative data. However, while constrained, its use cannot be overlooked and its potential may be realised through future revisions to the investigative methodology.

The development of the test methodology presented in Chapter Four was essentially achieved by the consideration of traditional Devon cob as a representation of end-product specification. Information regarding representative straw contents and densities of traditional cob was considered and a method specification for the compaction of cob utilising a 7-Blow Proctor Test has been developed. The specification and adoption of an appropriate, standardised and repeatable methodology will facilitate analysis, behavioural understanding and dissemination of the performance of Devon cob in earthen construction.

Utilising the 7-blow Proctor, and all associated methodology from Chapter Four, Chapter Five presented the UCC strength properties attributable to traditional Devon cobs, together with their associated variability. This Chapter highlighted the significance of the particulate nature of the soil matrix in being able to mobilise the tensile capacity of the included straw fibres within a 1.0% straw, cob matrix. Results illustrating the development of strength from the condition of cob manufacture to air-dried bear little resemblance to previously documented results, which are unsupported by empirical data (Warren, 1999).

Chapter Six addressed the role of straw within the soil matrix. It is postulated that the post-manufacture strength of a cob matrix is dependent on the mobilisation of the tensile capacity of the straw, essentially via the frictional properties of the macro-soil-fractions. Alternatively, long-term (air-dried) strength is the domain of the micro-fabric and micro-fractions. The physico-chemical behaviour of clays together with surface tension forces are predominant in this post dilatant phase and are believed to be collectively or independently responsible for strength. Straw within a dried cob matrix provides anchorage across a developing fracture plane in an air-dried cob matrix, delaying dislocation and therefore maintaining material integrity until excess straining induces failure. In the particular case of a clay-rich cob matrix, it is suggested that the post-dilatant phase is dominated by the particulate nature of the soil, which will define strength, irrespective of the inclusion of straw within the matrix. While clay-rich soils benefit from the inclusion of straw in the construction phase and for the distribution of shrinkage cracks, these soils are potentially more suited to adobe (Section 1.2.1) as opposed to Devon cob construction. Chapter six also illustrated the presence of a void space about the straw fibre upon air-drying via a micropore investigation utilising the pressure membrane technique and electron micographic photography. Establishing the presence of this space therefore dismisses the potential of straw to diffuse crack propagation energy via debonding, as has been presumed in previous research (Greer, 1996).

This final chapter concludes by compiling the classification data with the average peak strengths attributable to the cob samples of each of the five soils selected, and presenting these data as Figure 7.1. Skempton activity and methylene blue activity values are shown as A_s/A_{CB} respectively; liquid limit and plastic values *LL/PL* are apparent, and the peak average air-dried strengths and peak average wet strengths are shown to the dry and wet side of optimum moisture content on the respective dry density curves. It would appear that lower Atterberg limits might define the high density, high load-bearing characteristics associated with the well-graded granular soils. The higher density soils are also shown to display higher activity. High plasticity index soils regardless of activity may be compacted within 5% of maximum density and are still likely to attain peak strength.

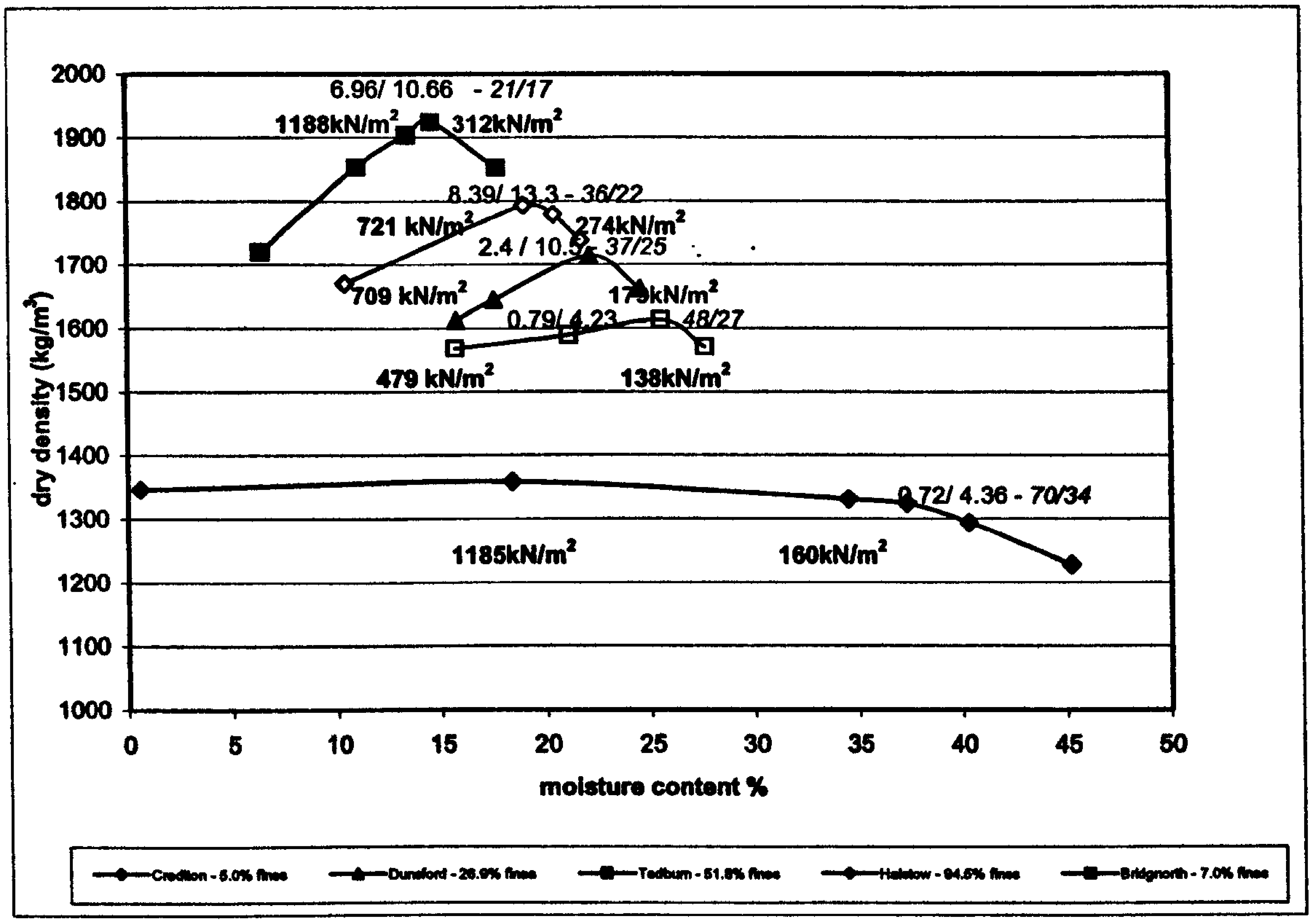


Figure 7.1 Data Synopsis

It is noteworthy to mention that both the Bridgnorth and Crediton Soil Series overlie the rocks of the Permo-Triassic formations, as discussed in Chapter 3. Keefe et al. (2000) have found cob buildings situated amid this geological area to be disproportionately prone to failure. Thus while the grading characteristics of these soils facilitate the production of high density, high load-bearing strength cob, failure may be induced by a reduction in negative pore water pressure. This situation may arise from the percolation of rainwater through the cob matrix as a result of cracked render or poor detailing.

7.2 Conclusions

- Current literature pertinent to cob construction lacks specification and documentation of a coherent test methodology.
- Presentation of 'The Soil Survey of England and Wales', requires modernisation to facilitate the broadening of its user-group and encompass its future application in the selection of suitable cob-building material.
- The 7-Bow Proctor is shown to offer a reproducible means of producing samples of traditional cob densities for laboratory testing within a rigorously established test methodology.
- Quantitative data from the laboratory investigation into the UCC strength determination of cob illustrates the role of straw within the soil-rich cob matrix is soil dependent.
- The development of UCC strength during the air-drying of a laboratory cob sample is shown occur in three successive phases namely; the dilatant frictional phase, the micro-dilatant phase and finally the non-dilatant phase.
- The pressure membrane apparatus has successfully been used to establish the pore space within a cob sample.
- Skempton's 'Activity' and 'Methylene Blue Activity' appear to provide a means to distinguish the compactability and load-carrying capacity of soils utilised in cob construction.

7.3 Recommendations for future work

- Given the existence of an established test-methodology for the UCC testing of cob, it is now possible to extend the scope of this existing work to encompass a wider selection of traditionally used Devon cobs. This information could easily form part of a database accompanying an inventory of cob buildings within Devon and thus provide technical data to support their conservation.

- The test methodology presented utilises 1.0% straw content only; the statistical significance/ insignificance of the strength gains attributable to the inclusion of straw within the cob matrix may vary with the percentage of straw inclusion. The mix utilised in this investigation attempted to replicate a traditional cob mix, informed by documentary evidence of historic cob buildings. The future of cob building within Devon may look to mix optimisation, in terms of density and straw contents, to maximise compressive strength characteristics. However, the density of Devon cob is equally linked to its thermal capacity via an inverse relationship. Thus mix optimisation must be considered holistically.
- Mix optimisation is inherently linked to material selection for cob. Integral to selection is the specification of requirement and an assessment of how this is determined. For example does the risk of collapse posed by the Bridgnorth Soil Series negate its use? What level of risk should be accepted?
- Micro-parametric studies utilising transition and scanning microscope techniques to illustrate the particle arrangement about the area of fibre inclusion would further clarify the influence of straw inclusion on the micro-fabric. This may potentially provide further insight to explain the evidence of accelerated strength gains of the cob samples over the soil samples on approaching air-dried conditions. A further development of this idea may be in the manipulation of cob fabric via the introduction of cation rich water within the mixing phase of cob construction, which, subject to the appropriate cation being used, may further improve strength. Implicit in this idea is the requirement to widen understanding of exchange reactions in clay-types that extend beyond kaolinite and montmorillonite. As this knowledge accrues, it is envisaged that reliable laws for mineral mixtures may develop.
- Micro-parametric studies may be extended utilising mercury porosimetry techniques, which would compliment the pressure membrane study, by extending the work to the next level of porosimetry. Inherent difficulties in the use of mercury porosimetry

techniques may be found in striving to obtain sample representativity, due the small volumes that can be analysed in this manner.

- Potential in extending the use of the pressure-membrane as a geotechnical classification tool which focuses on fabric classification, is foreseen. This would afford the first classification technique that maintains the structure of the natural soil to obtain classification. Drainage characteristics may be linked to porosimetry that may offer an insight into the requirement and specification of groundworks on development sites.

References

Al-Jalili, A.-B. K. (1976). *Pore size distribution and engineering properties of compacted clays*. PhD Thesis, University of Strathclyde.

Arnold, P. W. (1978). Surface-electrolyte interactions. In Greenland, D. J., & Hayes, M. H. B. (Eds.), The chemistry of soil constituents. Wiley Interscience, Chichester.

Avery, B. W. (1973). Soil classification in the soil survey of England and Wales. *Journal of Soil Science, 24,* 324-328.

Barnes, G. E. (2000). *Soil mechanics, principles and practice.* 2nd Edition. Macmillan Press Ltd.

Bee, B. (1997). *The Cob Builders Handbook. You Can Sculpt Your Own Home.* Groundworks, Murphy, U.S.A.

Bolger, N. B., Dinger, D. R., & Funk, J. E. (1993). Classification of select clays using methylene blue and particle-crowding indices. *Ceramic Engineering and Science Proceedings, 14 (1-2),* 206-211.

Bowles, J. E. (1984). *The physical and geotechnical properties of soils*. 2nd edition. McGraw-Hill.

Bradley, W. F., & Grim, R. E. (1961). Mica clay minerals. In Brown, G. (Ed.), *The X-ray identification and crystal structures of clay minerals*. Mineralogical Society: Clay Minerals Group, London.

Brady, N. C., & Weil, R. R. (2000). *Elements of the nature and properties of soils.* Prentice-Hall.

Brown, G. (Ed.) (1961) *The X-ray identification and crystal structures of clay minerals*. Mineralogical Society: Clay Minerals Group, London.

Brown, J. L. (1964). Laboratory techniques in the electron microscopy of clay minerals. In Rich, C. I. & Kunze, G. W. (Eds.), *Clay mineralogy*.

Brown, R.J. (1979). The English Country Cottage. Pub. Robert Hale. pp363.

British Standards Institute (1990). *BS1377. British standard methods for test of soils for civil engineering purposes.* British Standards Institute, London.

British Standards Institute (1985). *BS3921. British Standard Specification for Clay Bricks*, British Standards Institute, London.

Butler, B. E. (1980). *Soil classification for soil survey.* Clarendon Press, Oxford. pp.129.

Castro, J., & Naaman, A. E. (1981) Cement mortar reinforced with natural fibres. *Journal of the American Concrete Institution. Jan- Feb,* 69- 78.

CERF, (1996). *Engineering and Construction for Sustainable Development in the 21Century : Assessing Global Research Needs.* Report No. 96-5016A. Civil Engineering Research Foundation, Washington, DC.

Cernica, J. N. (1995) *Geotechnical Engineering, Soil Mechanics.* John Wiley & Sons, Inc. pp453.

Clayden, B. (1971). Memoirs of the soil survey of Great Britain, The Exeter District, Harpenden. The soil survey, Rothampsted Experimental Station, Harpenden, Herb.

CNRS, Centre National De La Researche Scientifique, (1995). Earth as a Building Material. URA – 1652, ENTPE, France pp8.

Croney, P., & Croney, D. (1998). *The design performance of road pavements.* 3rd Edition, McGraw-Hill.

Dada, Y. M. (1988). *The geotechnical interpretation of soils.* PhD Thesis, University of East Anglia, Norwich.

Day, D. E. (1966). Thermal stablisation of soils. Technical Report No. 6-706, U. S. Corps of Engineers, Washington D.C., 55.

Devon Historic Buildings Trust (1992). *The cob buildings of Devon 1, History, Building Methods and Conservation.* Devon Historic Building Trust.

Devon Historic Buildings Trust.(1993). *The cob buildings of Devon 2, Repair and Maintenance.* Devon Historic Building Trust.

Dinger, D. (1996). Prof. Ceramic Engineering, Clemson University. USA. Pers.Comm.

Durrance, E. M., & Laming, D. J. C. (Eds.) (1997). *Geology of Devon.* University of Exeter Press. pp.346.

Farmer, V. C. (1978). Water on particle surfaces. In Greenland, D. J., & Hays, M. H. B. (Eds.), *The chemistry of soil constituents.* Wiley Interscience, Chichester.

Filho, R.D.T., Barbosa, N.P., Ghavami, K. (1990) Application of sisal and coconut fibres in adobe blocks. RILEM Symposium on Vegetable Plants and their fibres as Building Materials, 2nd Proceedings. Sept. 1990 Brazil pp139-149.

Forde, M. L. (2002). *The development of a methodology for creating an earthen building inventory.* PhD Thesis, University of Plymouth.

Fountaine, E. R. (1954). Investigation into the mechanism of soil adhesion. *Journal of Soil Science. 5(2),* 251-253.

Ghavami, K., Filho, R. D. T., & Barbosa, N. P. (1999). Behaviour of composite soil reinforced with natural fibres. *Cement and Concrete Composites, 21,* 39-48.

Giasson, E., van Es, C., van Wambehe, A., & Bryant, R. B. (2000). Assessing the economic value of soil information using decision analysis techniques. *Soil Science, volume 165, No. 12,* December.

Gillilan, L. (1995). Mud, Mud Glorious Mud: Devon Cob Houses. *Cottage and Castle,* Issue No. 2., March. 29-33.

Goodhew, S. M. R. (1993). *An examination of the thermal performance of UK vernacular architecture: West Country cob buildings.* MSc Thesis, Cranfield Institute of Technology.

Goodhew, S. M. R.,(2000). *The thermal properties of cob buildings of Devon.*PhD. Thesis, University of Plymouth.

Goodhew, S., Griffiths, R., Short, D., & Watson, L. (2000). Some preliminary studies of the thermal properties of Devon cob walls. Preprints to TERRA 2000, *8th*

International Conference on the Study and Conservation of Earthen Architecture. Torquay, Devon, May. James & James, London. 139-143.

Greer, M. J. A. (1996). *The effect of moisture content and composition on the compressive strength and rigidity of cob made from of the Breccia measures near Teignmouth, Devon*. PhD Thesis, University of Plymouth.

Hall, D. G. M., Reeve, M. J., Thomasson, A. J., & Wright, V. F. (1977). Water retention, porosity and density of field soils. *Soil Survey Technical Monograph No. 9*. Herpenden.

Harries, R., Clark, D., & Watson, L. (2000). A rational return to earth as a contemporary building material. Preprints to TERRA 2000, 8th *International Conference on the Study and Conservation of Earthen Architecture*. Torquay, Devon, May. James & James, London. 319-321.

Harrison, R.(1992). *Devon Earth Building Initiative*. English Heritage Conservation Bulletin, issue 16 Feb. pp 10-11.

Harrison, R.(1999). The Conservation and Repair of Bowhill, Exeter: Working with Cob. *English Heritage Research Transactions. Earth Vol. 3 pp108.*

Hasan, S. E. (1994). Use of soil survey reports in geotechnical projects. *Bulletin of the Association of Engineering Geologists, 31(2)*, 367-376.

Hilf, J.W. (1975). Compacted Fill. In Fang, H.Y. & Winterkorn, H.F. (Eds.), *Foundation Engineering Handbook*. EdsVan Nostrand Reinhold Co., New York. pp244-264.

Historic Building Trust. (1992). The Cob Buildings of Devon I. History, Building Methods and Conservation. Technical Panel of the Historic Building Trust.

Houben, H. and Guillard, H. (1994). *Earth Construction, A Comprehensive Guide*. Intermediate Technology Publications. London 362pp.

ICCROM, International Centre for the Study of the Preservation and The Restoration of Cultural Property. (1987). *5th International Meeting of Experts on the Conservation of Earthen Architecture*. Rome 22nd to 23rd September 1987 pp110.

Indorante, S. J., McLeese, R. L., Hammer, R. D., Thompson, B. W., & Alexander, D. L. (1996). Positioning soil survey for the 21st century. *Journal of Soil and Water Conservation*, Jan-Feb. pp21-28.

Joshi, R. C., Gopal, A., Horsfield, D., & Nagaraj, T. S. (1994). Effect of heat treatment on strengths of clays. *Journal of Geotechnical Engineering, 120(6),* 1080-1088.

Keable, J. (1996). Rammed Earth Structures. Intermediate Technology Publications, London. pp114.

Keefe, L. (1998). *An investigation into the causes of structural failure in traditional cob buildings.* MPhil Thesis, University of Plymouth.

Keefe, L., & Child, P. (2000). *Devon and Cornwall.* Chapter 8 in Terra Britannica, a celebration of earthen structures in Great Britain and Ireland. ICCOMOS UK. James and James (Science Publishers) Ltd, London pp 34 – 40.

Keefe, L., Watson, L., & Griffiths, R (2000). Possible causes of structural failure in cob buildings. Preprints to TERRA 2000, *8th International Conference on the Study and Conservation of Earthen Architecture.* Torquay, Devon, May. James & James, London. 254 - 260.

Kelly, A., & MacMillan, N.H.(1986). Strong Solids. Third Edition. Claredon Press, Oxford pp423.

Krajcinovic, D. (1989). *A mesomechanical model of concrete and its application to the size effect phenomenon. Cracking and damage: strain localisation and size effect.* Elsevier Applied Science, pp.550.

Laboratoires des Ponts et Chauseés (1990). Essai au bleu de méthylene.

Laguros, J. G. (1969). Effect of temperature on some engineering properties of clay soils. *Highway Research Board Special Report 103*. National Research Council publications, pp.186-193.

Lambe, T. W., & Whitman, R. V. (1979). *Soil mechanics.* Series in Soil Engineering.

Laming, (1997). The new red sandstones. In Durrance, E. M., & Laming, D. J. C. (Eds.), *Geology of Devon.* University of Exeter Press.

Landon, J. R. (Ed.) (1991). *Booker Tropical Soil manual. A handbook for soil survey and agricultural land evaluation in the tropics and subtropics.* Chapter 6, Soil Physics. Longman Scientific and technical Publications.

Lautrin, D. (1989). Utilisation pratique des parametres dérivés de l'essai au bleu de methylène dans les projets de génie civil. *Bulletin de liaison bes Laboratoires Des Ponts et Chauseés 160*, February-March.

Lee, E. M., & Griffiths, J. S. (1987). The importance of pedological soil survey in land use planning, resource assessment and site investigation. *Planning and Engineering Geology, Geological Society Engineering Geology Special Publication No. 4, pp. 453-465.*

Little, B. and Morton, T. (2001). *Building with Earth in Scotland: Innovative design and sustainability.* Scottish Executive Central Research Unit. Crown Copyright.

Lilholt, H., & Lawther, M.J. (2000). Natural Organic Fibres in Comprehensive Composite Materials. Vol 1, Chapter 10. Elsevier Science, Pergammon.

Ley, T. (1995). Traditional crafts updates. Thatching and cob. In Watson, L. & Harries, R. (Eds.), *Out of Earth II.* National Conference on Earth Buildings. Centre for Earthen Architecture, University of Plymouth.

Ley, T. & Widgery, M. (1997). *Cob and the 1991 Building Regulations.*, Devon Earth Building Association.

McBratney, A. B., Odeh, I. O. A., Thomas, F. A., Bishop, M. L., Dunbar, M. S., & Shater, T. M. (2000). An overview of pedometric techniques for use in soil survey. Geoderma *97*, 293-327.

McCann, J. (1983). *Clay and Cob Buildings*. Shire Publications, London.

McLean, A. C., & Gribble, C. D. (1985). *Geology for civil engineers.* 2nd edition. George Allen & Unwin London pp314.

May, G.W. (1984). Structural Engineering for Earth Buildings. In McHenry, P.G. (Ed.), *Adobe and Rammed Earth Buildings.* John Wiley and Sons, New York.

Mesbah, A., & Olivier, O., (1990). Essais simplifies pour l'identification des sols. 1er Seminaire International sur l'Ingenierie des Constructions en Terre. Marrakech, Maroc. 30 May to 1 June pp12.

Mesbah, A., Morel, J.C., & Olivier, M. (1999). Comportemnet des sols fins argileux pendant un essai de compactage statique: determination des parametres pertinents. *Materiaux et Constructions. Nov. 32, 233, pp 687-694.*

Middleton, G. F. (1950), *Earth wall construction*. Notes on the Science of Building. Commonwealth Experimental Building Station, Melbourne, Australia.

Minke, G. (2000). *Earth Construction Handbook.* WIT Press Southampton. pp206.

Mitchel, J. K. (1976). *Fundamentals of soil behaviour*. New York, Wiley.

Moore, R. (1991). The chemical and mineralogical controls upon the residual strength of pure and natural clays. *Géotechnique 41, No. 1,* 35-47.

Morel, J.C., Ghavami, K., & Mesbah, A., (2000). Theoretical and experimental analysis of composite soil blocks reinforced with sisal fibres subjected to shear. *Masonry International. Vol. 13 No 2.*, pp54 – 62.

Muhanthan, B. (1991). Liquid limit and surface area of clays. Technical note. *Géotechnique 41, No 1,* 135-138.

Nagaraj, T. S., & Jayadeva, M. S. (1981). Re-examination of one-point methods of liquid limit determination. *Géotechnique 31, No. 3,* 413-425.

Narayanan, R.S. & Beeby, A.W. (2001). *Designer in a changing world.* in Introduction to design for Civil Engineers. Spon Press. Chptr.9 pp 177-189.

Neville, A. M. (1983). *Properties of Concrete.* Longmans Scientific and Educational.

Norton, J. (1986). *Building with Earth. A Handbook.* Intermediate Technology Publications pp68.

Olivier, M., & Mesbah, A., (1986). Le Materiau Terre – L' Essai de Compactage Statique pour la fabrication de briques de terre crue compresees " Bulletin de Liason des Laboratoires des Ponts et Chaussees, No.146, nov – dec, pp 37 – 43.

Olivier, M., Mesbah, A., & Adams, W. (1989). The influence of the mixing and the type of press on the making of compacted earth bricks. *Third CIB RILEM Symposium. Materials for Los Income Housing.* Topic 2 – Manufacturing Technologies. 6-10th November, Mexico.

Olivier, M., Mesbah, A., (1995). Laboratory Tests for Compacted Soils. *First International Conference on Unsaturated Soils.* Paris, 1995.

Ozkan, E., Al-Herbish., M.S. (1995). An experimental study of the critical properties of pressed and stabilised earth bricks. *Architectural Science Review, 38, 59-73.*

Road Research Technical Paper No. 24 (1952). *The suction of moisture held in soil and other porous materials.*

Rosenqvist, I. Th. (1961). Mechanical Properties of Soil Water Systems. *Transactions of the American Society of Civil Engineers, 126(1),* 745-767

Saxton, R. H. (1995). Performance of cob as a building material. *Structural Engineer, 4th April, 73(7),* 111-115.

Scott, C.R. (1980). *An Introduction to Soil Mechanics and Foundations. 3rd edition.* Applied Science Publishers Ltd. London

Scott, P. W., Hart, F. W., & Smith, D. (1996). The quantitative mineralogy of ceramic grade kaolin from the St. Austell granite and its relationship to chemistry and physical properties. *Proceedings of the Annual Conference of the Ussher Society,* January.

Selby, M. J. (1993). *Hillslope materials and processes.* 2nd edition. Oxford University Press, Oxford.

Sinha, S., & Schumann, P. (1994). *Earth building today*. The Architect's Journal. Sept. pp48 – 50.

Sivapullaiah, P.V. and Sridharan, A. (1985). Liquid limit of soil mixtures. *Geotechnical Testing Journal*, GTJODJ, 8, 3, 111-116.

Skempton (1953). The colloidal "activity" of clays. *Proceedings of the 3rd International Conference on Soil Mechanics and Foundation Engineering, Zurich, 1,* 57-61.

Sposito, G. (1984). *The surface chemistry of soils.* Oxford University Press.

Sridharan, A., Rao, S.M., & Murthy, N.S. (1988). Liquid limit of kaolinitic soils. *Geotechnique, 38(2),* 191-198.

Sridharan, A., Altschaeffl, A.G., Diamond, S. (1971). Pore size distribution studies. *Journal of the Soil Mechanics and Foundations Division.* Procs. of the American Society of Civil Engineers. 97, SM5, p771-787.

St. Loe Strachy., J. (1920) in Williams-Ellis C., (1920) *Building in Cob, Pise, Chalk and Clay.* George Newnes, London.

Swamy, N. M. S. (1988). Natural fibre reinforced cement and concrete. In Swamy, N. M. S. (Ed.), Concrete technology and design.

Thomas, R. (1997). The carboniferous rocks. In Durrance, E. M., & Laming, D. J. C. (Eds.), *Geology of Devon.* University of Exeter Press.

Trotman, P. (1993). Dampness in cob walls. Paper presented to the Devon Earth Building Association seminar, *The building and repair of cob walls.* Exeter, December.

TRRL (1996). Transport Road Research Laboratory Report 192.

URA Report No. 1652.(1995). Earth as a Building Material. Introduction to the Researches and Publications of the D.G.C.B., Laboratory Geomateriaux pp 8.

United Nations (1993). *Agenda 21: The United Nations Programme of Action from Rio.* United Nations.

Walker, P. (1997). Flexural Bond Strength of Pressed Cement Earth Block Masonry. *11th International Brick/Block Masonry Conference.* Tongji University. Shanghai, China, 14th –16th October pp 1-10.

Walker, P. (1999). Bond Characteristics of Earth Block Masonry. *Journal of Materials in Civil Engineering. 11(3)*, 249-256.

Walker, P., Venkatarama Reddy, B.V., Mesbah, A., & Morel, J.C. (2000). The Case for Compressed Earth Block Construction. In Venkatarama Reddy, B.V. & Sinha, B.P. (Eds.), *Proceedings of the 6th International Seminar on Structural Masonry for Developing Countries*. Allied Publishers Ltd.

Walker, P. (2002). A Non-Conventional Building Materials Course for Undergraduate Engineers. *Procs. 3rd International Conference on Non-Conventional Materials and Technologies*, Hanoi, March 2002, 260-264.

Walker, P. (2002). The Australian Earth Building Handbook. Australian Standards Publications. pp151.

Wang, M. K., Wang, S. L., & Wang, W. M. (1996). Rapid estimation of cation-exchange capacities of soils and clays with methylene blue exchange. *Soil Science Society of America Journal, 60,* 138-141.

Warkentin B.P., Yong, R.N. (1962). Shear strength of Monmorillonite and Kaolinite. *Clay and Clay Minerals. No. 9., 210-218.*

Warren, J. (1999). Conservation of Earth Structures. Butterworth, Heinemann, pp198.

Weller, H. O., (1922) in Building Research Board (1922) *Building in Cob and Pise de Terre.* Special Report No. 5. Department of Scientific and Industrial Research. HMSO. London.

Williams-Ellis C., and Eastwick–Field (1947) *Building in Cob, Pise, and Stabalised Earth.* Newnes and Country Life, London.

White, R. E. (1979). *Introduction to the principals and practice of soil science.* Blackwell Publicatations.

Wright, A. (1991). Craft Techniques for Traditional Buildings. BT Batsford Ltd. London, UK.

Young, R. N., & Warkentin, B. P. (1975). *Developments in Geotechnical Engineering 5, Soil Properties and Behaviour.* Elsevier Scientific Publishing Company.

Youssef, M. S., Ramli, A. H., & Sabry, A. S. (1961). Temperature changes and their effects on some physical properties of soils. *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering, Paris. Part 1*, pp. 419-421.

Appendix 1:

Sieving Data

Appendix 1 - Sieving data

Trillow/ Dunsford

app (mm)	app (phi)	befoot %passing	app (phi)	becut %passing
37.5	-5.23	100	-5.23	
28	-4.81	99.01	-4.81	100
20	-4.32	97.23	-4.32	94.43
14	-3.81	96.96	-3.81	92.6
10	-3.32	96.82	-3.32	88.9
6.3	-2.66	93	-2 66	83
5	-2.32	90.89	-2.32	80.31
3.35	-1.74	88.85	-1.74	73.15
2	-1.00	86.78	-1.00	63.22
1.18	-0.24	84.96	-0.24	52.22
0.6	0.74	83.63	0.74	44.53
0.425	1.23	83.33	1.23	41.12
0.3	1.74	83.05	1.74	38.46
0.212	2.24	82.85	2.24	38.23
0.15	2.74	82.71	2.74	37.85
0.063	3.99	82.09	3.99	37.58
0.02	5.64	60.35	5.64	12.74
0.006	7.38	44.07	7.38	8.64
0.002	8.97	28.19	8.97	5.13

Stockadon/ Halstow

app (mm)	app (phi)	Halstow 1, % passing	Halstow 2, %passing	Halstow 3, % passing	Halstow 4, %passing	Halstow 5, %passing
10	-3.32	99.71				
6.3	-2.66	99.55	99.88	99.94	99.68	
5	-2.32	99.50	99.79	99.89	99.68	99.28
3.35	-1.74	99.37	99.68	99.76	99.47	99.28
2	-1.00	99.14	99.51	99.61	99.35	99.09
1.18	-0.24	98.85	99.34	99.39	99.16	98.91
0.6	0.74	98.01	98.89	98.92	98.73	98.20
0.425	1.23	97.59	98.57	98.64	98.49	97.83
0.3	1.74	97.19	98.25	98.40	98.25	97.51
0.212	2.24	96.79	97.93	98.15	98.01	97.17
0.15	2.74	96.30	97.59	97.87	97.62	96.63
0.063	3.99	93.53	97.54	95.75	95.06	92.80
0.02	5.64	90.75	97.49	92.68	94.38	92.17
0.006	7.38	64.14	68.31	64.78	48.40	60.59
0.002	8.97	49.06	50.99	49.39	47.19	48.88

Chapel Down/ Crediton

app (mm)	app (phi)	Crediton 1, %passing	Crediton 2, % passing	Crediton 3, % passing
37.5	-5.23			
28	-4.81	100	100	
20	-4.32	99.98	98.61	100
14	-3.81	97 615	94.92	97.98
10	-3.32	93.646	89.98	92.78
6.3	-2.66	85.792	81 60	85.55
5	-2.32	78.698	72.27	81.06
3.35	-1.74	70.367	64.43	74.68
2	-1.00	56.47	51.36	64.98
1.18	-0.24	42.888	39.07	57
0.6	0.74	27.627	24.76	48.88
0.425	1.23	21.126	19.51	45.33
0.3	1.74	15 788	15.01	42.26
0.212	2.24	11.365	11.91	39.5
0.15	2.74	7.99	8.69	36.84
0.063	3.99	1.617	2.11	30.93
0.02	5.64	0.723	1.93	23.39
0.006	7.38	0.464	0.846	12.76
0.002	8.97	0.606	1.712	7.04

Exminster/ Bridgnorth

app (mm)	app (phi)	Bridgnorth 1 % passing	Bridgnorth 2 % passing	Bridgnorth 3 % passing	Bridgnorth 4 % passing	Bridgnorth 5 % passing
37.5	-5.23	100.00				
28	-4.81	96 96				
20	-4.32	94.63	100.00	100.00	100.00	
14	-3.81	94.63	96.92	93.24	96.45	100.00
10	-3.32	91.01	92.01	90.18	93.24	96.99
6.3	-2.66	84.67	85.31	82.90	85.22	95.13
5	-2.32	81.25	80.28	79.44	81.00	93.23
3.35	-1.74	76.90	76.30	73.58	75.21	92.24
2	-1.00	70.83	69.76	67.94	68.56	90.43
1.18	-0.24	65.51	64.37	61.48	63.17	88.63
0.6	0.74	60.49	58.88	56.52	58.01	84.31
0.425	1.23	57.29	56.34	54.16	55.64	75 41
0.3	1.74	47.27	48.82	46.80	48.21	62.90
0.212	2.24	35.31	33.66	29.58	32.84	49.83
0 15	2.74	22.26	17.84	13.30	16.43	36.85
0 063	3 99	8.16	0.44	0.01	0.54	26.00
0.02	5.64	6.497	0.145	0 001	0.154	20.273
0 006	7.38	7.296	0.17	0.002	0.181	10.569
0.002	8.97	6.518	0.157	0.001	0.096	5.868

TDSTM/Tedburn

app (mm)	app (phi)	Tedburn 1 % passing	Tedburn 2 % passing	Tedburn 3 % passing	Tedburn 4 % passing	Tedburn 5 % passing
50	-5.644	100	100	100		100
37.5	-5 23	93.927	93.492	93	100	94.5
28	-4.81	92.664	91.795	92 225	92.995	91.542
20	-4.32	89.874	89.686	89.771	89.042	89.001
14	-3.81	85.065	85 994	85 022	85.865	85.452
10	-3 32	80.249	80 500	82 329	81.444	81.292
6.3	-2.66	72.982	72.959	80 341	80.665	75.421
5	-2 32	69 408	69.677	79 562	79.233	69.589
3.35	-1.74	65.004	65.248	75.034	77.003	65.438
2	-1.00	59.229	59.701	72.062	71 032	59 513
1.18	-0.24	54 683	55.712	69.599	65 609	55.863
0.6	0.74	50.787	52.181	68.154	62.698	52 641
0 425	1.23	49 417	50 842	66 002	60 943	49.053
0.3	1.74	48.180	49 714	64.531	58.562	48.761
0 212	2 24	47.222	48.886	63 006	57.002	47.512
0 15	2.74	46 448	48.255	62.335	56.153	47.605
0 063	3.99	45.126	47.094	60.118	55.941	46.59
0 02	5.64	43.411	44.974	58.021	43 505	44.989
0.006	7.38	31.633	38.73	42.101	32.661	31.514
0.002	8.97	22.97	30.85	31.006	22.956	23.995

Appendix 2:

Atterberg Limit Values

Appendix 2 Atterberg Limit Values

	Plastic limit	Liquid limit	Plasticity index	soil
	0	19.9	19.9	exminster/bridgenorth
	0	20.8	20.8	
	0	20.4	20.4	
	0	20.4	20.4	
	17.4	24	6.6	
average	3.48	21.1	17.62	
st'dev'n	7.782	1.652	6.169	
	33.7	72	38.3	stockadon/halstow
	34.8	72.8	38	
	36.4	75.6	39.2	
	33.45	65.5	32.05	
	32.2	62.4	30.2	
average	34.11	69.66	35.55	
st'dev'n	1.579	5.492	4.116	
	20.9	36.2	15.3	chapel down/crediton
	21.9	37.3	15.4	
	23.8	36.3	12.5	
average	22.2	36.6	14.4	
st'dev'n	1.473	0.608	1.646	
	28	56	28	tdstmary/tedburn
	26	43.2	17.2	
	27	49	22	
	26.6	44.5	17.9	
	28.4	47.7	19.3	
	27.2	48.1	20.9	
average	27.2	48.083	20.883	
st'dev'n	0.885	4.480	3.921	
	26.9	43	16.1	dunsford/trillow
	25.8	43	17.2	
	29.8	53.2	23.4	
	24.6	36.9	12.3	
	24.5	37.9	13.4	
average	26.32	42.8	16.48	
st'dev'n	2.179	6.463	4.345	

Appendix 3:

Methylene Blue Procedure

Methylene Blue Test

1.0 Prnciple of the Test

The test consists of measuring the adsorption of the material by titration.

Elementary doses of a solution of methylene blue are injected in succession in an aqueous bath containing the test sample. The adsorption of methylene blue is checked after each addition by staining a filter paper (stain test, see 3.2.1)

For a simple conformity check, the amount of blue specified is injected in a single step.

2.0 Equipment

2.1 Specific apparatus

One burette:

- capacity: 100 or 50 cm^3
- graduation: 1/10 or 1/5 cm^3

Filter paper: quantitative and ashless (< 0.010) ; weight: $95 g/m^2$; thickness: 0.2 mm; filtration rate 75; retention 8μm.

One glass rod; length 300mm, diameter 8mm.

One paddle mixer: rotating between 400 and 700 revs/min.

One 500ml glass or plastic container, about 100mm in diameter.

2.2 Routine apparatus

A balance with a capacity compatible with the mass of the test sample and capable of weighing to within 1%.

A stopwatch or timer.

Equipment necessary for sampling the material.

2.3 Products Used

Medical grade methylene blue solution containing 10g + 0.1 g/l

De-ionised or distilled water.

2.4 Preparation of sample for test

A dry weight of fine material approximately equal to 30g should be extracted, via sieving, from the bulk of the soil sample.

3.0 Test procedure

3.1 Mixing of test sample

The test sample is placed in a 500ml beaker with 200cm^3 of deionosed or distilled water. The mixture is agitated for one minute at 700 revs/minute and then agitated permanently at 400revs/ minute throughout the duration of the test using the agitator, with the paddles 1cm above the bottom of the container.

3.2 Determination of quantity of blue adsorbed by titration

3.2.1 Definition of stain test

After each injection of blue (see 3.2.2), this test consists of using the glass rod to take a drop of suspension which is deposited on the filter paper., The stain formed consists of a central deposit of material, generally coloured deep blue, surrounded by a colourless wet zone.

The drop taken must be such that the deposit is 8 to 12 mm in diameter.

The test is positive if a pale blue halo appears around the central deposit, in the moist zone. It is negative if the halo is colourless.

3.2.2 Titration

Using the burette, a dose of $5cm^3$ of blue solution is injected into the container, and this addition is followed by the stain test on the filter paper.

This procedure is repeated until the test becomes positive. At this point, adsorption of the blue is allowed to continue by performing the tests at one minute intervals, without further additions.

If the blue halo disappears from the stain before the fifth minute, new elementary additions of blue are carried out as follows:

- $5cm^3$ as above if the volume of blue solution already introduced is greater than or equal to $30cm^3$.
- $2\ cm^3$ if this volume is less than $30cm^3$.

Each addition is followed by the tests, always performed at one minute intervals.
Repeat these operations until the test remains positive for five consecutive minutes. The titration is then considered to be at an end.

3.0 Expression of results

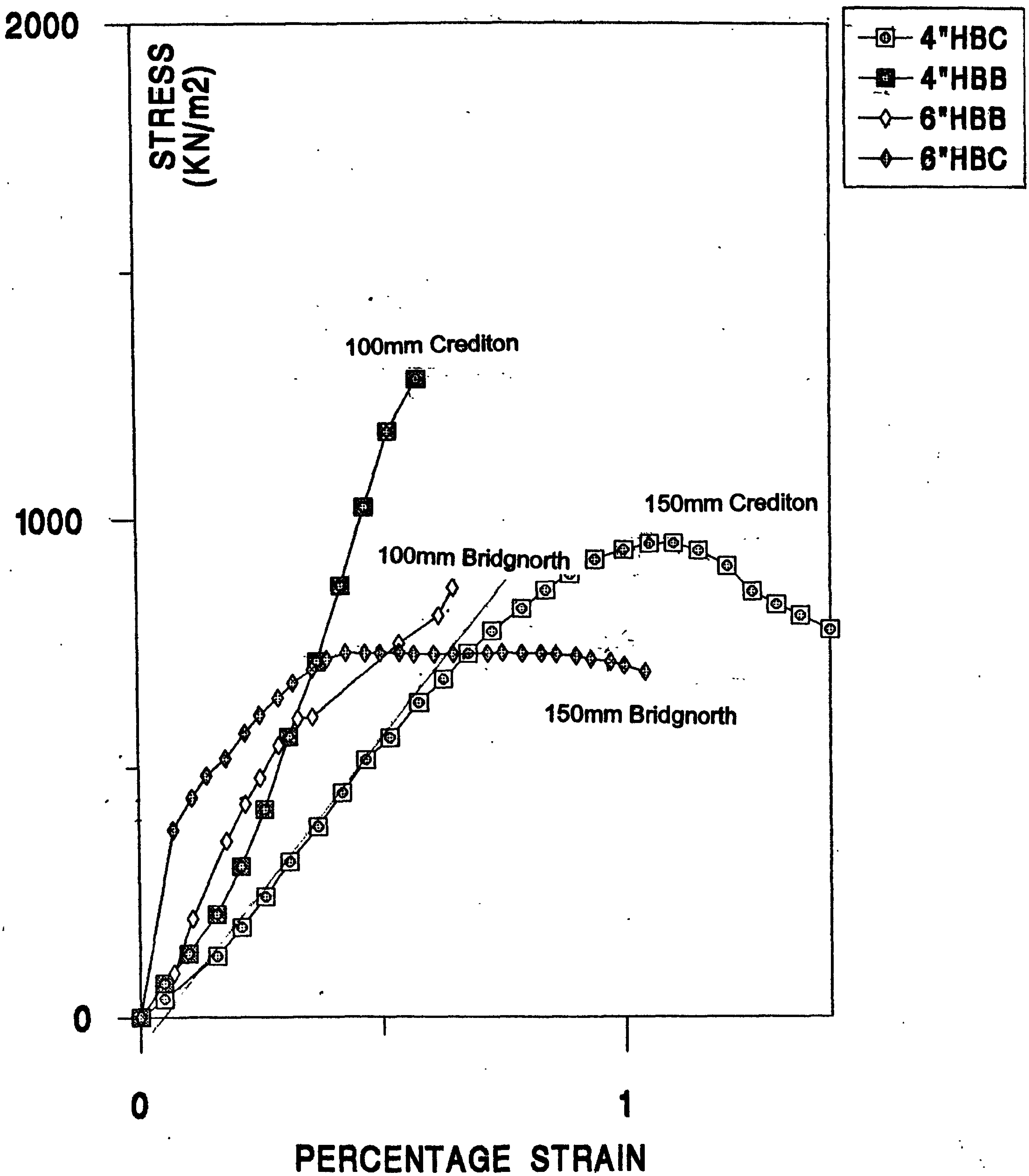
The 'blue activity' of the fines is expressed in grams of methylene blue dye fixed by 100g of clay fines.

$A_{CB} = V_{MB\ TOTAL}$ / % clay fraction

Appendix 4:

Comparison of cylinder size and unconfined compressive strength

Stress/ strain relationship for 100 and 150 mm diameter soil cylinders



Appendix 5:

Compaction Data

Compaction data for cob samples from 7- blow Proctor test

Soil Type								
Crediton		weight mould+ compacted cob (g)						
	moisture content	1.00	2.00	3.00	4.00	5.00		
	10.40	6171.60	6157.60	6152.30	6151.40	6153.20		
	19.00	6418.90	6433.70	6419.20	6446.00	6434.40		
	20.40	6435.60	6426.30	6446.30	6435.70	6446.20		
	21.70	6412.30	6405.30	6417.90	6423.50	6409.80		
		bulk density compacted cob (kg/m3)					mean	st'd dev'n
	10.40	1859.64	1844.81	1839.19	1838.24	1840.15	1844.41	7.94
	19.00	2121.61	2137.29	2121.93	2150.32	2138.03	2133.83	10.89
	20.40	2139.30	2129.45	2150.64	2139.41	2150.53	2141.86	7.98
	21.70	2114.62	2107.20	2120.55	2126.48	2111.97	2116.17	6.72
Dunsford		weight mould+ compacted cob (g)						
	moisture content	1.00	2.00	3.00	4.00	5.00		
	15.75	6210.00	6191.30	6162.30	6162.50	6163.40		
	17.55	6258.00	6252.20	6250.90	6229.80	6215.70		
	22.10	6411.90	6369.50	6407.40	6379.30	6391.80		
	24.50	6390.80	6341.50	6360.40	6388.20	6369.60		
		bulk density cob (kg/m3)					mean	st'd dev'n
	15.75	1900.32	1880.51	1849.79	1850.00	1850.95	1866.31	23.09
	17.55	1951.17	1945.02	1943.64	1921.29	1906.36	1933.50	18.93
	22.10	2114.19	2069.28	2109.43	2079.66	2092.90	2093.09	19.10
	24.50	2091.84	2039.62	2059.64	2089.09	2069.39	2069.92	21.63
Stockadon	moisture content %	weight of compacted cob(g)						
	0.60	1261.40	1271.60	1274.70	1298.70	1288.20		
	18.40	1502.90	1518.80	1503.40	1537.30	1534.20		
	34.50	1694.60	1694.60	1687.00	1713.60	1657.90		
	37.30	1724.10	1724.10	1662.40	1720.90	1747.30		
	40.30	1708.30	1708.30	1711.60	1707.70	1730.50		
	45.20	1694.00	1684.60	1684.50	1657.20	1695.90		
	mc	bulk densities					mean	stdev
	0.60	1336.20	1347.03	1350.32	1375.74	1364.62	1354.78	15.50
	18.40	1592.06	1608.90	1592.58	1628.50	1625.21	1609.45	17.31
	34.50	1795.13	1795.13	1787.08	1815.25	1756.25	1789.77	21.43
	37.30	1826.38	1826.38	1761.02	1822.99	1850.95	1817.54	33.53
	40.30	1809.64	1809.64	1813.14	1809.00	1833.16	1814.92	10.33
	45.20	1794.49	1784.53	1784.43	1755.51	1796.50	1783.09	16.39
Note: weight of mould = 4416.1 g								

Bridgnorth		weight mould+ cob						
	moisture content %	1.00	2.00	3.00	4.00	5.00		
	6.40	6150.70	6124.90	6155.40	6140.90	6145.30		
	11.00	6359.90	6389.90	6344.40	6347.70	6349.50		
	13.40	6463.00	6466.80	6457.30	6434.60	6449.00		
	14.60	6499.40	6489.80	6490.50	6511.90	6499.20		
	17.70	6480.80	6470.10	6471.00	6477.30	6476.10		
		bulk density cob					mean	st'd dev'n
	6.40	1837.50	1810.17	1842.48	1827.12	1831.78	1829.81	12.41
	11.00	2059.11	2090.89	2042.69	2046.19	2048.09	2057.39	19.71
	13.40	2168.33	2172.35	2162.29	2138.24	2153.50	2158.94	13.58
	14.60	2206.89	2196.72	2197.46	2220.13	2206.67	2205.57	9.47
	17.70	2187.18	2175.85	2176.80	2183.47	2182.20	2181.10	4.74
Tedburn		weight mould+ cob						
	moisture content %	1.00	2.00	3.00	4.00	5.00		
	15.70	6138.00	6120.60	6129.80	6128.30	6130.20		
	21.10	6214.10	6245.60	6224.10	6251.00	6232.90		
	25.50	6283.60	6331.90	6340.10	6339.60	6338.70		
	27.60	6317.80	6297.40	6295.00	6312.70	6321.50		
		bulk density cob					mean	st'd dev'n
	15.70	1824.05	1805.61	1815.36	1813.77	1815.78	1814.92	6.56
	21.10	1904.66	1938.03	1915.25	1943.75	1924.58	1925.25	16.05
	25.50	1978.28	2029.45	2038.14	2037.61	2036.65	2024.03	25.81
	27.60	2014.51	1992.90	1990.36	2009.11	2018.43	2005.06	12.73

Compaction data for cob samples from 7- blow Proctor test

	mc %	bulk density values (kg/m3)					mc ratio	dry density values (kg/m3)					mc %	mean	max	min
Crediton																
	10.4	1859.64	1844.809	1839.195	1838.242	1840.148	**0.104**	1684.46	1671.02	1665.94	1665.07	1666.80	***10.4***	**1670.66**	1684.46	1665.07
	19	2121.61	2137.288	2121.928	2150.318	2138.03	**0.19**	1782.87	1796.04	1783.13	1806.99	1796.66	***19***	**1793.14**	1806.99	1782.87
	20.4	2139.301	2129.449	2150.636	2139.407	2150.53	**0.204**	1776.83	1768.65	1786.24	1776.92	1786.15	***20.4***	**1778.96**	1786.24	1768.65
	21.7	2114.619	2107.203	2120.551	2126.483	2111.97	**0.217**	1737.57	1731.47	1742.44	1747.32	1735.39	***21.7***	**1738.84**	1747.32	1731.47
Dunsford	*mc %*	*bulk density values (kg/m3)*						*dry density values (kg/m3)*					*mc %*			
	15.75	1900.32	1880.51	1849.79	1850.00	1850.95	**0.1575**	1641.74	1624.63	1598.09	1598.27	1599.10	**15.75**	**1612.37**	1641.74	1598.09
	17.55	1951.17	1945.02	1943.64	1921.29	1906.36	**0.1755**	1659.86	1654.63	1653.46	1634.45	1621.74	**17.55**	**1644.83**	1659.86	1621.74
	22.1	2114.19	2069.28	2109.43	2079.66	2092.90	**0.221**	1731.53	1694.74	1727.62	1703.24	1714.09	**22.1**	**1714.25**	1731.53	1694.74
	24.5	2091.84	2039.62	2059.64	2089.09	2069.39	**0.245**	1680.20	1638.25	1654.33	1677.98	1662.16	**24.5**	**1662.58**	1680.20	1638.25
Tedburn	*mc%*	*bulk density values (kg/m3)*						*dry density values (kg/m3)*					*mc%*			
	15.7	1824.05	1805.61	1815.36	1813.77	1815.78	**0.157**	1576.53	1560.60	1569.02	1567.65	1569.39	**15.7**	**1568.64**	1576.53	1560.60
	21.1	1904.66	1938.03	1915.25	1943.75	1924.58	**0.211**	1572.80	1600.35	1581.55	1605.08	1589.25	**21.1**	**1589.81**	1605.08	1572.80
	25.5	1978.28	2029.45	2038.14	2037.61	2036.65	**0.255**	1576.32	1617.09	1624.01	1623.59	1622.83	**25.5**	**1612.77**	1624.01	1576.32
	27.6	2014.51	1992.90	1990.36	2009.11	2018.43	**0.276**	1578.77	1561.84	1559.84	1574.54	1581.84	**27.6**	**1571.37**	1581.84	1559.84
Bridgnorth	*mc%*	*bulk density values (kg/m3)*						*dry density values (kg/m3)*					*mc%*			
	6.4	1837.50	1810.17	1842.48	1827.12	1831.78	**0.064**	1726.97	1701.29	1731.65	1717.22	1721.60	**6.4**	**1719.75**	1731.65	1701.29
	11	2059.11	2090.89	2042.69	2046.19	2048.09	**0.11**	1855.05	1883.68	1840.26	1843.41	1845.13	**11**	**1853.51**	1883.69	1840.26
	13.4	2168.33	2172.35	2162.29	2138.24	2153.50	**0.134**	1912.10	1915.65	1906.78	1885.57	1899.03	**13.4**	**1903.83**	1915.65	1885.58
	14.6	2206.89	2196.72	2197.46	2220.13	2206.67	**0.146**	1925.73	1916.86	1917.50	1937.28	1925.54	**14.6**	**1924.58**	1937.28	1916.86
	17.7	2187.18	2175.85	2176.80	2183.47	2182.20	**0.177**	1858.27	1848.64	1849.45	1855.12	1854.04	**17.7**	**1853.10**	1858.27	1848.64
Halstow	*mc%*	*bulk density values (kg/m3)*						*dry density values (kg/m3)*					*mc%*			
	0.6	1336.20	1347.03	1350.32	1375.74	1364.62	**0.006**	1328.23	1339.00	1342.26	1367.54	1356.48	**0.6**	**1346.70**	1367.54	1328.23
	18.4	1592.06	1608.90	1592.58	1628.50	1625.21	**0.184**	1344.64	1358.87	1345.09	1375.42	1372.65	**18.4**	**1359.33**	1375.42	1344.64
	34.5	1795.13	1795.13	1787.08	1815.25	1756.25	**0.345**	1334.67	1334.67	1328.68	1349.63	1305.76	**34.5**	**1330.68**	1349.63	1305.76
	37.3	1826.38	1826.38	1761.02	1822.99	1850.95	**0.373**	1330.21	1330.21	1282.61	1327.74	1348.11	**37.3**	**1323.77**	1348.11	1282.61
	40.3	1809.64	1809.64	1813.14	1809.00	1833.16	**0.403**	1289.84	1289.84	1292.33	1289.38	1306.60	**40.3**	**1293.60**	1306.60	1289.38
	45.2	1794.49	1784.53	1784.43	1755.51	1796.50	**0.452**	1235.88	1229.02	1228.94	1209.03	1237.26	**45.2**	**1228.03**	1237.26	1209.03

Appendix 6:
Barley versus wheat straw

	UCC values from Bridgnorth wheat cob (kN/m^2)	UCC values from Bridgnorth barley cob (kN/m^2)
Cylinder Number		
1		1212
2	923	976
3	1035	1285
4	1078	1091
5	1207	1352
6	1070	1183
7	1140	1334
8	1216	1070
Mean value	1095	1188
Standard deviation	$\pm$ 103	$\pm$ 134

Appendix 7:

Sample Monitoring and Manufacture Data

Halstow manufacture and monitoring data for soil cylinders Test Series 1

on manu'								
date	time	sample	tin	sample wgt.	av. hgt	av. circ	mc	bulk density (kg/m3)
5.08.97 ·		1.00		3111.70	203.00	323.00	33.66	1846.30
		2.00		3135.60	204.00	324.00	33.95	1840.00
		3.00		3089.50	202.00	324.00	33.95	1830.90
		4.00		3093.30	202.50	324.00	34.54	1828.60
		5.00		3120.90	204.00	324.50	34.08	1825.70
		6.00		3109.50	203.00	323.50	33.98	1839.30
		7.00		3103.70	203.00	323.50	34.37	1835.90
		8.00		3090.90	201.50	324.00	33.92	1836.20
							AV	1835.36
prior to oven drying							STDEV	6.73
5.08.97	0.71	1.00		3104.00	202.00	323.00		
		2.00		3128.00	203.50	203.50		
		3.00		3084.00	201.00	201.00		
		4.00		3087.00	201.50	201.50		
		5.00		3117.00	203.00	203.00		
		6.00		3107.00	202.00	202.00		
		7.00		3102.00	202.00	202.00		
		8.00		3090.00	201.50	201.50		
6.08.97	0.65	1.00		2945.00	194.00	314.00		
		2.00		3017.00	199.00	316.00		
		3.00		2961.00	196.00	315.50		
		4.00		3002.00	197.00	318.50		
		5.00		2958.00	196.00	314.00		
		6.00		2958.00	195.50	314.50		
		7.00		2918.00	193.50	312.50		
		8.00		2909.00	193.50	312.50		
7:8:97	0.42	1.00		2865.00	191.50	308.50		
		2.00		2944.00	196.00	311.50		
		3.00		2908.00	194.00	312.50		
		4.00		2952.00	195.00	315.00		
		5.00		2870.00	193.00	309.50		
		6.00		2870.00	192.50	308.50		
		7.00		2832.00	190.50	308.00		
		8.00		2818.00	190.50	307.00		
8.8.97	0.64	1.00		2757.00	189.50	306.00		
		2.00		2833.00	193.00	306.50		
		3.00		2817.00	191.00	308.00		
		4.00		2840.00	191.00	308.50		
		5.00		2786.00	191.50	306.00		
		6.00		2800.00	191.00	306.00		
		7.00		2737.00	189.50	305.00		
		8.00		2732.00	189.50	305.00		

9.8.97	0.41	1.00		2689.00	189.50	306.00		
		2.00		2761.00	193.00	306.50		
		3.00		2739.00	191.00	308.00		
		4.00		2773.00	191.00	308.50		
		5.00		2722.00	191.50	306.00		
		6.00		2741.00	191.00	306.00		
		7.00		2683.00	189.50	305.00		
		8.00		2690.00	189.50	305.00		
10.8.97	0.68	1.00		2602.00	188.50	304.50		
		2.00		2658.00	191.50	304.50		
		3.00		2650.00	189.00	304.50		
		4.00		2669.00	188.00	304.00		
		5.00		2633.00	189.50	304.50		
		6.00		2642.00	190.00	304.50		
		7.00		2617.00	188.50	303.50		
		8.00		2624.00	189.00	304.50		
11:08:97	0.43	1.00		2561.00	188.50	304.50		
		2.00		2611.00	191.50	304.50		
		3.00		2584.00	189.00	304.00		
		4.00		2597.00	187.50	303.50		
		5.00		2594.00	190.00	305.00		
		6.00		2590.00	190.00	304.50		
		7.00		2565.00	189.00	304.50		
		8.00		2574.00	189.00	304.50		
12.8.97	0.58	1.00		2515.00	189.00	303.50		
		2.00		2548.00	191.50	304.00		
		3.00		2510.00	189.00	303.50		
		4.00		2511.00	187.00	304.00		
		5.00		2531.00	190.50	304.00		
		6.00		2537.00	189.50	303.50		
		7.00		2515.00	188.50	304.00		
		8.00		2516.00	188.50	304.00		
13.8.97	0.47	1.00		2494.00	187.50	304.00		
		2.00		2520.00	191.00	304.00		
		3.00		2481.00	189.00	303.00		
		4.00		2478.00	187.50	303.50		
		5.00		2500.00	190.50	303.50		
		6.00		2498.00	189.50	303.00		
		7.00		2482.00	188.00	303.00		
		8.00		2482.00	189.00	303.00		
15.8.97	0.49	1.00		2467.00	187.50	304.00		
		2.00		2486.00	191.00	304.00		
		3.00		2448.00	188.50	303.50		
		4.00		2442.00	187.00	303.50		
		5.00		2473.00	189.50	303.50		
		6.00		2467.00	190.00	303.50		
		7.00		2454.00	188.00	303.00		
		8.00		2452.00	189.50	303.00		

17.8.97	0.51	1.00		2454.00	188.00	303.50		
		2.00		2470.00	190.50	303.50		
		3.00		2434.00	188.50	304.00		
		4.00		2427.00	187.00	304.00		
		5.00		2458.00	190.00	304.00		
		6.00		2452.00	190.00	303.50		
		7.00		2440.00	188.00	303.00		
		8.00		2438.00	190.00	304.00		
18.8.97	0.43	1.00		2451.00	188.00	304.00		
		2.00		2467.00	191.00	305.00		
		3.00		2430.00	188.50	304.00		
		4.00		2423.00	187.00	303.50		
		5.00		2454.00	190.00	304.00		
		6.00		2447.00	189.50	303.50		
		7.00		2436.00	188.00	303.50		
		8.00		2434.00	189.00	304.00		

Halstow manufacture and monitoring data for cob cylinders Test Series 1

on manu'							
date	time	sample	sample wgt.	av. hgt	av. circ	mc	density
31.08.97		1.00	3049.20	203.00	324.00	34.21	1798.10
		2.00	3030.30	201.50	324.50	34.44	1794.70
		3.00	3063.00	202.00	324.00	34.11	1815.20
		4.00	3029.60	202.50	324.00	34.77	1790.90
		5.00	3027.90	204.50	324.00	34.81	1772.40
		6.00	3048.10	203.00	323.50	34.28	1802.99
		7.00	3055.10	205.50	323.00	34.76	1790.68
		8.00	3047.20	206.00	324.00	34.18	1770.73
prior to oven drying							
31.08.97	0.50	1.00	3039.00	202.50	323.00	33.76	
		2.00	3022.00	199.50	324.50	34.07	
		3.00	3056.00	201.50	323.50	33.80	
		4.00	3023.00	202.50	324.00	34.48	
		5.00	3023.00	203.50	323.50	34.59	
		6.00	3044.00	203.50	323.00	34.10	
		7.00	3051.00	203.50	323.50	34.58	
		8.00	3047.00	206.00	324.00	34.17	
1.9.97	0.44	1.00	2868.00	193.50	315.00	26.23	
		2.00	2897.00	194.00	319.00	28.53	
		3.00	2912.00	195.00	315.50	27.50	
		4.00	2844.00	194.00	316.00	26.51	
		5.00	2855.00	195.00	316.00	27.11	
		6.00	2887.00	196.00	315.50	27.18	
		7.00	2930.00	197.50	318.50	29.25	
		8.00	2942.00	200.00	319.00	29.55	
2.9.97	0.41	1.00	2801.00	191.50	311.00	23.28	
		2.00	2787.00	190.00	314.00	23.65	
		3.00	2825.00	191.50	314.00	23.69	
		4.00	2729.00	191.50	313.50	21.40	
		5.00	2722.00	192.50	311.50	21.19	
		6.00	2753.00	191.50	311.00	21.28	
		7.00	2793.00	193.50	313.00	23.20	
		8.00	2823.00	194.50	314.00	24.31	
3.9.97	0.75	1.00	2697.00	189.00	309.00	18.71	
		2.00	2652.00	190.00	313.50	17.66	
		3.00	2694.00	190.00	310.00	17.95	
		4.00	2595.00	190.00	311.00	15.44	
		5.00	2621.00	190.00	311.00	16.70	
		6.00	2673.00	191.00	310.50	17.75	
		7.00	2678.00	190.50	311.00	18.13	
		8.00	2745.00	193.00	313.00	20.87	

5.9.97	0.63	1.00	2534.00	189.00	309.00	11.53	
		2.00	2511.00	190.00	310.00	11.40	
		3.00	2537.00	189.00	309.00	11.08	
		4.00	2493.00	190.00	311.00	10.90	
		5.00	2495.00	191.00	310.50	11.09	
		6.00	2554.00	191.50	310.00	12.51	
		7.00	2581.00	190.00	310.50	13.85	
		8.00	2590.00	192.50	312.00	14.05	
6.9.97	0.71	1.00	2463.00	188.50	307.00	8.41	
		2.00	2445.00	189.00	310.00	8.47	
		3.00	2472.00	189.00	307.00	8.23	
		4.00	2437.00	190.50	310.50	8.41	
		5.00	2442.00	190.00	310.00	8.73	
		6.00	2478.00	191.00	310.00	9.16	
		7.00	2484.00	190.00	309.00	9.57	
		8.00	2500.00	192.00	311.00	10.08	
7.9.97	0.57	1.00	2439.00	188.50	308.00	7.35	
		2.00	2420.00	189.00	311.00	7.36	
		3.00	2450.00	189.00	307.50	7.27	
		4.00	2414.00	190.00	311.00	7.38	
		5.00	2419.00	191.00	310.50	7.70	
		6.00	2451.00	191.00	310.00	7.97	
		7.00	2454.00	190.00	309.50	8.25	
		8.00	2466.00	190.50	310.50	8.59	
8.9.97	0.59	1.00	2421.00	188.00	307.00	6.56	
		2.00	2403.00	186.50	309.50	6.61	
		3.00	2432.00	189.00	307.00	6.48	
		4.00	2397.00	190.00	311.00	6.63	
		5.00	2400.00	190.50	310.50	6.86	
		6.00	2429.00	190.50	310.00	7.00	
		7.00	2429.00	190.50	309.00	7.15	
		8.00	2438.00	192.50	310.50	7.35	
9.9.97	0.69	1.00	2408.00	188.50	300.50	5.99	
		2.00	2390.00	187.50	311.00	6.03	
		3.00	2419.00	188.50	308.00	5.91	
		4.00	2384.00	189.00	311.00	6.05	
		5.00	2384.00	190.00	310.00	6.14	
		6.00	2411.00	190.50	309.00	6.21	
		7.00	2410.00	190.50	308.00	6.31	
		8.00	2418.00	193.00	309.00	6.47	
11.9.97	0.54	1.00	2395.00	188.50	308.00	5.41	
		2.00	2376.00	189.00	309.50	5.41	
		3.00	2406.00	189.00	307.00	5.34	
		4.00	2371.00	190.00	311.00	5.47	
		5.00	2370.00	190.00	310.00	5.52	
		6.00	2396.00	190.50	310.00	5.55	
		7.00	2395.00	192.00	311.00	5.65	
		8.00	2401.00	191.00	311.00	5.72	

13.9.97	0.64	1.00	2385.00	189.00	307.50	4.97	
		2.00	2367.00	189.50	310.00	5.01	
		3.00	2397.00	188.50	307.00	4.95	
		4.00	2362.00	190.00	309.00	5.07	
		5.00	2359.00	190.50	309.00	5.03	
		6.00	2385.00	191.00	309.50	5.07	
		7.00	2383.00	191.00	309.00	5.12	
		8.00	2389.00	193.00	311.00	5.20	
15.9.97	0.70	1.00	2380.00	189.00	307.50	4.75	
		2.00	2361.00	189.00	310.00	4.75	
		3.00	2391.00	189.50	309.00	4.68	
		4.00	2357.00	190.00	310.50	4.85	
		5.00	2353.00	190.00	309.00	4.76	
		6.00	2370.00	192.00	309.00	4.41	
		7.00	2376.00	191.00	308.50	4.81	
		8.00	2381.00	193.00	310.00	4.84	
17.9.97	0.76	1.00	2376.00	188.00	307.50	4.58	
		2.00	2358.00	187.50	310.00	4.61	
		3.00	2388.00	188.50	308.00	4.55	
		4.00	2353.00	190.00	311.00	4.67	
		5.00	2349.00	190.00	309.50	4.59	
		6.00	2374.00	191.00	310.00	4.58	
		7.00	2371.00	190.00	309.00	4.59	
		8.00	2377.00	193.00	310.00	4.67	
19.9.97	0.52	1.00	2374.00			4.49	
		2.00	2356.00			4.53	
		3.00	2385.00			4.42	
		4.00	2350.00			4.54	
		5.00	2347.00			4.50	
		6.00	2372.00			4.49	
		7.00	2369.00			4.50	
		8.00	2374.00			4.54	
21.9.97	0.50	1.00	2372.00			4.40	
		2.00	2354.00			4.44	
		3.00	2384.00			4.38	
		4.00	2348.00			4.45	
		5.00	2344.00			4.36	
		6.00	2370.00			4.41	
		7.00	2367.00			4.41	
		8.00	2372.00			4.45	
23.9.97	0.69	1.00	2370.00			4.31	
		2.00	2353.00			4.39	
		3.00	2381.00			4.25	
		4.00	2346.00			4.36	
		5.00	2343.00			4.32	
		6.00	2368.00			4.32	
		7.00	2365.00			4.32	
		8.00	2370.00			4.36	

29:9:97	0.39	1.00	2368.00			4.23	
		2.00	2350.00			4.26	
		3.00	2379.00			4.16	
		4.00	2345.00			4.31	
		5.00	2341.00			4.23	
		6.00	2367.00			4.27	
		7.00	2364.00			4.28	
		8.00	2369.00			4.32	
30:10:97	0.40	1.00	2368.00	190.00	309.00		
		2.00	2350.00	189.00	319.50		
		3.00	2379.00	190.00	316.00		
		4.00	2344.00	192.00	310.00		
		5.00	2341.00	193.50	309.00		
		6.00	2367.00	192.50	312.00		
		7.00	2363.00	190.00	309.00		
		8.00	2369.00	193.50	310.00		

Sample manufacture and monitoring data

Halstow soil samples - manufacture data for Test Series 2							
18/07/97 manufacture data							
sample	Av H(mm)	Av O(mm)	wgt (g)	bulk density (kgm-3)	dry weight	moisture content	
1.00	202.50	323.00	3100.70	1844.33	2317.00	33.82	
2.00	204.70	323.00	3131.00	1842.34	2345.00	33.52	
3.00	203.00	323.00	3120.90	1851.77	2340.00	33.37	
4.00	202.30	323.00	3111.50	1852.59	2327.00	33.71	
5.00	203.70	323.00	3122.60	1846.42	2337.00	33.62	
6.00	202.30	323.00	3131.50	1864.50	2350.00	33.26	
7.00	203.00	323.00	3110.30	1845.49	2328.00	33.60	
8.00	203.00	323.00	3126.30	1854.98	2342.00	33.49	
			3119.35	1850.30		33.55	av
test data			10.93	7.25		0.18	stdev
sample	Av H(mm)	Av O(mm)	wgt (g)	bulk density (kgm-3)	dry weight	moisture content	stress
1.00	203.00	323.00	3088.00	1832.26	2317.00	33.28	88.66
2.00	204.00	322.50	3116.00	1845.51	2345.00	32.88	94.23
3.00	203.30	323.00	3105.00	1839.62	2340.00	32.69	100.31
4.00	202.30	322.50	3092.00	1846.69	2327.00	32.87	99.30
5.00	203.00	322.50	3103.00	1846.87	2337.00	32.78	95.25
6.00	202.30	322.50	3111.00	1858.04	2350.00	32.38	97.27
7.00	202.00	323.00	3089.00	1841.92	2328.00	32.69	95.25
8.00	202.00	322.50	3103.00	1856.01	2342.00	32.49	102.34
av				1845.87		32.76	96.58
stdev				8.39		0.27	4.26

Halstow cob samples - manufacture data for Test Series 2

18/07/97 manufacture data							
sample	Av H(mm)	Av O(mm)	wgt (g)	bulk density (kgm-3)	dry weight	moisture content	
1.00	202.00	323.50	3083.40	1832.90	2327.00	32.51	
2.00	201.50	324.50	3083.40	1826.15	2330.00	32.33	
3.00	203.00	323.00	3058.90	1814.99	2306.00	32.65	
4.00	202.50	323.50	3047.80	1807.27	2296.00	32.74	
5.00	203.00	323.50	3004.20	1777.03	2265.00	32.64	
6.00	204.50	323.50	3074.90	1805.51	2328.00	32.08	
7.00	204.00	324.00	3072.80	1811.99	2323.00	32.28	
8.00	203.00	324.00	3081.20	1816.95	2336.00	31.90	
			3063.33	1811.60		32.39	av
test data			27.01	16.72		0.30	stdev
sample	Av H(mm)	Av O(mm)	wgt (g)	bulk density (kgm-3)	dry weight	moisture content	stress
1.00	202.00	323.00	3065.00	1827.61	2327.00	31.71	156.00
2.00	201.50	324.00	3070.00	1823.83	2330.00	31.76	153.02
3.00	203.00	323.50	3044.00	1800.57	2306.00	32.00	151.48
4.00	202.00	323.50	3041.00	1807.70	2296.00	32.45	149.46
5.00	202.00	323.50	2984.00	1773.82	2265.00	31.74	167.64
6.00	202.00	324.50	3056.00	1805.44	2328.00	31.27	150.55
7.00	203.00	324.00	3051.00	1799.14	2323.00	31.34	167.12
8.00	201.50	323.00	3058.00	1816.70	2336.00	30.91	183.35
av				1806.85		31.65	159.83
stdev				16.94		0.47	11.90

Halstow manufacture data for soil cylinders Test Series 3

ON MANUFACTURE	sample	sample wgt.(without tins)	dry wgt(no tins)	mc. manuf	maximum load	mc. test%	MANU DEN	no wgts. taken with tins	
time	1.00	3101.00	2319.00	33.72	85.11	33.72	1824.70		
11:27-16:28	2.00	3114.80	2328.00	33.80	136.41	31.86	1848.80		
	3.00	3104.00	2320.00	33.79	208.14	30.15	1850.90		
	4.00	3121.80	2303.00	35.55	218.66	31.29	1843.90		
	5.00	3104.50	2320.00	33.81	345.98	27.59	1846.10		
	6.00	3114.70	2333.00	33.51	490.58	25.80	1842.40		
	7.00	3100.70	2322.00	33.54	853.17	21.36	1846.20		
	8.00	3109.20	2327.00	33.61	686.08	23.59	1841.90		
	9.00	3117.60	2324.00	34.15	1069.75	20.35	1835.70		
	10.00	3111.30	2318.00	34.22	1083.21	18.21	1855.20		
	11.00	3108.40	2321.00	33.93	990.14	15.38	1844.40		
	12.00	3110.80	2317.00	34.26		11.65	1846.40		
	13.00	3110.80	2313.00	34.49	1077.39	9.99	1854.90		
	14.00	3093.30	2332.00	32.65	1059.21	6.56	1834.20		
	15.00	3104.00	2328.00	33.33	1300.14	5.28	1853.40		

Halstow manufacture data for cob cylinders Test Series 3

ON MANUFACTURE									
date	time	sample	sample wgt.(without tins)	prior sample wgt	post test wgt.	dry wgts.	mc manu %	maximum load capacity(kN/m2)	mc. test%
13/10/1997	11:30-14:54	1	3066.6	3063.9	3062.5	2285.00	34.21	150.18	34.03
		2	3045.7	2995	2995	2266.00	34.41	157.94	32.17
		3	3041.7	2940	2939	2267.00	34.17	247.11	29.64
		4	3049.6	2948.1	2847.8	2269.00	34.40	341.59	25.51
		5	3069.6	2923.2	2923	2289.00	34.10	594.93	27.70
		6	3075.1	2815	2814	2293.00	34.11	831.17	22.72
		7	3044.3	2726	2725	2265.00	34.41	955.47	20.31
		8	3068.1	2578	2577	2287.00	34.15	1057.89	12.68
		9	3058.6	2471	2471	2280.00	34.15	1041.72	8.38
		10	3055.7	2425	2425	2276.00	34.26	1130.44	6.55
		11	3018.8	2377	2376	2250.00	34.17	1072.81	5.60
		12	3032.3				#DIV/0!		#DIV/0!
		13	3032.4	2366	2366	2260.00	34.18	1028.86	4.69
		14	3039.3	2369	2368	2262.00	34.36	1113.22	4.69
		15	3026.1	2337	2337	2283.00	32.55	1271.33	4.88

Appendix 8:

Test Series Results

Crediton soil - Test Series 1, test data

A strain %	B strain %	C strain %	D strain %	E strain%	F strain %	G strain %	H strain %
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.13	0.15	0.13	0.13	0.13	0.13	0.13
0.38	0.25	0.30	0.25	0.25	0.25	0.25	0.26
0.51	0.38	0.45	0.38	0.51	0.38	0.38	0.52
0.63	0.51	0.50	0.50	0.76	0.51	0.50	0.65
0.76	0.64	0.63	0.63	0.88	0.63	0.63	0.78
1.02	0.76	0.76	0.76	1.01	0.76	0.75	0.91
1.27	1.02	1.01	1.01	1.14	0.89	0.88	1.04
1.52	1.15	1.26	1.26	1.26	1.02	1.00	1.17
1.65	1.27	1.51	1.51	1.52	1.27	1.25	1.30
1.78	1.40	1.76	1.76	1.77	1.52	1.38	1.43
2.03	1.53	2.02	2.02	2.02	1.65	1.50	1.56
2.28	1.65	2.27	2.12	2.22	1.78	1.75	1.69
2.34	1.78	2.52	2.27	2.32	2.03	2.00	1.82
2.54	1.91	2.77	2.52	2.53	2.16	2.25	2.08
2.66	2.04	3.02	2.64	2.78	2.28	2.38	2.34
2.79	2.16	3.27		2.90	2.54	2.50	2.60
	2.29	3.53		2.98	2.66	2.75	2.86
	2.42	3.78			2.79	3.00	3.12
	2.54	4.03			2.84	3.13	3.32
	2.67	4.28				3.25	
	2.80	4.53				3.50	
	2.93						
	3.05						
	3.18						

A stress (kN/m2)	B stress (kN/m2)	C stress (kN/m2)	D stress (kN/m2)	E stress (kN/m2)	F stress (kN/m2)	G stress (kN/m2)	H stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
140.87	75.69	44.15	105.13	35.74	56.77	42.05	14.72
166.10	136.66	96.72	149.28	86.20	119.84	92.51	71.49
189.23	178.71	128.25	178.71	157.69	151.38	124.05	161.89
210.25	210.25	138.77	210.25	214.46	178.71	147.18	191.33
229.17	237.58	164.00	237.58	241.79	203.94	168.20	220.76
260.71	262.81	185.02	262.81	262.81	233.38	189.23	245.99
285.94	304.86	214.46	298.56	288.04	256.51	208.15	271.22
311.17	323.79	231.28	327.99	306.97	279.63	224.97	294.35
319.58	340.61	241.79	351.12	338.50	317.48	260.71	315.38
327.99	355.32	262.81	363.73	359.53	344.81	273.33	334.30
336.40	367.94	300.66	365.84	372.14	354.27	288.04	349.02
336.40	376.35	332.20	363.73	372.14	361.63	306.97	363.73
327.99	382.66	356.37	351.12	365.84	365.84	321.68	376.35
304.86	388.96	372.14	317.48	346.91	365.84	325.89	388.96
281.74	391.07	382.66	296.45	306.97	357.43	325.89	393.17
252.30	391.07	382.66		283.84	332.20	321.68	382.66
	384.76	374.25		267.02	306.97	302.76	353.22
	367.94	353.22		0.00	288.04	273.33	294.35
	340.61	306.97			277.53	256.51	252.30
	306.97	235.48				237.58	
	267.02	164.00				201.84	
	235.48						
	199.74						
	166.10						

Crediton cob - Test Series 1, test data

1 strain %	3 strain %	4 strain %	5 strain %	6 strain %	7 strain %	8 strain %
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.13	0.10	0.13	0.10	0.05	0.13	0.13
0.25	0.15	0.38	0.20	0.10	0.25	0.38
0.38	0.20	0.50	0.25	0.20	0.38	0.50
0.51	0.25	0.63	0.38	0.30	0.50	0.63
0.65	0.38	0.75	0.50	0.40	0.63	0.76
0.76	0.51	1.01	0.63	0.50	0.75	0.88
0.89	0.63	1.26	0.76	0.75	0.88	1.01
1.02	0.76	1.51	0.88	1.01	1.01	1.26
1.14	0.89	1.76	1.01	1.26	1.26	1.51
1.27	1.01	2.01	1.13	1.51	1.51	1.76
1.52	1.14	2.26	1.26	1.76	1.76	2.02
1.78	1.27	2.51	1.39	2.01	2.01	2.27
2.03	1.39	2.76	1.51	2.26	2.26	2.52
2.28	1.52	3.02	1.64	2.51	2.51	2.77
2.54	1.77	3.27	1.77	2.76	2.76	3.02
2.79	2.03	3.52	2.02	3.02	3.02	3.27
3.05	2.28	3.77	2.32	3.27	3.27	3.53
3.30	2.53	4.02	2.52	3.52	3.52	3.78
3.55	2.78	4.30	2.77	3.77	3.77	4.03
3.81	3.04	4.52	3.03	4.02	4.02	4.28
4.06	3.29	4.77	3.28	4.27	4.27	4.53
4.31	3.54	5.03	3.53	4.52	4.52	4.79
4.57	3.80	5.18	3.78	4.77	4.77	5.04
4.67	4.05	5.28	4.04	5.03	5.03	5.29
4.82	4.35	5.53	4.29	5.18	5.28	5.39
4.95	4.51	5.78	4.41	5.53	5.53	5.54
5.08	4.81	6.03	4.59	5.73	5.78	5.84
5.20	4.94	6.28	5.17	6.03	6.03	6.05
5.33	5.06	6.53	5.55	6.28	6.28	6.30
5.58	5.32	7.04	6.05	6.53	6.78	6.55
5.84	5.57	7.29	6.31	6.88	6.83	6.80
6.09	5.82	7.39	6.56		7.04	7.05
6.29	6.08	7.54	6.91		7.16	7.20
	6.33		7.06			7.25
	6.58		7.41			7.56
	6.84		7.57			7.81
	7.09					7.91
	7.34					7.96
	7.85					
	8.05					
	8.10					
	8.35					

1 stress (kN/m2)	3] stress (kN/m2)	4 stress (kN/m2)	5 stress (kN/m2)	6 stress (kN/m2)	7 stress (kN/m2)	8 stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.26	151.38	119.84	136.66	145.07	184.81	103.83
111.43	214.46	237.58	229.17	182.92	232.57	267.87
206.05	304.86	304.86	264.92	252.30	276.18	319.79
267.02	325.89	355.32	332.20	304.86	313.56	363.40
313.27	372.14	388.96	378.45	342.71	348.86	394.54
351.12	403.68	454.14	409.99	372.14	377.93	421.54
382.66	431.01	502.50	439.42	433.12	404.93	446.46
409.99	454.14	544.55	462.55	475.17	446.46	483.83
435.22	473.06	578.19	485.68	510.91	483.83	521.21
458.35	491.99	607.62	506.70	546.65	514.98	541.98
494.09	510.91	637.06	525.63	578.19	554.44	581.43
527.73	527.73	655.98	544.55	609.73	571.05	606.35
559.27	540.34	677.01	563.47	632.85	595.97	629.19
586.60	555.06	695.93	578.19	655.98	616.73	649.96
607.62	580.29	710.65	592.91	672.80	635.42	666.57
646.52	605.52	719.06	622.34	689.62	643.73	683.18
662.29	624.44	727.47	651.78	702.24	656.19	687.34
673.85	643.37	735.88	668.60	712.75	666.57	712.25
683.31	658.08	740.08	687.52	721.16	671.76	718.48
687.52	672.80	742.18	702.24	727.47	676.95	722.64
689.62	682.26	742.18	714.85	727.47	677.99	726.79
687.52	691.72	742.18	727.47	727.47	679.03	730.94
683.31	699.08	740.08	735.88	725.36	674.88	733.02
681.21	704.34	735.88	742.18	714.85	664.49	733.02
674.90	694.88	725.36	746.39	704.34	664.49	730.94
666.49	708.54	712.75	748.49	672.80	664.49	728.87
658.08	708.54	710.65	750.59	645.47	664.49	718.48
639.16	707.66	710.65	748.49	620.24	664.49	708.10
611.83	706.44	710.65	733.77	609.73	659.30	693.57
588.70	702.24	704.34	721.16	609.73	558.59	674.88
536.14	691.72	666.49	721.16	563.47	539.90	645.80
	683.31	571.88	721.16		506.68	639.58
	670.70	540.34	712.75			622.96
	658.08		693.83			564.82
	643.37		569.78			556.51
	628.65		550.86			548.21
	613.93					519.14
	597.11					429.84
	597.11					
	557.16					
	548.75					
	531.93					

Halstow soil - Test Series 1, test data

1 strain %	2 strain %	3 strain %	4 strain %	5 strain%	6 strain %	7 strain %	8 strain %
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.13	0.10	0.08	0.11	0.05	0.05	0.13	0.13
0.21	0.21	0.11	0.21	0.11	0.13	0.27	0.26
0.32	0.31	0.19	0.32	0.16	0.26	0.43	0.42
0.43	0.45	0.27	0.43	0.26	0.40	0.53	0.53
0.53	0.52	0.37	0.53	0.42	0.53	0.80	0.74
0.66	0.65	0.53	0.80	0.53	0.66	1.06	0.93
0.80	0.79	0.66	0.94	0.66	0.79	1.33	1.06
0.93	0.92	0.80	1.07	0.79	0.92	1.38	1.32
1.06	1.05	1.06	1.34	1.05	1.06	1.46	1.46
1.33	1.18	1.33	1.60	1.32	1.21	1.60	1.53
1.60	1.31	1.43	1.68	1.42	1.32	1.70	1.64
1.73	1.47	1.59	1.76	1.53	1.58	1.81	1.80
1.86	1.57	1.70	1.87	1.58	1.90	1.86	1.90
2.13	1.68		2.03	1.68	2.01		
	1.83			1.74	2.11		
	1.94			1.79	2.24		
	2.09			1.89	2.32		
1 stress (kN/m2)	**2 stress (kN/m2)**	**3 stress (kN/m2)**	**4 stress (kN/m2)**	**5 stress (kN/m2)**	**6 stress (kN/m2)**	**7 stress (kN/m2)**	**8 stress (kN/m2)**
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
223.50	4.55	230.41	230.41	119.81	101.38	184.33	9.22
414.74	115.92	299.53	387.09	207.37	184.33	460.82	122.12
564.51	318.22	414.74	541.47	264.97	304.14	668.19	294.93
679.71	454.59	506.90	661.28	403.22	387.09	790.31	398.61
794.92	506.87	645.15	760.36	571.42	479.25	1039.15	599.07
926.25	611.43	824.87	1036.85	670.50	573.72	1207.35	771.88
1043.76	727.35	940.08	1152.05	785.70	668.19	1292.61	850.22
1152.05	834.18	1041.46	1244.22	882.47	762.66	1297.21	1214.27
1251.13	934.19	1175.10	1336.38	1064.50	852.52	1293.76	1232.70
1375.55	993.29	1200.44	1377.86	1145.14	940.08	1271.87	1218.87
1412.42	1041.02	1152.05	1359.42	1154.36	983.85	1264.96	1177.40
1387.07	1081.94	1052.98	1327.17	1154.36	1078.32	1221.18	1129.01
1313.34	1093.30	1013.81	1267.26	1147.45	1105.97	1152.05	1036.85
1036.85	1097.85		1152.05	1117.49	1094.45		
	1068.30			1094.45	1092.15		
	1022.84			1066.80	1071.41		
	909.19			1004.59	933.16		

Halstow cob - Test Series 1, test data

1 strain %	2 strain %	3 strain %	4 strain %	5 strain%	6 strain %	7 strain %	8 strain %
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.13	0.16	0.13	0.16	0.16	0.16	0.13	0.13
0.26	0.26	0.26	0.26	0.26	0.26	0.53	0.26
0.39	0.40	0.45	0.39	0.44	0.39	0.68	0.39
0.53	0.53	0.53	0.52	0.54	0.55	0.82	0.52
0.66	0.66	0.66	0.65	0.65	0.65	0.92	0.65
0.79	0.93	0.79	0.78	0.78	0.78	1.05	0.78
0.92	1.06	0.92	0.91	0.90	0.96	1.18	0.90
1.05	1.19	1.05	1.04	1.03	1.09	1.32	1.03
1.18	1.32	1.18	1.17	1.16	1.22	1.45	1.16
1.32	1.46	1.45	1.43	1.29	1.30	1.58	1.29
1.50	1.59	1.58	1.56	1.42	1.43	1.84	1.42
1.63	1.72	1.71	1.72	1.55	1.56	2.11	1.55
1.71	1.88	1.84	1.82	1.81	1.82	2.37	1.81
1.84	2.12	2.11	2.08	2.07	2.08	2.63	2.07
2.11	2.38	2.37	2.37	2.33	2.36	2.89	2.33
2.37	2.65	2.63	2.60	2.58	2.60	3.16	2.58
2.63	2.91	2.89	2.86	2.84	2.86	3.42	2.84
2.89	3.17	3.16	3.13	3.10	3.12	3.68	3.10
3.16	3.44	3.42	3.39	3.41	3.38	3.95	3.36
3.26	3.60	3.68	3.65	3.62	3.64	4.21	3.62
3.42	3.76	3.79	3.91	3.88	3.90	4.34	3.88
	3.86	4.08	4.17	4.13	4.03	4.58	4.13
	3.97	4.21	4.43	4.39	4.16	4.74	4.39
			4.69	4.65	4.42	5.00	4.65
			4.95	4.91	4.68	5.11	4.91
			5.08	5.17	4.78	5.16	5.17
			5.21	5.43			5.43
			5.47				5.68
			5.73				5.94
			6.02				6.46
			6.25				6.72
			6.54				6.98

1 stress (kN/m2)	2 stress (kN/m2)	3 stress (kN/m2)	4 stress (kN/m2)	5 stress (kN/m2)	6 stress (kN/m2)	7 stress (kN/m2)	8 stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17.71	32.99	17.71	5.50	3.32	11.94	39.85	4.40
75.27	50.59	95.19	19.80	11.07	28.23	95.19	20.90
208.09	92.38	216.95	50.59	35.42	65.14	150.53	50.59
382.98	151.77	39.85	105.58	59.77	145.49	205.88	92.38
531.30	226.55	345.34	160.57	88.55	178.06	247.94	149.57
635.34	310.14	413.97	206.76	139.47	228.00	305.50	178.16
721.68	378.32	475.95	250.75	197.02	306.17	369.69	219.96
803.59	450.91	546.79	296.94	256.79	369.15	431.68	250.75
878.85	510.30	606.56	340.93	323.21	425.60	487.02	290.34
951.91	558.69	659.69	428.91	391.83	456.00	546.79	327.73
1040.46	598.28	708.40	481.70	453.82	516.80	650.84	367.33
1089.16	644.47	757.10	534.49	515.80	586.29	763.74	411.32
1113.51	684.06	808.02	569.68	604.35	705.72	863.36	483.90
1151.15	732.45	856.72	659.87	692.90	796.92	960.76	563.09
1208.70	798.44	943.05	741.25	794.73	896.81	1042.67	648.87
1239.69	873.22	1011.68	811.64	885.50	970.64	1113.51	723.65
1254.08	930.41	1073.66	882.02	967.40	1031.44	1168.85	805.04
1252.98	978.80	1122.37	952.41	1038.24	1079.21	1202.06	866.62
1224.20	1016.19	1153.36	1011.80	1102.44	1107.44	1226.41	921.61
1202.06	1034.89	1162.21	1057.99	1135.65	1131.32	1228.63	1189.96
1151.15	1038.19	1157.79	1090.98	1166.64	1135.66	1226.41	1229.55
	1027.19	1151.15	1112.98	1177.71	1133.49	1206.49	1264.74
	1003.00	1122.37	1125.07	1175.50	1122.64	1186.56	1302.14
	987.60	1106.87	1130.57	1166.64	1092.24	1126.79	1330.73
			1119.57	1151.15	1046.64	1095.80	1348.33
			1115.17	1135.65	1037.95	1078.09	1357.13
			1103.08	1098.02			1357.13
			1299.94				1354.93
			1275.74				1339.53
			1251.55				1330.73
			1216.35				1299.94
							1258.15

Crediton soil - Test Series 2, test data

Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7		Sample 8	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	5.07	0.25	6.08	0.25	5.07	0.59	14.19	0.27	4.05	0.25	9.12	0.25	10.13	0.25	8.11
0.54	11.15	0.49	10.13	0.49	11.15	0.99	19.25	0.49	8.11	0.54	14.19	0.74	18.24	0.49	13.17
0.74	14.19	0.74	13.17	1.13	19.25	1.48	26.34	0.79	13.17	0.74	16.21	1.04	22.29	0.74	17.23
0.99	16.21	0.98	16.21	1.48	22.29	2.08	30.40	1.11	18.24	0.99	19.25	1.24	24.32	1.08	22.29
1.23	20.27	1.23	19.25	1.82	26.34	2.57	34.45	1.48	22.29	1.48	24.32	1.58	26.34	1.48	26.34
1.48	22.29	1.47	21.28	2.02	28.37	3.56	44.58	1.97	28.37	1.98	28.37	2.48	36.48	1.97	31.41
1.72	24.32	1.96	26.34	2.46	33.44	4.94	58.77	2.46	32.93	2.47	33.44	3.47	46.61	2.22	33.44
1.97	26.34	2.45	30.40	2.95	38.50	6.18	68.90	3.00	38.50	2.97	38.50	4.95	59.78	3.94	51.68
2.46	29.38	2.94	34.45	3.59	44.58	7.41	79.03	3.45	42.56	3.46	42.56	6.44	70.93	4.93	60.80
2.96	34.45	3.68	41.54	4.18	50.66	8.90	87.14	3.94	48.64	4.00	42.56	7.43	77.01	6.16	71.94
3.45	38.50	3.97	44.58	4.92	59.78	9.89	92.21	4.43	52.69	4.45	49.65	8.91	86.13	6.95	79.03
3.94	38.50	4.41	49.65	6.03	68.90	10.87	96.26	5.05	57.76	4.99	58.77	9.90	89.17	7.39	83.09
4.48	47.62	4.90	53.70	7.38	81.06	11.86	98.29	5.91	65.86	5.49	62.82	10.89	93.22	8.62	90.18
5.17	52.69	5.39	58.77	8.90	91.19	12.41	99.30	6.90	73.97	5.93	66.87	12.57	95.25	9.85	97.27
5.47	54.72	5.88	62.82	9.84	94.23	12.85	99.30	7.39	77.01	6.43	71.94	12.87	93.73	10.34	99.81
5.91	58.77	6.47	65.86	10.82	100.31	13.35	99.30	7.88	81.06	6.97	75.99	13.37	92.21	10.84	101.33
6.40	62.82	6.86	69.91	11.31	99.30	13.84	98.79	8.37	84.10	7.46	79.03	13.86	83.09	11.33	102.34
6.90	65.86	7.84	75.99	11.81	100.31	14.38	97.27	8.87	87.14	8.90	88.15	14.36	73.97	11.82	102.34
7.39	68.90	8.38	80.05	12.30	100.31	14.83	94.23	9.46	89.17	10.13	94.23	14.85	64.85	12.32	102.34
7.88	71.94	8.82	83.09	12.79	99.81	15.32	86.13	9.95	91.70	10.38	95.25	15.10	60.80	12.66	100.31
8.42	74.98	9.31	85.11	13.28	99.30	15.82	78.53	10.34	93.22	11.37	97.27			12.81	99.30
8.87	78.02	9.80	87.14	13.77	95.25			10.89	94.23	11.86	97.27			13.30	95.25
9.36	81.06	10.29	88.66	14.26	89.17			11.33	95.25	12.36	97.27			13.84	88.15
9.90	83.09	10.78	90.18	14.76	84.10			11.82	95.25	12.90	95.25			14.29	83.09
10.34	83.09	11.27	92.21	15.25	79.03			12.81	95.25	13.35	91.19			14.53	78.02
10.89	85.11	11.76	93.22	15.35	77.01			13.30	95.25	13.84	87.14				
11.38	86.13	12.35	94.23					13.79	93.22	14.38	85.11				
11.82	88.15	12.84	94.23					14.29	90.18	14.88	91.19				
12.32	88.66	13.33	92.21					14.78	85.11	15.32	78.02				
12.81	88.66	13.73	89.17					15.27	79.03						
13.35	88.66	14.22	85.11					15.76	67.89						
13.79	88.66	14.71	82.07					16.26	57.76						
14.29	83.09	15.20	74.98												
14.78	72.95	15.83	63.83												
15.27	64.85														
15.76	52.69														

Crediton cob - Test Series 2, test data

Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7		Sample 8	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.12	4.00	0.29	4.05	0.49	17.23	0.73	23.30	0.49	16.02	0.68	19.02	0.54	20.02	0.54	24.32
0.24	8.51	0.49	9.12	0.98	29.89	1.46	43.57	0.98	30.04	0.98	28.03	1.03	38.05	1.46	62.82
0.44	13.02	0.97	18.24	1.51	44.58	2.44	74.98	1.95	56.07	1.47	43.05	1.47	55.07	2.44	107.40
0.49	14.02	1.46	28.37	2.05	60.80	3.90	121.59	2.93	86.10	1.96	60.07	1.96	76.09	3.51	154.01
0.61	16.02	1.95	38.50	2.44	72.95	4.88	149.96	3.91	113.13	2.93	94.11	2.45	95.11	4.49	192.52
0.73	19.02	2.43	50.66	2.93	89.17	5.93	180.36	4.89	141.17	3.91	131.16	2.94	114.14	4.88	207.72
0.97	24.03	2.92	64.85	3.41	103.35	6.83	198.60	5.86	161.19	4.89	163.19	3.43	132.16	5.37	225.96
1.21	28.03	3.41	78.53	3.90	117.54	7.80	210.76	6.84	182.22	5.87	193.73	3.92	148.18	5.85	243.18
1.46	33.04	3.94	93.22	4.39	132.74	9.27	224.94	7.82	200.24	7.33	226.27	4.41	164.20	6.83	273.58
1.70	38.05	4.48	107.40	4.88	145.91	9.76	224.94	8.79	212.25	8.31	238.28	4.89	181.22	7.80	297.90
1.94	44.55	4.87	119.56	5.37	159.08	10.24	224.94	9.77	228.27	9.29	246.29	5.38	195.23	8.83	321.20
2.43	57.07	5.35	131.72	6.83	192.52	10.73	220.38	10.75	238.28	9.78	248.30	5.87	207.25	9.76	338.43
2.92	71.08	5.94	146.92	8.78	220.89	11.22	216.84	11.24	243.29	10.27	248.30	6.51	220.26	10.24	344.51
3.40	86.10	6.33	156.04	9.76	229.00	11.71	210.76	11.72	249.30	10.76	248.30	6.85	229.27	11.56	352.61
3.89	100.12	6.81	168.20	11.22	235.07	12.20	202.14	12.21	254.30	11.30	247.29	7.34	237.28	11.71	352.61
4.37	114.14	7.30	180.36	11.71	234.06			12.70	258.31	11.78	249.30	7.83	248.30	12.59	356.67
4.86	129.65	7.79	190.49	12.20	233.05			13.19	262.31	12.22	250.30	8.32	256.30	13.17	356.67
5.34	144.17	8.27	198.60	12.68	231.02			13.68	264.31	12.71	252.30	8.81	262.31	13.66	354.64
5.83	158.19	8.76	207.72	13.17	231.02			14.17	266.32	13.69	242.29	9.30	266.32	14.15	354.64
6.32	171.20	9.49	215.82	13.66	229.00			14.66	267.32	14.18	236.28	9.79	270.32	14.68	351.60
6.80	182.22	9.73	221.90	14.15	229.00			15.14	268.32	14.67	233.28	10.33	274.33	15.12	349.07
7.29	194.23	10.22	229.00	14.63	226.97			15.63	268.32			10.77	277.33	15.61	344.51
7.77	203.74	10.71	233.05					16.12	268.32			11.26	276.33	16.10	342.48
8.02	208.75	11.19	238.11					16.61	267.32			11.75	276.33	16.59	338.43
8.26	213.75	11.68	257.37					17.15	263.31			12.24	274.33	17.07	334.88
8.75	220.26	12.17	273.58					17.59	261.31			12.73	272.32		
9.23	230.77	12.65	280.67					18.37	256.30			13.22	269.32		
9.72	239.28	12.77	279.66					18.56	256.30			13.75	264.31		
10.20	245.29	12.90	279.66					19.05	253.30			14.19	262.31		
10.59	256.30	13.19	278.64					19.54	249.30			14.68	257.31		
10.69	256.30	13.63	279.66												
10.93	260.81	14.11	281.18												
11.18	265.82	14.60	281.68												
11.42	280.83	15.09	282.70												
11.71	282.34	15.57	283.20												
11.90	282.34	16.06	283.71												
12.15	285.84	16.55	283.71												
12.63	291.35	17.03	283.71												
13.12	292.35	17.52	283.20												
13.61	293.35	18.00	281.68												
14.09	293.35	18.49	279.15												
14.58	293.85	18.98	275.60												
15.06	294.35	19.46	273.07												
15.55	294.35	19.61	271.55												
16.03	294.35														
16.38	293.35														

Dunsford soil - Test Series 2, test data

Sample A		Sample B		Sample C		Sample D		SampleE		Sample F		Sample G		Sample H	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.50	4.00	0.50	3.00	0.50	12.51	0.50	10.01	0.54	6.08	0.50	24.03	0.60	8.11	0.50	1.01
1.50	12.01	2.97	32.04	1.50	26.03	1.49	22.03	1.63	18.24	0.99	33.04	1.05	11.15	1.01	10.13
2.00	14.02	4.95	43.05	2.50	37.54	2.48	34.04	3.07	33.44	1.49	40.05	1.80	17.23	1.51	19.76
2.50	17.52	6.93	61.07	3.00	43.05	2.97	40.05	4.46	48.64	2.98	56.07	2.00	18.24	2.01	27.36
3.00	20.02	8.42	72.59	4.00	52.06	4.46	58.07	6.09	66.87	4.47	70.08	3.49	30.40	2.51	34.45
3.49	24.03	9.90	82.10	5.00	62.07	5.95	76.59	7.43	79.03	5.96	82.60	4.99	43.06	3.02	40.53
3.99	26.03	11.39	89.11	6.50	76.09	7.44	90.11	9.90	97.27	6.95	90.11	6.53	56.74	4.52	59.78
4.49	30.04	11.88	91.11	8.00	86.10	8.92	100.62	10.89	100.82	7.44	92.11	7.98	68.90	5.53	70.93
4.99	34.04	12.38	93.11	10.00	96.11	9.92	106.13	11.88	104.87	8.98	98.12	9.98	82.07	6.03	77.01
5.49	37.04	12.87	94.11	11.50	101.12	10.91	110.63	12.87	107.40	9.68	100.12	10.47	86.13	6.53	82.07
7.49	50.06	14.36	97.12	13.00	103.62	11.40	112.13	13.86	107.40	10.42	102.12	10.97	89.17	7.04	85.11
9.99	63.08	14.85	97.52	13.50	103.62	11.90	112.63	15.84	107.40	12.41	102.12	11.97	93.22	7.54	88.66
11.98	72.09	15.35	98.12	14.00	103.62	12.39	113.13	16.09	106.90	12.70	101.12	12.97	97.78	8.14	91.19
12.48	73.09	15.84	98.62	14.50	103.62	14.38	113.13	16.39	105.38	13.15	100.12	13.97	101.33	8.54	93.73
12.98	75.09	16.34	98.62	15.00	103.62	14.87	111.63	16.83	103.35	13.40	99.12	14.46	102.34	9.05	95.75
13.98	78.09	16.83	98.62	15.50	102.62	15.37	107.63	17.62	99.30	13.95	97.12	17.46	102.34	9.55	96.77
14.48	79.09	17.38	98.62	16.00	100.12	15.87	102.12	18.07	97.27	14.94	86.10	17.76	101.33	10.55	97.27
14.98	79.59	17.82	98.12	16.80	96.11	16.36	98.12	18.56	93.22	15.29	82.10	17.96	99.81	12.31	97.27
15.48	80.10	18.32	98.12	17.05	92.11	16.86	91.11	19.31	89.17			18.95	93.22	12.36	96.77
15.98	80.60	18.86	97.62	17.50	88.10	17.75	78.09	19.80	86.13			19.50	89.17	13.07	93.73
16.48	81.60	19.31	96.11	18.00	81.10			19.90	85.11			19.95	85.11	13.57	92.21
16.97	81.60	19.80	94.11									20.25	83.09	14.07	89.17
17.47	81.60	20.35	93.61											14.57	85.11
17.97	81.10	20.79	90.11											15.08	81.06
18.47	80.60	21.29	87.60												
18.97	80.10	22.03	84.10												
19.47	79.59	22.28	82.10												
19.97	78.09	22.77	78.09												
20.47	75.59														
20.79	68.08														

Dunsford cob - Test Series 2, test data

Sample A		Sample B		Sample C		Sample D		SampleE		Sample F		Sample G		Sample H	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.49	4.51	0.65	16.02	0.49	12.01	0.54	4.00	0.54	24.03	0.59	13.02	0.49	14.02	0.49	18.02
0.99	7.51	1.00	32.54	0.99	19.52	1.49	9.51	0.99	34.04	0.98	20.02	1.04	22.03	0.99	26.03
1.48	9.01	1.49	63.08	1.97	30.04	1.98	15.02	1.48	42.55	1.57	28.03	1.93	34.04	1.48	37.04
2.96	22.53	1.99	78.09	2.56	36.04	2.48	20.02	2.46	58.07	2.06	36.04	2.22	38.05	1.97	47.06
3.95	31.04	2.49	86.10	4.43	59.07	2.97	26.03	3.00	65.08	4.91	77.09	2.57	40.05	2.56	59.07
5.93	48.06	2.99	91.11	4.98	65.08	4.46	43.05	4.93	90.11	6.44	96.11	2.96	47.06	3.45	78.09
7.90	65.08	3.58	97.62	5.91	76.09	5.94	60.07	6.01	104.12	7.86	110.63	4.44	68.08	4.93	106.13
9.38	77.09	3.98	101.62	7.93	97.12	7.43	77.09	7.39	115.14	9.34	128.15	5.93	88.10	7.39	147.68
10.37	92.11	4.48	105.13	9.51	112.13	7.92	82.10	8.87	129.15	11.50	144.17	7.90	114.14	8.87	170.20
11.36	104.12	5.02	110.13	10.84	126.15	8.42	86.60	10.34	137.16	13.27	158.19	9.38	130.15	9.85	180.21
12.35	108.13	5.47	114.14	11.87	133.16	9.90	100.62	11.82	145.67	13.76	160.19	10.37	141.17	10.84	192.23
13.33	116.14	5.97	118.14	12.96	141.67	10.89	110.13	12.96	148.18	15.23	168.20	11.36	151.18	11.82	200.24
14.37	123.15	6.97	125.15	14.29	150.18	11.88	118.14	14.78	154.18	16.71	175.21	12.84	164.20	12.81	207.25
15.46	130.15	7.96	131.16	14.78	152.18	12.87	126.15	15.76	155.69	17.20	176.21	14.32	175.21	13.79	213.25
16.30	134.16	8.96	138.16	16.26	160.19	13.86	132.16	16.75	158.19	18.38	182.22	15.31	181.22	14.78	217.26
17.28	140.17	9.95	142.17	17.34	164.20	14.85	140.17	17.88	159.19	19.66	184.72	16.30	185.22	15.76	222.26
17.78	141.17	10.95	146.67	18.72	166.20	15.84	145.17	18.72	159.19	21.28	189.23	17.28	195.73	16.75	226.27
18.27	142.67	11.94	151.18	19.70	168.20	16.83	149.18	19.70	159.19	21.97	190.23	18.27	198.24	17.78	231.28
18.77	144.17	12.99	156.19	20.20	168.20	17.82	153.18	22.17	159.19	23.10	190.23	19.75	203.24	18.72	232.28
19.26	145.67	13.93	160.19	21.18	168.20	18.81	156.19	22.76	155.18	23.69	190.73	20.74	204.74	19.70	232.28
19.75	147.18	14.93	164.20	22.71	168.20	19.80	158.19	24.19	150.18	24.13	191.23	21.23	205.24	20.69	235.28
20.25	148.18	15.92	164.20	23.15	167.20	20.79	160.19	24.88	147.18	24.62	191.23	21.73	206.25	23.65	235.28
20.25	147.68	16.92	165.20	23.69	163.19	21.78	161.69	25.79	141.17	27.52	191.23	22.22	207.25	24.14	236.28
21.23	148.18	17.41	165.70	24.63	160.19	23.27	161.69			28.01	190.23	22.72	207.25	24.63	236.28
21.73	148.18	17.91	166.20			25.25	161.69			28.65	185.72	23.21	207.25	25.17	235.28
22.72	147.68	18.41	166.20			25.74	161.69			29.48	182.22	23.70	206.25	25.67	234.28
23.46	147.18	18.91	167.70							30.47	180.21	25.19	201.74	26.11	234.28
23.70	146.17	19.40	167.70									25.68	200.24	26.70	230.27
24.20	144.17	19.90	167.70									25.75	199.74	27.09	229.27
24.69	144.17	20.50	167.20											27.59	226.27
25.19	143.17	20.95	167.20											28.08	224.27
25.68	141.17	21.39	167.20											28.72	220.26
26.17	140.17	21.89	167.20												
26.72	140.17	22.39	166.20												
27.16	139.17	22.94	164.20												
27.65	136.66	23.38	164.20												
28.20	136.66	28.86	162.19												
28.64	136.16	29.35	162.19												
29.23	135.16	29.85	160.19												
29.63	135.16														
30.12	132.16														

Tedburn soil - Test Series 2, test data

Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7		Sample 8	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.12	8.11	1.97	26.34	0.50	10.13	2.99	50.66	0.50	17.23	0.50	18.24	0.50	12.16	0.50	17.23
0.25	10.13	2.46	29 38	2.50	32.42	3.99	60 80	1.98	40.53	1.74	40.53	2.49	35.46	1.99	36.48
0.37	11.15	3.94	45.60	5.00	50.66	5.48	72.95	3.97	63.83	2.99	54.72	3.98	50.66	3.99	52.69
0.50	12.16	4.93	52.69	7.50	67.38	6.98	83.09	5.45	77.51	4.48	70.42	5.47	62.82	5.98	73.97
0.62	14.19	5.91	58.77	9.00	74.98	8.47	91.19	6.94	89.17	6.47	87.14	7.46	79.03	7.47	85.11
0.74	15.20	6.90	64.85	11.00	81.06	9.47	95.25	7.59	93.22	7.46	93.73	8.96	86.13	7.97	88.66
0.87	16.21	7.88	69.91	12.50	83.09	9.97	96.77	8.43	96.77	8.96	103.35	9.95	92.21	9.97	99.30
0.99	18.24	8.87	73.97	13.00	83.09	10.46	97.27	8.97	99.30	10.45	114.50	10.95	95.25	10.96	102.85
1.24	20.27	9.85	77.51	13.50	83.09	10.96	97.78	9.92	108.42	11.24	113.48	11.44	96.26	11.96	105.38
1.49	22 29	10.84	80.55	14.00	83.09	11.46	97.78	10.41	112.47	11.44	113.48	11.94	96.77	12.95	106.90
1.73	24.32	11.82	81.06	14.50	83.09	11.96	97.78	10.91	112.47	11.94	111.96	12.44	97.27	13.45	107.40
1.98	26.34	12.81	82.58	15.00	83.09	12.46	95.25	11.40	111.46	12.44	109.94	12.94	98.29	13.95	107.40
2.48	30.40	13.79	82.58	15.50	83.09	13.15	91.19	11.90	108.92	13.43	102.34	13.43	98.29	14.45	106.90
2.97	33.94	14.78	82.58	16.00	83.09	13.95	81.06	12.89	92 21	14.43	81.06	13.93	97.78	14.95	105.38
3.47	37.49	15.27	82.07	16.50	83.09	14.95	65.86	13.88	62.82	14.93	62.82	14.43	95.25	15.45	103.86
3.96	40.53	15.76	81.57	17.15	81.06	15.45	56.74	14.38	51.68			14.93	92.21	15.94	101.33
4.70	46.10	16.75	77.01	18.55	70.93							15.42	91.19	16.44	96.26
5.69	51.68	17.73	66.87	19.50	57.76							15.92	87.65	16.94	89.17
6.44	55.73	18.23	57.76	20.00	50.66							16.42	84.10	17.44	79.03
7.43	60.80	18.72	52.49												
8.42	64.85	19.21	47.62												
9.90	70.93														
11.88	74.98														
12.38	74.98														
12.87	74 98														
13.37	74.98														
13.61	74.47														
13.86	72.95														
14.36	70.42														
14.85	64.85														
15.35	60.80														
15.84	56.74														
16.34	50.66														
16.83	46.61														
17.33	42.56														
17.82	38.50														
18.32	34.45														

Tedburn cob - Test Series 2, test data

Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7		Sample 8	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.50	12.01	0.49	17.02	0.54	12.01	0.49	16.02	0.51	12.16	0.87	24.32	0.99	30.40	0.50	23.30
0.99	19.02	0.98	24.03	0.99	19.02	1.03	26.03	1.08	24.32	1.24	32.42	1.49	36.48	0.99	36.98
1.49	25.03	1.47	30.54	1.53	24.03	1.48	32.04	1.57	32.42	1.53	40.53	2.48	48.64	1.49	46.81
1.98	30.04	1.96	36.04	1.97	30.04	2.56	44.05	2.55	46.61	2.10	47.62	2.97	51.17	2.48	62.82
2.48	34.04	2.45	41.05	2.61	37.04	2.96	49.06	2.99	52.69	2.97	51.68	3.47	58.77	2.97	68.90
2.97	38.05	2.94	46.05	2.96	39.05	3.45	54.06	3.92	66.87	3.47	54.72	5.50	77.01	3.47	77.01
3.47	42.55	3.43	51.06	3.45	44.05	3.94	58.07	5.15	79.03	4.95	70.93	7.43	90.18	3.96	83.09
3.96	47.06	3.92	56.07	4.09	50.06	6.40	79.09	6.37	89.17	7.43	93.22	9.41	100.31	5.94	105.38
4.46	50.06	4.41	60.57	4.43	52.06	7.39	86.10	7.84	100.31	8.91	103.35	10.89	112.47	8.17	117.54
4.95	54.06	4.90	64.08	5.07	57.07	8.87	94.11	10.29	113.48	11.88	118.55	13.37	120.58	10.50	127.87
5.45	58.07	5.39	68.08	6.45	67.08	12.81	110.63	12.45	121.59	12.87	122.60	14.85	125.64	11.88	131.72
5.94	61.07	5.88	72.09	7.88	76.09	14.29	114.14	13.73	125.64	14.85	129.70	16.44	128.68	12.38	135.78
6.44	64.08	6.37	77.09	9.51	85.10	15.76	118.14	15.20	128.68	15.84	132.74	17.33	130.71	13.86	141.86
6.93	67.08	6.86	81.10	9.85	87.10	16.85	120.64	16.67	131.72	16.34	133.75	18.32	131.72	15.99	147.93
7.43	69.08	7.35	81.60	11.82	96.11	18.72	124.15	17.65	133.75	17.82	137.80	19.80	132.74	17.33	149.96
7.92	72.09	8.43	89.11	13.79	102.12	20.94	126.15	18.14	135.78	18.81	141.86	20.79	132.74	18.47	151.99
8.42	74.59	9.36	92.11	16.26	110.13	22.17	128.15	20.10	135.78	21.29	144.90	21.29	131.72	19.80	154.01
8.91	77.09	10.44	98.12	18.97	117.14	23.65	130.15	20.74	136.28	23.27	146.42	22.28	129.19	20.79	155.03
9.50	80.10	11.27	101.12	20.44	120.14	24.63	131.66	22.21	136.28	25.25	146.42	22.77	127.67	21.44	155.03
9.90	81.10	12.25	105.13	22.17	123.15	25.12	132.16	23.53	135.78	25.74	147.93			22.28	155.03
10.40	83.10	13.24	107.63	23.94	127.15	25.62	136.16	23.77	133.75	26.24	146.92			23.37	154.01
10.99	86.10	14.22	109.13	25.12	129.15	26.11	135.16	24.02	133.75	27.72	144.39			24.26	151.99
11.44	87.60	15.20	111.13	25.62	130.15	26.60	115.14	25.00	131.72	28.71	139.83			25.25	149.96
12.03	90.11	16.18	113.13	28.08	134.16	27.09	115.14								
12.43	91.11	17.65	114.14	29.56	135.16	27.73	115.14								
12.92	93.11	18.14	116.14	30.54	135.16	28.08	115.14								
13.37	94.11	19.41	116.64	31.53	136.16	28.57	115.14								
13.86	95.11	21.57	115.64	32.51	136.16	29.06	113.13								
14.36	97.12	23.04	114.14	33.00	136.16										
14.85	99.12	24.02	112.13	33.50	136.16										
15.35	100.62	24.51	110.13	34.48	136.16										
15.84	102.12	25.00	109.13	35.57	135.16										
16.34	103.12	25.49	108.13	35.96	134.16										
16.83	104.12			36.45	133.16										
17.33	106.13			36.95	133.16										
17.82	108.13			37.44	132.16										
19.31	112.13														
19.80	113.13														
20.40	115.14														
20.79	116.14														
21.91	120.14														
22.77	121.64														
23.76	124.15														
25.74	129.15														
26.73	131.16														
27.72	133.16														
28.96	135.16														
29.70	136.16														
30.69	138.16														
31.68	140.17														
32.72	141.67														
33.66	142.17														
34.65	144.17														
35.64	146.17														
36.63	147.18														
37.62	148.18														
38.61	148.18														
39.60	146.67														
40.15	145.17														

Halstow soil - Test Series 2, test data

Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7		Sample 8	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	5.07	0.25	6.08	0.25	5.07	0.59	14.19	0.27	4.05	0.25	9.12	0.25	10.13	0.25	8.11
0.54	11.15	0.49	10.13	0.49	11.15	0.99	19.25	0.49	8.11	0.54	14.19	0.74	18.24	0.49	13.17
0.74	14.19	0.74	13.17	1.13	19.25	1.48	26.34	0.79	13.17	0.74	16.21	1.04	22.29	0.74	17.23
0.99	16.21	0.98	16.21	1.48	22.29	2.08	30.40	1.11	18.24	0.99	19.25	1.24	24.32	1.08	22.29
1.23	20.27	1.23	19.25	1.82	26.34	2.57	34.45	1.48	22.29	1.48	24.32	1.58	26.34	1.48	26.34
1.48	22.29	1.47	21 28	2 02	28.37	3.56	44.58	1.97	28.37	1.98	28.37	2.48	36.48	1.97	31.41
1.72	24.32	1.96	26.34	2.46	33.44	4.94	58.77	2.46	32.93	2.47	33.44	3.47	46.61	2.22	33.44
1.97	26.34	2.45	30.40	2.95	38.50	6.18	68.90	3.00	38.50	2.97	38.50	4.95	59.78	3.94	51.68
2.46	29 38	2.94	34.45	3.59	44.58	7.41	79.03	3.45	42.56	3.46	42.56	6.44	70.93	4.93	60 80
2.96	34.45	3.68	41.54	4.18	50.66	8.90	87.14	3.94	48.64	4.00	42.56	7.43	77.01	6.16	71 94
3.45	38.50	3.97	44.58	4.92	59.78	9.89	92.21	4.43	52.69	4.45	49.65	8.91	86.13	6.95	79 03
3.94	38.50	4.41	49.65	6.03	68.90	10.87	96.26	5.05	57.76	4.99	58.77	9.90	89.17	7.39	83.09
4.48	47.62	4.90	53.70	7.38	81.06	11.86	98.29	5.91	65.86	5.49	62.82	10.89	93.22	8.62	90.18
5.17	52.69	5.39	58.77	8.90	91.19	12.41	99.30	6.90	73.97	5.93	66.87	12.57	95.25	9.85	97.27
5.47	54.72	5.88	62.82	9.84	94.23	12.85	99.30	7.39	77.01	6.43	71.94	12.87	93.73	10.34	99.81
5.91	58.77	6.47	65.86	10.82	100.31	13.35	99.30	7.88	81.06	6.97	75.99	13.37	92.21	10.84	101.33
6.40	62.82	6.86	69.91	11.31	99.30	13.84	98.79	8.37	84.10	7.46	79.03	13.86	83.09	11.33	102.34
6.90	65.86	7.84	75 99	11.81	100.31	14.38	97.27	8.87	87.14	8.90	88.15	14.36	73.97	11.82	102.34
7.39	68.90	8.38	80.05	12.30	100.31	14.83	94.23	9.46	89.17	10.13	94.23	14.85	64.85	12.32	102.34
7.88	71.94	8.82	83.09	12.79	99.81	15.32	86.13	9.95	91.70	10.38	95.25	15.10	60.80	12.66	100 31
8.42	74.98	9.31	85.11	13.28	99.30	15.82	78.53	10.34	93.22	11.37	97.27			12.81	99.30
8.87	78.02	9.80	87.14	13.77	95.25			10.89	94.23	11.86	97.27			13.30	95.25
9.36	81.06	10.29	88.66	14.26	89.17			11.33	95.25	12.36	97.27			13.84	88.15
9.90	83.09	10.78	90.18	14.76	84.10			11.82	95.25	12.90	95.25			14.29	83.09
10.34	83.09	11.27	92.21	15.25	79.03			12.81	95.25	13.35	91.19			14.53	78.02
10.89	85.11	11.76	93.22	15.35	77.01			13.30	95.25	13.84	87.14				
11.38	86.13	12.35	94.23					13.79	93.22	14.38	85.11				
11.82	88.15	12.84	94.23					14.29	90.18	14.88	91.19				
12.32	88.66	13.33	92.21					14.78	85.11	15.32	78.02				
12.81	88.66	13.73	89.17					15.27	79.03						
13.35	88.66	14.22	85.11					15.76	67.89						
13.79	88.66	14.71	82.07					16.26	57.76						
14.29	83.09	15.20	74.98												
14.78	72.95	15.83	63.83												
15.27	64.85														
15.76	52.69														

Halstow cob - Test Series 2, test data

Sample 1		Sample 2		Sample 3		Sample 4		Sample 5		Sample 6		Sample 7		Sample 8	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.12	1.01	0.15	1.01	0.20	5.05	0.10	2.02	0.12	2.52	0.12	2.01	0.12	2.01	0.12	1.52
0.25	3.04	0.30	3.02	0.54	18.18	0.25	3.03	0.25	4.04	0.25	3.51	0.27	4.03	0.25	4.05
0.37	6.08	0.45	4.53	0.74	24.24	0.37	4.54	0.37	5.05	0.50	11.04	0.37	7.05	0.37	6.08
0.50	10.13	0.89	18.12	0.99	28.28	0.49	7.07	0.54	7.07	0.74	19.07	0.49	11.07	0.50	10.13
0.87	18.23	0.99	24.16	1.48	35.34	0.74	14.14	0.74	15.15	0.99	20.07	0.79	16.11	0.74	14.18
0.99	21.27	1.64	34.23	1.97	42.41	0.99	20.20	0.99	26.26	1.49	36.13	1.13	34.23	0.99	16.21
1.49	28.36	2.48	46.31	2.46	48.47	1.23	24.24	1.24	36.35	2.48	56.20	2.22	58.39	1.99	52.67
3.07	49.64	2.98	52.35	2.96	54.53	1.48	28.28	1.63	44.43	4.06	88.32	2.96	68.46	2.98	69.90
4.46	63.82	4.47	68.46	3.94	67.66	2.47	40.39	2.08	53.52	6.93	108.39	3.94	84.57	3.97	85.09
4.95	69.90	5.71	81.55	5.42	83.82	2.96	46.45	2.97	66.65	7.92	118.43	4.93	96.65	4.96	97.25
5.94	83.06	7.10	93.63	6.40	92.91	3.95	56.55	4.46	90.89	8.91	126.46	6.40	112.75	6.50	117.51
6.93	93.19	7.99	100.67	7.39	103.00	4.94	66.65	5.94	107.04	9.90	132.48	7.88	125.34	7.94	130.67
7.92	100.29	9.43	110.74	7.88	111.08	5.98	76.75	7.43	118.15	10.89	138.50	9.85	140.94	9.43	143.84
9.41	113.45	10.67	118.79	8.87	114.11	6.91	84.83	9.01	129.26	11.39	141.51	11.33	146.98	10.42	150.93
10.40	121.56	12.06	123.83	9.85	121.18	7.90	90.89	9.90	133.30	12.38	146.53	12.32	153.02	11.41	158.02
11.39	127.64	12.90	130.88	10.89	128.25	8.89	97.96	11.39	141.38	13.37	148.04	13.30	157.05	12.90	166.13
12.52	133.71	13.90	135.91	11.82	133.30	9.88	104.01	12.87	146.43	14.36	149.04	14.29	159.06	13.45	168.15
13.86	139.79	14.89	140.94	12.81	137.34	10.37	106.54	13.86	150.47	15.35	150.55	15.27	161.08	14.39	172.21
14.85	143.84	15.63	141.95	13.30	139.36	10.91	109.06	14.85	153.50	16.34	150.55	16.26	163.09	15.38	177.27
15.84	148.91	16.38	143.96	14.29	143.40	11.36	111.08	16.09	157.54	17.33	150.55	16.75	163.09	15.53	178.28
17.33	151.95	16.87	144.97	14.78	144.41	11.85	113.10	16.83	159.56	17.82	149.54	17.24	165.10	16.38	179.30
18.56	152.96	17.37	146.98	16.01	147.44	12.35	117.14	17.82	162.59	18.32	148.54	18.23	165.10	17.87	182.34
19.80	153.97	17.87	149.00	17.00	149.46	12.84	121.18	18.81	165.62			18.72	165.10	18.36	182.34
20.79	153.97	18.36	151.01	17.73	150.47	13.33	121.18	19.80	165.62			19.21	167.12	18.86	183.35
21.29	156.00	18.86	150.00	18.72	151.48	13.83	123.20	20.30	165.62			19.70	167.12	19.35	183.35
21.78	152.96	19.35	150.00	19.70	151.48	14.32	125.22	20.79	167.64			20.69	146.98	20.35	183.35
		19.85	150.00	21.18	151.48	14.81	126.74	21.29	167.64			22.17	167.12	20.84	183.35
		20.84	150.00			15.31	129.26	21.78	167.64			22.41	163.09	21.34	183.35
		21.34	151.01			15.85	131.28	22.28	158.55					21.84	183.35
		22.08	151.01			16.30	131.28							22.08	182.34
		23.33	153.02			16.79	133.30							23.08	181.32
		23.82	153.02			17.28	133.30							23.33	180.31
		24.32	153.02			17.78	135.32								
		24.81	153.02			18.27	136.83								
						18.77	137.34								
						19.26	139.36								
						19.75	139.36								
						20.25	139.36								
						20.74	139.36								
						21.23	141.38								
						21.73	141.38								
						22.22	141.38								
						22.72	142.39								
						23.21	142.39								
						23.70	142.39								
						24.20	142.39								
						24.44	149 46								
						24.69	142.39								
						25.43	140.37								

Bridgnorth soil - Test Series 2, test data

Sample A		Sample B		Sample C		Sample D		SampleE		Sample F		Sample G		Sample H	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.05	8.01	0.25	7.51	0.12	5.07	0.12	1.00	0.20	4.00	0.25	20.27	0.15	4.00	0.12	4.00
0.12	12.01	0.49	15.02	0.25	11.15	0.25	1.50	0.30	5.51	0.37	37.49	0.25	8.01	0.25	8.01
0.25	19.02	0.74	24.03	0.37	14.69	0.37	2.00	0.40	9.01	0.49	49.65	0.37	12.01	0.37	12.01
0.37	26.03	0.99	38.05	0.49	20.27	0.49	4.51	0.50	11.01	0.62	61.81	0.50	16.02	0.49	17.02
0.50	33.04	1.23	54.06	0.61	26.34	0.62	6.01	0.59	14.02	0.74	74.98	0.62	20.02	0.61	23.03
0.62	42.05	1.48	70.08	0.74	34.45	0.74	10.01	0.69	18.02	0.89	87.14	0.74	26.03	0.78	32.04
0.74	50.06	1.73	88.10	0.98	50.66	0.86	14.02	0.79	22.03	0.99	94.23	0.87	32.04	0.86	36.04
0.87	62.07	1.97	102.12	1.23	69.91	0.99	18.02	0.89	26.03	1.23	110.95	0.99	38.05	0.98	46.05
0.99	72.09	2.10	108.13	1.47	91.19	1.11	22.03	0.99	31.04	1.48	115.51	1.14	48.06	1.23	66.08
1.12	82.10	2.22	112.13	1.72	111.46	1.23	26.03	1.24	46.05	1.63	111.46	1.24	52.06	1.47	88.10
1.24	92.11	2.34	115.14	1.89	121.59	1.36	33.04	1.49	62.07	1.73	107.40	1.49	70.08	1.72	110.13
1.36	102.12	2.47	116.14	1.96	125.64	1.48	40.05	1.73	82.10	1.85	103.35	1.74	88.10	1.96	124.15
1.49	110.13	2.59	116.14	2.08	128.68	1.73	54.06	1.98	102.12	1.97	103.35	1.98	105.13	2.21	126.15
1.61	114.14	2.71	116.14	2.21	128.68	1.97	71.08	2.23	120.14	2.10	100.31	2.23	119.14	2.33	125.65
1.74	117.14	2.84	114.14	2.33	127.67	2.22	89.11	2.48	132.16	2.22	99.30	2.48	125.15	2.45	122.65
1.86	117.14	2.96	108.13	2.50	111.46	2.47	107.13	2.72	132.16	2.34	97.27	2.60	124.15	2.70	111.13
1.98	116.14	3.08	102.12	2.57	102.34	2.71	124.15	2.85	128.15	2.47	115.51	2.73	121.14	2.89	100.12
2.11	110.13	3.21	94.11	2.70	91.19	2.96	132.16	2.97	123.15	2.59	82.07	2.97	120.14	3.06	89.11
2.23	106.13	3.33	84.10	2.84	74.98			3.22	100.12			3.10	126.15		
2.35	100.12	3.45	74.09	2.94	64.85			3.37	84.10			3.22	100.12		
2.48	92.11	3.58	64.08	3.06	52.69			3.47	75.09			3.35	94.11		
2.60	78.09														
2.73	72.09														
2.85	60.07														

Bridgnorth cob - Test Series 2, test data

Sample A		Sample B		Sample C		Sample D		SampleE		Sample F		Sample G		Sample H	
strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)	strain %	stress (kN/m2)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.15	6.01	0.19	4.00	0.12	4.00	0.12	5.01	0.12	4.00	0.12	5.01	0.12	2.00
		0.29	12.01	0.29	6.01	0.24	8.01	0.24	10.01	0.24	8.01	0.25	10.01	0.24	4.00
		0.44	16.02	0.39	9.61	0.36	12.01	0.37	14.02	0.37	12.01	0.37	15.02	0.37	5.51
		0.61	24.03	0.49	12.01	0.49	16.02	0.54	22.03	0.54	18.02	0.54	22.03	0.49	11.01
		0.73	30.04	0.61	16.02	0.61	22.03	0.73	32.04	0.76	28.03	0.74	36.04	0.73	20.02
		0.97	46.05	0.73	20.52	0.73	27.03	0.98	50.06	0.98	44.05	1.03	58.07	1.10	40.05
		1.21	66.08	0.97	30.04	0.97	42.05	1.22	74.09	1.22	64.08	1.23	81.10	1.22	48.06
		1.45	92.11	1.27	47.06	1.22	64.08	1.46	108.13	1.46	93.11	1.47	114.14	1.46	70.08
		1.69	126.15	1.46	60.07	1.46	91.11	1.71	146.17	1.71	125.15	1.79	160.19	1.73	104.12
		1.94	164.20	1.70	80.10	1.70	128.15	1.95	184.22	1.95	160.19	1.96	183.22	2.05	142.17
		2.18	202.24	1.95	106.13	1.95	166.20	2.20	218.26	2.20	194.23	2.70	214.25	2.20	164.20
		2.42	238.28	2.19	134.16	2.19	202.24	2.44	248.30	2.44	222.26	3.04	242.29	2.44	196.23
		2.66	274.33	2.48	172.20	2.43	236.28	2.68	270.32	2.68	248.30	3.19	250.30	2.68	220.26
		2.91	302.36	2.68	194.23	2.68	263.31	2.93	286.34	2.93	267.32	3.43	259.31	2.93	244.29
		3.15	326.39	2.92	222.26	2.92	281.33	3.17	290.35	3.17	280.33	3.77	263.31	3.17	256.30
		3.39	338.40	3.17	250.30	3.16	290.35	3.41	291.35	3.41	286.34	3.97	262.31	3.41	264.31
		3.63	348.41	3.41	274.33	3.41	294.35	3.54	288.34	3.66	289.34	4.17	258.31	3.66	266.32
		3.87	353.42	3.65	296.35	3.60	294.35	3.66	284.34	3.90	288.34	4.41	246.29	3.90	264.31
		4.02	354.42	3.90	312.37	3.70	292.35	3.90	270.32	4.15	278.33	4.66	230.27	4.24	252.30
		4.26	353.42	4.14	326.39	3.89	284.34	4.15	251.30	4.39	268.32			4.39	252.30
		4.36	353.42	4.38	336.40	4.14	276.33			4.63	250.30			4.63	252.30
		4.41	352.42	4.63	343.41	4.38	262.31							4.78	248.30
		4.60	347.41	4.87	349.42										
		4.84	332.40	5.11	352.42										
		4.99	326.39	5.36	354.42										
				5.60	354.42										
				5.75	353.42										
				5.85	351.42										
				6.09	345.41										
				6.33	338.40										
				6.45	336.40										
				6.58	331.39										

Helstow soil - Test Series 3, test data

sample1

date 19/8/97
time
wgt. pre test -3101
wgt. post test-3101
av. circ -323
av.height -204.7
dry weight=2319
mc.test=33.72
test bulk density=1824.7

strain%	stress(kN/m2)
0.00	0.00
0.12	3.55
0.24	5.07
0.37	6.08
0.49	8.11
0.73	10.13
1.22	14.19
1.47	16.21
1.95	20.27
2.44	24.32
3.03	32.42
3.42	35.46
3.96	39.52
4.89	47.62
5.86	56.74
6.84	64.85
7.82	69.91
8.79	77.01
9.77	82.07
10.92	85.11
11.72	85.11
12.46	83.09
13.14	79.03
13.68	71.94
14.17	59.78

sample2

date- 19/8/97
time-
wgt.pre test-3069.6
wgt. post test-3068.9
av. circ. -321
av.height -199.5
dry weight=2328
mc.test=31.82
bulk density=1876.6

strain%	stress(kN/m2)
0.00	0.00
0.13	10.26
0.30	16.41
0.38	18.46
0.50	22.56
0.63	24.61
0.75	28.20
0.90	32.82
1.15	36.92
1.50	44.10
1.75	48.20
2.01	51.28
2.51	59.49
3.01	65.64
3.51	71.79
4.01	77.95
4.51	84.10
5.01	91.28
5.51	96.41
6.02	102.56
6.52	107.69
7.02	112.82
7.52	117.95
8.02	123.07
8.52	128.20
9.02	130.25
9.52	133.33
10.03	134.35
10.53	135.38
10.58	136.41
11.03	136.41
11.53	136.41
12.13	133.33
12.53	131.28
13.03	121.02
13.53	105.64
14.04	93.33

sample 3

date -20/8/97
time -10:00
wgt. pre test -3019.5
wgt. post test-3019.0
av. circ. -319
av. height -197.3
dry weight=2320
mc.test=30.13
test bulk density=1889.9

strain%	stress(kN/m2)
0.00	0.00
0.13	22.84
0.25	33.22
0.38	39.45
0.51	47.76
0.63	53.99
0.76	58.14
1.01	68.53
1.52	86.18
2.03	99.67
2.53	111.10
3.04	122.00
3.55	133.94
4.05	143.28
4.61	153.66
5.07	157.82
5.58	166.20
6.08	176.51
6.59	184.81
7.10	193.12
7.60	198.31
8.11	202.46
8.62	207.65
9.12	211.81
9.63	213.88
10.19	217.52
10.64	218.04
11.15	218.04
11.51	211.81
11.66	209.73
11.91	201.42
12.16	191.04
12.42	166.12

sample 4

date -20/8/97
time -16:13
wgt. pre test -3023.6
wgt. post test-3023.3
av. circ. -317.5
av. height -199
dry weight=2303
mc.test=29.59
test bulk density=1894

strain%	stress(kN/m2)
0.00	0.00
0.13	29.44
0.38	39.95
0.56	54.67
0.75	67.28
1.01	77.79
1.26	90.41
1.51	98.82
1.81	107.23
2.01	113.54
2.26	121.95
2.51	128.25
2.76	132.46
3.02	138.77
3.27	145.07
3.62	152.43
3.77	157.69
4.02	160.84
4.27	166.10
4.52	170.30
4.77	176.61
5.03	180.82
5.40	187.12
5.53	189.23
5.78	192.38
6.03	196.58
6.28	199.74
6.53	201.84
6.78	204.99
7.04	208.15
7.29	210.25
8.04	216.56
8.29	218.66
8.54	216.56
9.05	206.05
9.30	195.53
9.55	178.71
9.80	157.69

sample 5

date -20/8/97
time -20.08
wgt. pre test -2960
wgt. post test-2960
av. circ. -316
av. height -195
dry weight=2320
mc.test=27.48
test bulk density= 1910.3

strain%	stress(kN/m2)
0.00	0.00
0.13	25.55
0.26	61.74
0.38	76.65
0.51	91.55
0.64	106.46
0.77	119.23
1.03	138.39
1.54	172.46
2.05	202.27
2.56	223.56
3.08	244.85
3.59	255.49
4.10	261.88
4.62	270.40
5.13	276.78
5.64	283.17
6.22	290.62
6.67	303.40
7.18	309.79
7.69	317.24
8.21	327.88
8.81	336.40
9.23	342.79
9.74	345.98
10.10	344.92
10.26	344.92
10.77	330.01
11.03	317.24
11.28	306.59

sample 6

date -21/8/97
time -8:54
wgt. pre test -2935
wgt. post test-2935
av. circ. -313.5
av. height -195
dry weight=2333
mc.test=25.86
test bulk density=1924.5 kg/m:

strain%	stress(kN/m2)
0.00	0.00
0.13	122.92
0.26	150.95
0.38	174.67
0.51	194.08
0.64	211.33
0.77	228.58
1.08	265.24
1.28	288.96
1.54	314.84
2.05	356.89
2.56	390.31
3.08	418.34
3.59	442.06
4.10	459.32
4.62	474.41
5.13	485.19
5.64	489.51
5.94	490.58
6.15	490.58
6.67	489.51
#DIV/0!	470.10
7.69	433.44

sample 7

date -22/8/97
time -11:05
wgt. pre test -2818
wgt. post test-2818
av. circ. -308.5
av. height -191.5
dry weight=2322
mc.test=21.36
test bulk density= 1943

strain%	stress(kN/m2)
0.00	0.00
0.13	66.39
0.26	126.15
0.39	199.18
0.52	225.74
0.65	265.56
0.78	307.63
1.04	376.24
1.36	447.06
1.57	489.11
2.09	582.06
2.61	658.41
3.13	721.49
3.66	774.61
4.18	813.34
4.70	839.89
5.22	853.17
5.54	852.07
5.74	818.87
6.01	783.46
6.27	692.72

sample 8

date -23/8/97
time -10:07
wgt. pre test -2876
wgt. post test-2876
av. circ. -310
av. height -193
dry weight=2327
mc.test=23.6
test bulk density=1948.6 kg/m3

strain%	stress(kN/m2)
0.00	0.00
0.13	37.62
0.26	81.89
0.41	141.64
0.52	194.76
0.67	219.10
0.78	243.45
1.04	303.20
1.55	387.30
2.07	453.70
2.59	506.81
3.11	553.29
3.63	588.70
4.15	624.11
4.40	637.39
4.66	650.67
4.92	661.73
5.18	670.59
5.70	683.87
5.96	686.08
6.22	686.08
6.40	684.97
6.74	670.59
6.99	653.99

sample 9

date -24/8/97
time -
wgt. pre test -2797
wgt. post test-2797
av. circ. -307
av. height -190
dry weight=2324
mc.test=
bulk density=1962.8 kg/m3

strain%	stress(kN/m2)
0.00	0.00
0.13	56.07
0.26	168.20
0.39	235.46
0.53	289.30
0.66	340.89
0.79	387.98
1.05	470.96
1.32	549.45
1.58	616.73
1.84	684.01
2.18	766.99
2.37	805.12
2.63	861.18
2.89	910.52
3.16	950.89
3.42	986.77
3.68	1015.93
3.95	1040.60
4.21	1059.66
4.47	1069.75
4.74	1065.27
5.00	1002.47
5.21	919.49

sample 10

date -25/8/97
time -13:15
wgt. pre test -2740
wgt. post test-2740
av. circ. -307.5
av. height -189.5
dry weight=2318
mc.test=18.21
test bulk density=1921.6k

strain%	stress(kN/m2)
0.00	0.00
0.13	121.10
0.26	195.11
0.40	262.39
0.53	327.43
0.79	446.29
1.06	549.45
1.37	663.83
1.64	758.02
1.90	843.24
2.11	910.52
2.37	969.02
2.64	1058.54
2.90	1083.21
3.14	1069.75
3.22	1058.54
3.30	1056.30
3.43	1056.30
3.69	1042.84
3.80	1027.14
3.85	997.99

sample 11

date -25/8/97
time -
wgt. pre test -2678
wgt. post test-2678
av. circ. -307
av. height -192
dry weight=2321
mc.test=15.38
test bulk density=1859.7kg/m3

strain%	stress(kN/m2)
0.00	0.00
0.13	107.65
0.26	204.08
0.42	284.82
0.52	334.16
0.78	441.81
1.04	538.24
1.30	623.46
1.56	708.68
1.80	780.45
2.08	867.91
2.34	926.22
2.60	973.32
2.76	990.14
2.47	984.53
2.60	971.07
2.86	915.01
2.97	874.64

sample 12

date -26/8/97
time -18:35
wgt. pre test -2587
wgt. post test-2587
av. circ. -305
av. height -188.5
dry weight=2317
mc.test=11.65
test bulk density= 1853.9 kg/m3

strain%	stress(kN/m2)
0.00	0.00
0.05	129.56
0.16	227.30
0.27	300.03
0.40	379.59
0.53	461.41
0.80	602.34
1.06	734.17
1.33	868.28
1.59	1191.04
-1.49	1136.49
1.33	868.28
1.38	954.65
1.49	7.23
1.27	1136.49
1.22	1191.04
1.49	1136.49
0.80	1022.84

sample 13

date -26/8/97
time -
wgt. pre test -2544
wgt. post test-2544
av. circ. -306
av. height -190
dry weight=2313
mc.test=9.99
test bulk density= 1796.9kg/m3

strain%	stress(kN/m2)
0.00	0.00
0.05	184.11
0.13	234.12
0.26	397.77
0.35	577.34
0.37	647.80
0.42	734.17
0.53	850.09
0.58	922.83
0.59	981.92
0.53	1034.20
0.42	1054.66
0.37	1077.39
0.42	1068.30
0.53	1056.93
0.66	1034.20
0.79	1006.93
0.89	966.01
1.05	909.19

sample 14

date -30/8/97
time -15:00
wgt. pre test -2485
wgt. post test-2485
av. circ. -304
av. height -189
dry weight=2332
mc.test=6.56
test bulk density=1796.9 kg/m3

strain%	stress(kN/m2)
0.00	0.00
0.05	170.47
0.13	284.12
0.26	440.96
0.40	563.70
0.53	688.71
0.66	811.45
0.79	927.37
1.01	1059.21
1.11	1056.93
1.24	1045.57
1.32	1027.38
1.46	977.38
1.59	913.74

sample 15

date -1/9/97
time -10:47
wgt. pre test -2451
wgt. post test-2451
av. circ. -304
av. height -190
dry weight=2328
mc.test=5.28
bulk density= kg/m3

strain%	stress(kN/m2)
0.00	0.00
0.13	13.64
0.26	15.91
0.39	52.28
0.53	227.30
0.66	375.04
0.79	259.12
1.05	702.35
1.32	891.01
1.58	1036.48
1.84	1163.76
2.11	1261.50
2.37	1300.14
2.45	1297.87
2.53	1272.86
2.58	1234.22
2.68	1136.49

Page numbering as found in the original thesis

Crediton Soil - Test Series 3, test data

sample a
date -26/9/96
time -
wgt. pre test -3537
wgt. post test-3535
av. circ -323.7
av.height -198
dry weight=3045
mc.test=16.16%
bulk density at test= 2142 kg/m3

post test circ=335.7
post test hgt.=185

strain%	stress(kN/m2)
0.00	0.00
0.13	12.16
0.25	12.67
0.38	14.19
0.51	14.19
0.63	15.20
0.76	16.21
0.88	16.21
1.01	18.24
1.14	18.24
1.52	20.27
1.77	21.28
2.02	22.29
2.27	24.32
2.53	24.32
3.03	28.37
3.54	30.40
4.04	32.42
4.55	34.45
5.05	35.46
5.56	36.48
6.06	38.50
6.57	38.50
7.07	39.52
7.58	39.52
8.08	38.50
8.59	38.50
9.09	38.00
9.60	36.48
10.10	34.45
10.61	31.41
10.86	30.40
11.11	28.37

sample b
date- 27/9/96
time- 16:00
wgt.pre test-3532
wgt. post test-3531
av. circ. -321.5
av.height -197
dry weight=3082
mc.test=14.6%
bulk density at test=2180 kg/m3

post test circ=345
post test hgt.=180

strain%	stress(kN/m2)
0.00	0.00
0.13	7.18
0.25	18.46
0.38	28.72
0.51	32.82
0.76	45.13
1.02	51.28
1.27	55.38
1.52	59.49
1.78	63.59
2.03	67.69
2.28	70.77
2.54	73.84
2.79	76.92
3.05	80.00
3.30	82.05
3.55	85.13
3.81	88.20
4.06	90.25
4.31	92.30
4.57	94.36
4.82	96.41
5.08	98.46
5.33	99.48
5.58	102.05
6.09	102.56
6.35	102.56
6.60	102.56
6.85	102.56
7.11	102.56
7.36	102.56
7.61	101.54
7.87	100.51
8.12	96.41
8.38	94.36
8.63	90.25
8.88	86.15
9.14	82.05
9.39	77.95
9.64	73.84
9.90	69.74
10.15	65.64
10.41	59.49

sample c
date -28/9/96
time -
wgt. pre test -3527
wgt. post test-3526
av. circ. -322.5
av. height -198
dry weight=3078
mc.test=14.55%
bulk density at test=2152 kg/m3

post test circ=349
post test hgt.=181

strain%	stress(kN/m2)
0.00	0.00
0.13	7.09
0.25	11.15
0.51	22.29
0.76	30.40
1.01	38.50
1.26	42.56
1.52	48.64
1.77	50.66
2.02	54.72
2.27	58.77
2.53	62.82
2.78	64.85
3.03	68.90
3.28	70.93
3.54	72.95
3.79	75.99
4.04	79.03
4.29	81.06
4.55	83.09
4.80	85.11
5.05	86.13
5.30	87.14
5.56	89.17
5.81	89.17
6.06	91.19
6.31	91.19
6.57	91.19
6.82	91.19
7.07	91.19
7.32	91.19
7.58	91.19
7.83	89.17
8.08	87.14
8.59	81.06
9.09	68.90
9.60	56.74
9.75	50.66

sample d
date -1/10/96
time -
wgt. pre test -3407
wgt. post test-3407
av. circ. -320.3
av. height -197
dry weight=3085
mc.test= %
bulk density at test= 2118 kg/m3

post test circ=329
post test hgt.=190.3

strain%	stress(kN/m2)
0.00	0.00
0.13	20.51
0.25	63.59
0.38	100.51
0.51	127.18
0.63	149.74
0.76	168.20
0.89	184.61
1.02	198.97
1.14	211.28
1.27	225.63
1.52	246.15
1.78	262.56
2.03	274.86
2.28	281.02
2.54	285.12
2.79	285.12
2.99	283.07
3.05	281.02
3.30	271.79
3.65	246.15
3.81	231.79
4.06	213.33
4.19	201.02
4.31	188.71

sample e
date -2/10/96
time -
wgt. pre test -3444
wgt. post test-3442
av. circ. -318.8
av. height -198.8
dry weight=
mc.test=
bulk density at test= 2142 kg/m3

post test circ=330.3
post test hgt.=190.3

strain%	stress(kN/m2)
0.00	0.00
0.13	20.77
0.25	83.06
0.38	103.83
0.55	128.75
0.63	137.05
0.75	151.59
1.01	176.51
1.13	186.89
1.26	197.27
1.38	207.65
1.51	215.96
1.76	228.42
2.01	238.80
2.26	246.07
2.52	250.22
2.77	251.26
3.02	250.22
3.22	245.03
3.52	232.57
3.65	226.34
3.77	220.11
4.02	203.50
4.15	195.20
4.28	186.89
4.40	176.51
4.53	168.20

sample f
date -4/10/96
time -10:00
wgt. pre test -3386
wgt. post test-3385
av. circ. -320.8
av. height -198
dry weight=
mc.test=
bulk density at test= 2088 kg/m3

post test circ=328
post test hgt.=194

strain%	stress(kN/m2)
0.00	0.00
0.13	59.49
1.09	94.36
0.38	123.07
0.51	145.64
0.63	166.15
0.76	186.66
0.88	203.07
1.01	219.48
1.14	235.89
1.26	246.15
1.39	256.40
1.52	264.61
1.64	271.79
1.77	275.89
1.89	278.97
2.02	281.02
2.22	279.99
2.42	274.86
2.53	268.71
2.78	250.25
3.03	227.69
3.16	198.97

sample g
date - /10/96
time -
wgt. pre test -3324
wgt. post test-3324
av. circ. -320
av. height -199.8
dry weight=3111
mc.test=6.78
bulk density at test=2041 kg/m3

post test circ=
post test hgt.=

strain%	stress(kN/m2)
0.00	0.00
0.13	58.14
0.25	97.60
0.38	126.67
0.50	149.51
0.63	170.28
0.75	191.04
0.88	211.81
1.00	230.50
1.25	263.72
1.50	288.64
1.75	295.91
1.88	311.48
2.00	314.60
2.13	314.60
2.25	311.48
2.50	292.79
2.75	261.64
3.00	232.57

sample h
date -9/10/96
time -
wgt. pre test -3261
wgt. post test-3260
av. circ. -318.3
av. height -200
dry weight=3118
mc.test=
bulk density at test= 1933 kg/m3

post test circ=326.7
post test hgt.=195

strain%	stress(kN/m2)
0.00	0.00
0.13	128.67
0.26	159.89
0.38	186.89
0.51	211.81
0.64	234.65
0.77	255.41
0.90	274.10
1.03	290.72
1.15	301.10
1.28	315.63
1.41	323.94
1.54	332.25
1.67	338.48
1.79	342.63
2.05	342.63
2.13	340.55
2.31	330.17
2.44	315.63
2.56	294.87
2.82	242.96
2.95	207.65
3.08	184.81

Appendix 9:

Pressure Membrane Results

		original bulk desit	original moisture conte	dry density	dry wgt/ original vol Dbt (kg/m3)	Dbt/Dw	Particle Density Dp	Total Pore Space	%increase in pore space				
Stockadon	0	1895	32.06	1434.95	1435	1.435	2770	48.19					
Crediton	0	2069	15.49	1791.50	1791.3	1.7913	2860	37.37					
TDSTM	0	1866	21.65	1533.91	1534.2	1.5342	2730	43.80					
Exminster	0	2022	13.29	1784.80	1784.5	1.7845	2745	34.99					
Becut	0	2072	16.43	1779.61	1779.5	1.7795	2705	34.21					
Stockadon	1	1619	35.23	1197.22	1197.5	1.1975	2770	56.77	17.79				
Crediton	1	1959	18.86	1648.16	1648.5	1.6485	2860	42.36	13.36				
TDSTM	1	1788	24.74	1433.38	1433.4	1.4334	2730	47.49	8.43				
Exminster	1	1755	13.53	1545.85	1545.8	1.5458	2745	43.69	24.85				
Becut	1	1921	18.37	1622.88	1622.6	1.6226	2705	40.01	16.95				
Soil Sample	Straw %				prior wgt (g)	wgt. after 0.1bar	wgt. after 0.3bar	wgt. after 0.5bar	wgt. after 1bar	wgt. after 3bar	wgt. after 5bar	wgt. after 15bar	sample dry wgts (g)
Stockadon	0				349.07	351.73	348.42	347.14	343.89	337.31	333.64	333.13	264.33
Crediton	0				489.35	489.92	486.32	484.88	482.49	476.48	472.39	470.93	423.7
TDSTM	0				518.78	518.55	514.82	513.84	510.83	504.68	499.77	499.21	426.46
Exminster	0				631.92	620.55	613.56	610.04	605.66	598.3	592.31	590.04	557.77
Becut	0				583.55	580.35	575.64	574.11	572.32	567.92	563.83	562.46	501.19
Stockadon	1				461.76	464.96	460.06	457.15	453.83	445.4	438.01	437.19	341.46
Crediton	1				421.82	420.21	416.53	414.63	412.11	404.88	397.4	396.95	354.88
TDSTM	1				513.62	514.64	508.92	506.16	500.84	491.3	486.56	486.35	411.75
Exminster	1				528.96	527.73	521.22	516.81	511.95	503.48	497	495.56	465.93
Becut	1				440.67	439.36	437.73	435.26	433.04	426.3	421.7	420.59	372.28
					grav.mc. at manu'	grav. mc. after 0.1bar	grav. mc. after 0.3bar	grav. mc. after 0.5bar	grav. mc. after 1bar	grav. mc. after 3bar	grav. mc. after 5bar	grav. mc. after 15bar	
Stockadon	0				32.06	33.06	31.81	31.33	30.10	27.61	26.22	26.03	
Crediton	0				15.49	15.63	14.78	14.44	13.88	12.46	11.49	11.15	
TDSTM	0				21.65	21.59	20.72	20.49	19.78	18.34	17.19	17.06	
Exminster	0				13.29	11.26	10.00	9.37	8.59	7.27	6.19	5.79	
Becut	0				16.43	15.79	14.85	14.55	14.19	13.31	12.50	12.22	
Stockadon	1				35.23	36.17	34.73	33.88	32.91	30.44	28.28	28.04	
Crediton	1				18.86	18.41	17.37	16.84	16.13	14.09	11.98	11.85	
TDSTM	1				24.74	24.99	23.60	22.93	21.64	19.32	18.17	18.12	
Exminster	1				13.53	13.26	11.87	10.92	9.88	8.06	6.67	6.36	
Becut	1				18.37	18.02	17.58	16.92	16.32	14.51	13.27	12.98	
						wgt. water after 0.1bar	wgt. water after 0.3bar	wgt. water after 0.5bar	wgt. water after 1bar	wgt. water after 3bar	wgt. water after 5bar	wgt.water after 15bar	
Stockadon	0					87.40	84.09	82.81	79.56	72.98	69.31	68.80	
Crediton	0					66.22	62.62	61.18	58.79	52.78	48.69	47.23	
TDSTM	0					92.09	88.36	87.38	84.37	78.22	73.31	72.75	
Exminster	0					62.78	55.79	52.27	47.89	40.53	34.54	32.27	
Becut	0					79.16	74.45	72.92	71.13	66.73	62.64	61.27	
Stockadon	1					123.50	118.60	115.69	112.37	103.94	96.55	95.73	
Crediton	1					65.33	61.65	59.75	57.23	50.00	42.52	42.07	
TDSTM	1					102.89	97.17	94.41	89.09	79.55	74.81	74.60	
Exminster	1					61.80	55.29	50.88	46.02	37.55	31.07	29.63	
Becut	1					67.08	65.45	62.98	60.76	54.02	49.42	48.31	
						water vol after 0.1bar	water vol. after 0.3bar	water vol.after 0.5bar	water vol.after 1bar	water vol.after 3bar	water vol.after 5bar	water vol.after 15bar	
Stockadon	0					47.45	45.65	44.96	43.19	39.62	37.63	37.35	
Crediton	0					28.00	26.47	25.87	24.85	22.31	20.58	19.97	
TDSTM	0					33.13	31.79	31.44	30.35	28.14	26.37	26.17	
Exminster	0					20.09	17.85	16.72	15.32	12.97	11.05	10.32	
Becut	0					28.11	26.43	25.89	25.26	23.69	22.24	21.75	
Stockadon	1					43.31	41.59	40.57	39.41	36.45	33.86	33.57	
Crediton	1					30.35	28.64	27.76	26.58	23.23	19.75	19.54	
TDSTM	1					35.82	33.83	32.87	31.01	27.69	26.04	25.97	
Exminster	1					20.50	18.34	16.88	15.27	12.46	10.31	9.83	
Becut	1					29.24	28.53	27.45	26.48	23.54	21.54	21.06	
					pF = log 10 h (where h = cm head water)	***2.00***	***2.50***	***2.70***	***3.00***	***3.50***	***3.70***	***4.20***	