Strength of soil-structure interfaces

STRENGTH OF SOIL-STRUCTURE INTERFACES

BY

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DEDICATION

TO : My parents, who inspired me to work,

brothers and sisters,

friends and colleagues for good cheer.

ABSTRACT

This research work deals with the development of the shearbox apparatus by introducing a micro-computer to automatically collect all the results, and to apply normal and shear stresses. A continuous statement of time, channel number, and transducer input and output is produced for each test, the sequences of applied rates of displacement and normal stresses for which were programmed.

An efficient computer program written, in both assembly language and Basic, for a B.B.C micro-computer/PCI data logger has been developed. The program controls the motor speed, reads and stores the output of the transducers and controls the variation of the direct current input into the electropneumatic converter, which controls the high pressure pneumatic system that applies normal load automatically instead of using dead weights.

The first series of experiments consisted of tests on six different clays. Each clay was sheared under normally consolidated drained conditions, and against both rock and glass. These tests defined the minimum residual strength obtained in each case and provided a basis for a comparison with other published research. The influence of Atterberg limits, rate of shear and clay fraction on the residual shear strength are discussed. It is demonstrated that the residual strength depends mainly on the magnitude of the clay fraction. The minimum value of residual strength was obtained with the clay sheared against glass.

The influence of vibrations, simulated by applying high rates of shear, on both the peak and residual strength was investigated by shearing the clay against rock for 2000 cycles of 1mm displacement, followed by slow drained shearing. There is a marked decrease in the peak strength following vibration but no significant change in the residual strength.

The experimental programme also included Bromhead ring shear tests on the six natural clays. It was found that the values of residual strength measured by the ring shear were between the values for clay sheared against rock and clay sheared against glass using the shear box.

DECLARATION

This is to certify that I am responsible for the work submitted in this thesis, the original work is my own except as specified in acknowledgements or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or an other institution for a higher degree.

Signed A. ROUAIGUIA

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NOTATION :

Those symbols which do not appear here are defined where they appear in the text.

C'	effective cohesion intercept (kN/m^2)
CF	clay fraction (%)
C'_R	effective residual cohesion intercept for a linear Mohr-Coulomb envelope (kN/m^2)
D	particle diameter
F	factor of safety
Gs	specific gravity
IB	brittleness index (IB = (Sf - Sr)/Sf , suggested by Bishop, 1967)
LL =WL	liquid limit(%)
PI =Ip	plasticity index(%)
PL =Wp	plastic limit(%)
R	residual factor
S	the average shear strength at the time of the slip (kN/m^2)
$S_f = \tau_p = \tau_f = \tau_{max}$	peak shear stress, also peak strength (kN/m^2)
$S_R = \tau_r = \tau_R$	residual shear stress, also residual strength (kN/m^2)
e	void ratio
k	coefficient of permeability (m/s)
n	porosity
$\tan\phi'$	effective coefficient of friction
$\tan\phi'_A$	apparant coefficient of friction ($\tau/\sigma n$)

$\tan\phi'_R$	effective residual coefficient of friction, equal to $\tau_R/\sigma'n$
$\tan\phi_u$	Interparticle coefficient of friction
$\tan\phi'$	effective coefficient of friction
$\tan\phi'_A$	apparant coefficient of friction ($\tau/\sigma n$)
u_w	pore water pressure
w	water content (%)
$\tau/\sigma'n$	effective stress ratio, coefficient of friction
$\tau_R/\sigma'n$	effective residual stress ratio, residual friction coefficient
σ_n	normal stress (kN/m^2)
σ'_n	normal effective stress(kN/m^2)
ϕ'	effective friction angle of shearing resistance (Degrees)
$\phi'p=\phi'max$	peak effective friction angle of shearing(Degrees)
$\phi'R=\phi'res=\phi'r$	residual friction angle (Degrees)
ϕu	interparticle friction angle (Degrees)
μ'	effective stress ratio (coefficient of friction)
μ'_r	effective residual stress ratio (residual friction coefficient)
D.V.M	digital voltmeter
L.V.D.T	linear variable differential transformer
O.C.R	overconsolidation ratio

CHAPTER ONE

INTRODUCTION

1.1 General

One of the most difficult problems encountered in geotechnical engineering and construction is how to ensure the stability of the slopes of cuttings and retaining walls, and consequently how to assess the limiting strength of soil. For the last twenty years, the drained residual strength of soils has played a great role in defining the extent of the loss in strength which can occur in overconsolidated fissured clays. It represents also the available strength along existing shear surfaces formed in any cohesive soil.It can be defined as the drained strength reached at a large shear displacement for which, if the soil is sheared further under drained conditions, there is no further loss in strength. Therefore, if previous large movements have occurred in the field leading to the formation of shear planes, knowledge of the residual strength will be required for design purposes.

Earlier investigations have been undertaken to achieve the large strains necessary to measure the residual shear strength. These involved the development of equipment specifically for this purpose and included torsional shear, Bromhead ring shear, Imperial College ring shear, shearbox and triaxial shear. Torsional shear tests have been carried out by numerous workers on both solid cylindrical specimens and ring-shaped specimens. This method undoubtedly provides the best means of shearing the specimens, but the interpretation of the results from torsional tests is not easy and the preparation of ring-shaped specimens presents some problems. Triaxial specimens containing a precut and/or artificially polished shear plane have been successfully tested, but allowance has to be made for the effect of the friction of the cell piston and the restraints imposed on the specimen by the rubber membrane and paper filter drain. It appears that the most convenient routine method of measuring the residual strength of soils is by means of the reversible shearbox. Nowdays, the improvement of technology and overwhelming need for economic savings in manpower has led to the introduction of new computer systems into conventional testing laboratories.

The main purpose of this study is the automation of the standard shearbox, by introducing a B.B.C micro-computer, and the determination of the residual shear strength of soil using soil/soil, soil/rock and soil/glass interfaces. Previous attempts to correlate residual shear strength with index properties, clay fraction and rate of shear are reviewed and discussed in the light of the results of this research.

The research has been carried out by using a shearbox apparatus, designed and built in the laboratory, which allows the test specimen to be sheared continuously to displacements large enough to establish residual conditions. The movement of the box and the shearing force developed are recorded automatically from transducers by using data logger systems. The work compares the shear strength of soil interfaces (rock or glass) with the same soil when sheared alone. Also the effect of vibrationary movement, achieved by repeated reversals of the box, on both the peak and residual shear strength have been studied. The test programme included Bromhead ring shear tests on the six natural clays to provide comparative results.

1.2 Outline of the thesis

The thesis consists of nine chapters and four appendices.

Chapter two is a literature review of investigations into, or related to, residual strength. The literature review represents the history and the definition of residual strength, and the mechanism of progressive failure which leads to residual strength development. Its role in geotechnical engineering is also described.

Chapter three describes a review of the main factors influencing residual shear strength such as the influence of Atterberg limits and water content, effect of clay fraction, rate of shear, normal stress, placement conditions, clay mineralogy, effect of vibrations and the effect of interfaces. Finally a conclusion has been drawn in the light of this literature.

Chapter four presents a description of both the ring shear apparatus developed by Bromhead (1979) and the ring shear apparatus developed by Bishop (1971). Methods of the interpretation of the results, descriptions and general principles for each technique are presented, also the description of the conventional and Swedish direct shear box is given. Little information about the triaxial test apparatus is given.

Chapter five provides a description of the modified shearbox. Emphasis is given to the parts of the equipment which allow the machine to be more versatile and less expensive to use than the conventional shearbox, such as displacement transducers, the submersible load cell, and the electro-pneumatic converter. Modifications to the equipment are also discussed, together with methods of calibration of the equipment and the effect of temperature on the stability of the equipment. An introduction to the automation used in this study is also given.

Chapter six gives a description of the characteristics of the materials used in the experimental programme, together with a plan of the tests, and the experimental methods of the modified shearbox tests, interface tests, and Bromhead ring shear tests.

Chapter seven presents the results of all the tests.

Chapter eight presents a discussion of the tests used in this study. It also gives the interpretation of the results on the vibrationary loading for both 200 and 2000 cycles, and the final moisture content .

Chapter nine presents the conclusions and suggestions for further research.

Four appendices are included in this thesis. One appendix shows the steps used to run the computer program and the other three present the listing of the main programs used in this study.

CHAPTER TWO

LITERATURE REVIEW OF PREVIOUS INVESTIGATIONS OF SOIL STRENGTH TESTING

2-1 Shear strength of soils

The materials which constitute the earth's crust are divided, somewhat arbitrarily by engineers, into soil and rock. Soil is taken to refer to comparatively soft, loose and uncemented deposits, while rock refers to hard, rigid and strongly cemented deposits (Sutton,1979). Thus, soil has been defined as an assemblage of discrete particles,together with a variable amount of water and air. Generally speaking, every building or structure that is founded in or on the earth imposes loads on the soil which supports the foundations. The stresses set up in the soil cause deformations of the soil in three ways (Head,1982) :

a) by the elastic deformation of the soil particles,

b) by the change in volume of the soil resulting from the expulsion of fluid (water and/or gas) from the voids between the solid particles,and

c) by the slippage of soil particles, one on another, which may lead to the sliding of one body of soil relative to the surrounding mass.

This study is concerned with the third process, which is known as shear failure and occurs when shear stresses set up in the soil mass exceed the maximum shear resistance which the soil can offer, its shear strength. The shear strength of the soil is derived from three basic components (Wray,1986):

a) Resistance to displacement because of interlocking of the individual soil particles.
b) Resistance to particle translation because of friction between individual soil particles at their common points of contact.
c) Cohesion between the surfaces of the soil particles.

As mentioned above, the soil particles are in contact with one another, forming an uncemented skeletal structure, and the spaces between them form a system of interconnecting voids or pores. However, a fluid cannot provide resistance to shear and consequently shear stresses in soil are transmitted entirely by forces at the points of intergranular contact,in other words by the soil skeleton itself. For this reason, the term effective stress (σ') was introduced to soil mechanics by Terzaghi as the difference between the total stress (σ) and the pore water pressure (u_w), or

$$\sigma' = \sigma - u_w \qquad (1.1)$$

Moreover, the resistance to the shear along a given plane depends on the effective stress normal to that plane, not on the total normal stress.The Coulomb equation which gives the maximum resistance to shear on a plane of failure was modified by Terzaghi as follows in equation (1.2).

$$S = C' + (\sigma - u_W).\tan\phi' \qquad (1.2)$$

where :

S - Total shear strength of cla

C' - Effective cohesion intercept

ϕ' - Effective angle of shearing resistance

Laboratory shear tests are frequently stopped once peak strength has been reached . It is now accepted that, for soils with brittle strength characteristics; progressive failure in the field can lead to average mobilised shear strengths that are much lower than peak values and the complete stress-strain curve must then be taken into account (De Beer, 1967).Consequently, the concept of residual shear strength has appeared in soil mechanics literature since 1937. However it was largely the work of Skempton(1964) that first highlighted the concept of residual shear strength as an important factor to be cosidered in the long term stability analysis of natural slopes and cuts. Early attempts to measure the strengths of cohesive soils at large shear deformations were reported by Tiedeman(1937), who recognized the existence of a constant strength at large shear displacements and called it "pure sliding resistance". Haefeli(1938) referred to the ultimate point of the stress-displacement curve as the "remaining shear strength". Hvorslev(1939) stated that the decrease of shearing resistence after failure needs an apparatus which gives more displacement to achieve the residual shear strength than those currently available at that time.

Garga(1970) gave a description of the shearing of soil as follows. When a soil is subjected to a shearing force, the shear strength of the material progressively increases until the "maximum" or "peak" strength is reached.If the process of shearing is continued after the peak strength has been surpassed then a process compared to strain softening takes place. During this stage considerable changes in soil structure occur and the shear strength drops until after large displacements a state is achieved when further straining would result in no decrease in shear strength.This srength of the soil is referred to us as "ultimate" or "residual" strength of soil.The drop in strength from peak to residual is often more marked in clays than in granular soils, and therefore has important implications on the long-term stability of clay slopes.

Skempton(1964) studied the long-term stability of clay slopes and described it using a value of the factor of safety (F). He found that when a slip occurred, the factor of safety must be equal to 1.0 and the actual average shear strength of the clay at the time of the slip, S, must be equal to the average shear stress. Thus

stable slope : $F > 1$, $\Sigma\tau = \Sigma c' + \Sigma((\sigma - u)/F).\tan\phi')$, $\Sigma\tau < \Sigma S$ (2.1)

when a slip occurs : $F = 1$, $\Sigma\tau = \Sigma S$ $\tau = S$ (2.2)

after a slip occurs : $F < 1$, $\Sigma\tau > \Sigma S$ (2.3)

where :

τ	Shear stress
$\sigma' = \sigma - u$	Effective normal stress
σ	Total normal stress
u	Pore pressure

However, the dilemma facing today's engineers is in deciding what strength (peak,residual, or some value in between) can be counted on to exist during the life of the soil. Skempton (1964) discussed whether the peak or the residual strength should be used in a design problem. His procedure is to describe the slip and then to present the results of a stability analysis of the slip. He suggested that by comparing the value of S with the values of Sf and Sr, it could be seen immediately whether the strength of the clay involved in the slip was at the peak,or at the residual or, perhaps, at some intermediate value.In order to have a convenient quantitative expression for the amount by which the average strength has fallen, he defined the "residual factor" by the expression :

$$R = (Sf - S)/(Sf - Sr) \quad \text{or} \quad S = R.S_r + (1-R).S_f \qquad (3.1)$$

where :

R Residual factor

S Average shear strength along slip surface

S_r Residual strength

S_f Peak strength

If no reduction in strength has occurred and the whole of the clay is at the peak strength then R=0, whereas if the average strength has reached the residual value then R=1. His final conclusion from this study is :" it would therefore seem that the presence of fissures and joints can indeed lead to progressive failure in a clay slope and,in the limit, this process can continue until the residual strength is reached .But in clays which are not fissured or jointed the decrease in strength from the peak value is small, or even negligible" .

Lupini (1981) defined three modes of residual shear strength :

a) Turbulent mode involves large strain rotation of rotund particles, such as occur in granular soils, and particle orientation has a negligible effect.

b) Sliding mode occurs where there is a high proportion of clay particles present, in which case a continuous orientated shear surface can form between the rotund particles.

c) Transitional mode involves a combination of both turbulent and sliding shear.

2-2 The mechanism of progressive failure

Terzaghi(1936) described the mechanism of progressive failure in stiff fissured clays as the softening of clays with time due to the presence of small fissures and cracks, which allow the water to seep through to the more intact zone causing local swelling. This in turn leads to the development of further cracks and fissures. Townsend and Gilbert (1974) believed that the large strength reductions from peak to a residual condition are due to :

a) rupturing of some interparticle diagenetic bonds, and

b) adsorption of water, which increases the water content and subsequent parallel alignment of the clay particles in the failure zone. Observations on landslides and avalanches have led to the conclusion that rupture never occurs simultaneously at all points on a surface of rupture, but takes place successively (progressive rupture). Once rupture has started at the weakest spot, it spreads along the most unfavourable shearing surface at a certain speed which is dependent on the mechanical properties at the material in question. Skempton(1964) concluded that the post-peak drop in drained shear strength of an overconsolidated clay may be considered as taking place in two stages.

First, at relatively small displacement the strength decreases to the fully softened or critical state value,owing to an increase in water content (dilatancy). Second, after much large displacement, the strength falls to the residual value owing to reorientation of platey clay minerals parallel to the direction of shearing (Figure 2.1).

Field investigations were carried out in landslides and tectonic shear zones where large movements have taken place, chiefly concentrated on " principal slip surfaces" (Skempton,1985). Examination of thin sections showed little or no preferred orientation in the intact clay, but he discovered that the slip surface consisted of a band about 20 to 30 microns wide in which the clay particles were strongly oriented. A section showing these various features is given in Figure 2.2.

2-3 Shear strength of interface and filling

Only a few investigators have studied the shear strength of soil-structure interfaces and filled joints in rock. The majority of them have described peak strength (S), or have sampled and tested the rock alone or the soil alone. However, Patton (1968) suggested that the shear strength of soil-rock interfaces might be lower than that of either material alone. The problem of zones of weakness is significant in many phases of engineering projects which involve the shear strength of soil and rock masses. Examples include foundations and abutments of dams, tunnels, retaining walls and other underground openings. In addition the subject of the minimum shear strength of soil and rock masses is particularly important to engineering geologists where clay is in contact with relatively smooth, polished, slickensided rock surfaces.The presence of joints in a rock mass has a decisive influence on both its strength and deformational behaviour.

Kulhawy and Peterson(1979) presented an extensive testing program to examine the strength and stress-deformation behaviour of sand-concrete interfaces. The results show that for smooth interfaces the friction angle of the interface is less than the soil friction angle. Similar results found by Brumund and Leonards(1973) concluded that when the structural surface is rough in comparison to the sand grain size, the interface friction angle is greater than the soil friction angle and the shear surface occurs in the sand. Matthews (1988) suggested that the direct and simple shear shear tests are appropriate to the study of the shear behaviour of an interface between soil and some other material. This can be of importance in determining wall or shaft friction for retaining walls and piles and also in the design of soil reinforcement. Tomlinson(1971), in his significant contribution to the understanding of the behaviour of piles in clay over the years, agreed that it was important to focus on the behaviour of a thin layer of soil adjacent to the pile. He suggested that the effect of hammering the pile into the ground was to cause a succession of failures at the pile-soil interface causing extensive alignment of soil particles. He found it difficult to see how the soil could degrade further under subsequent cyclic loading. Martins and Potts (1985) suggested that rate effects during residual shear control the rate at which landslides move under gravitational loading, and effect other phenomena such as the strength at shear zones on the sides of piles which are formed by pile driving.

2-4 Role of residual shear strength

The role of residual shear strength is to define the extent of the loss in strength which can occur in overconsolidated fissured clays. It represents also the available strength along existing shear surfaces formed in any cohesive soil. Therefore, if previous large movements have occurred in the field leading to the formation of shear planes, knowledge of the residual strength will be required for design purposes. In addition, the residual strength controls the behaviour of landslips and retaining walls in such matrials and is important in the assessment of the risk of progressive failure in stability problems in general.Engineers need to be aware of this problem when undertaking construction work on clay slopes which may have been subjected to movement in the past. The values of C' and ϕ' are very necessary for the determination of the factor of safety F, and the relationship between these parameters and C'r and $\phi'r$ should be determined.

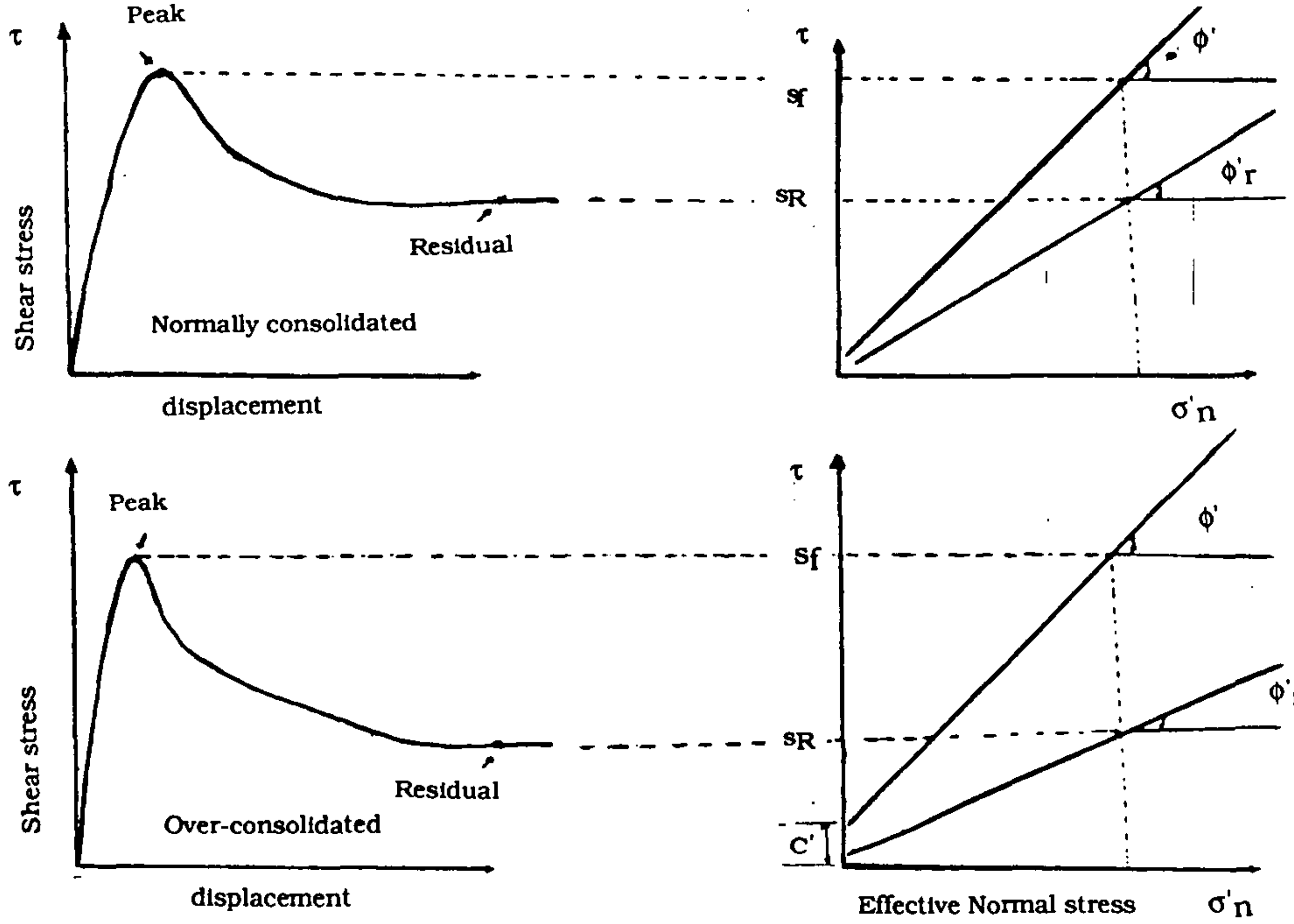


Fig. 2.1 Simplified shear strength properties of clay
(After Skempton and Hutchinson, 1969).

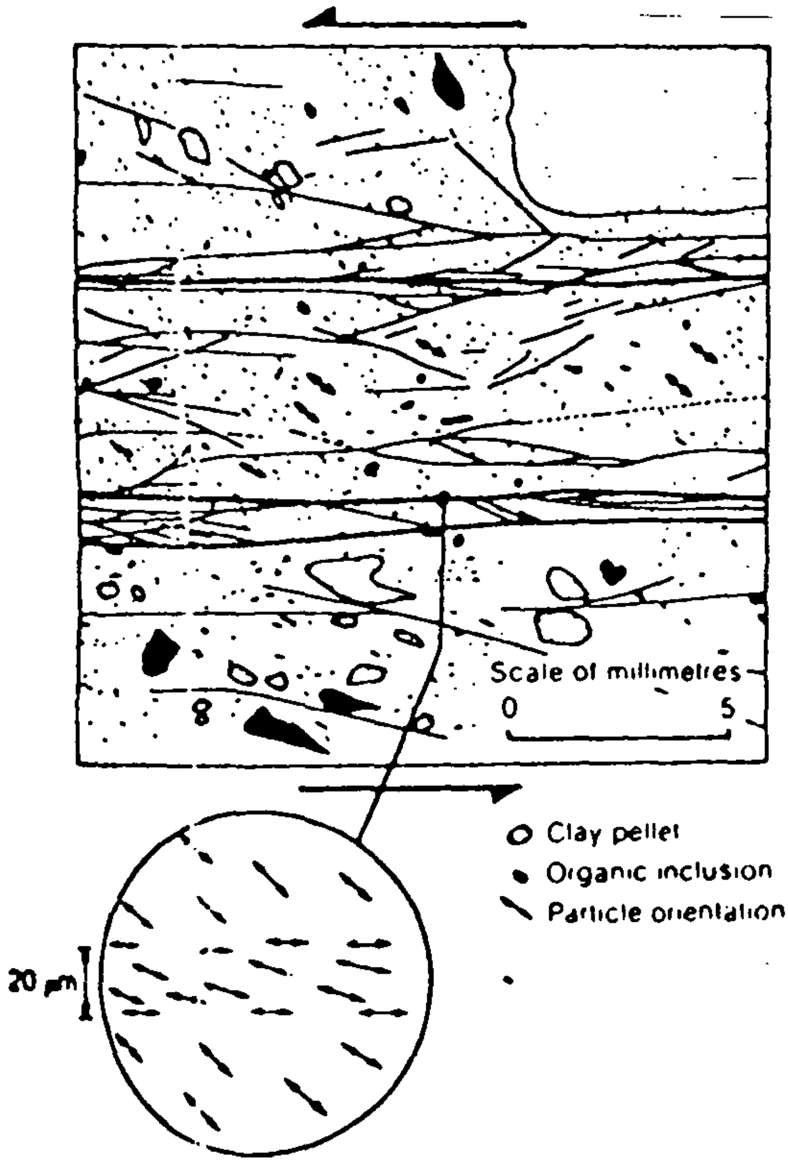


Fig. 2.2 Fabric of shear zone and slip surface at Walton's Wood (After Skempton, 1985).

CHAPTER THREE

REVIEW OF THE FACTORS INFLUENCING RESIDUAL SHEAR STRENGTH

The development of the knowledge of residual strength has been pushed forward mainly by the need to understand the basic mechanisms of the behaviour of landslides and other problems in geotechnical engineering. A review of the main factors influencing shear strength is given in this chapter.

3.1 Influence of Atterberg limits and water content

The behaviour of soil often depends on the amount of water contained in the soil mass, and this can be related to the Atterberg limits. Voight (1973) made reference to the correlation between Atterberg plasticity limits and residual shear strength of natural soils. He claimed that further examination of this correlation was warranted, having found the relationship between plasticity index and the residual strength coefficient (μ'_r) shown in Figure 3.1. He produced a relationship between $\tan\phi'_r$ and PL/LL, which is reproduced in Figure.3.2.

The initial moisture content was found to have no influence on the residual shear strength at a given effective normal stress. However, the moisture content in the shear zone at the residual state was found to correlate well with corresponding values of residual shear strength, which decreased linearly with increase in moisture content.

In contrast, Kenney (1967) claimed that no relationship existed between residual strength and soil plasticity. This conclusion was perhaps based on liquid or plastic limit distribution rather than plasticity index. There is ample evidence from the field, as well as from the laboratory, of an increased water content in sheared overconsolidated clays. For example, Skempton (1964) described a case concerning London clay, which had a water content of about 34% on and near slip surface compared with 30% in neighbouring unsheared material.Voight (1973) found a relationship between water content at residual strength (Wr) and the residual strength coefficient. He found that overlap existed for Wr in the range of 20-30%, with equivalent μ'_r values varying over the (large) range of 0.25-0.60. Soils with $\mu'_r < 0.20$ consistently had Wr > 40%. Anomalous values were present for the Ottawa clay. The principle conclusions of his study were that plasticity index appears to be a useful field guide to the important engineering property of residual strength of natural soils, and that further examination of this correlation is warranted. Haefeli (1951) has investigated brittleness in a ring shear apparatus in which the shear stress was applied by dead weights. He found that the magnitude of the drop in strength from peak to residual in clays increased with liquid limit. Good agreement was found between ϕ'_r and plasticity index Ip by Bjerrum and Simone (1960), who presented a curve relating these two parameters. Other results were published by Kenney(1967), Holt(1962), Skempton (1964), Brooker and Ireland(1965), Bjerrum(1967), De Beer(1967) and Mitchell(1976). However, it is not clear from the published results whether the correlation corresponds to peak or residual strength in all cases.

Kanji (1974b) found that the curve for peak values coincides with the curve of Brooker and Ireland (1965).He concluded that correlation between both $\phi'p$ and $\phi'r$ with Ip exists, but in the case of $\phi'p$ the stress level and the soil structure must be considered in any correlation. In the light of this study, he related Ip with $\phi'r$ by the formula:

$$\phi'_r = 46.6 / Ip^{0.446}$$

Seycek (1978) presented the results of a large number of reversal shearbox tests carried out mainly on tertiary clays of the North-Bohemian brown-coal-basin. He also gathered other results from the literature and reported that there was a better correlation between residual friction angle, $\phi'r$ and plasticity index, Ip, than with other parameters. His correlations are shown in Figure 3.3 and Figure 3.4, which shows the same data as Figure 3.3 but on a logarithmic scale. Deere (1968) also suggested a relationship between residual shear strength and both liquid limit and plasticity index (see Figure 3.5).

Ramiah and Purushothamaraj(1971b) studied the structure at peak and residual stages by the shrinkage ratio technique, for which a small core cutter (37 mm dia. and 14 mm thick) was pushed into the middle of the sample which had reached the residual stage, so as to have the shear zone at the middle of the cutter. The sample was air-dried and then oven-dried at 110 ^{0} C for the concordant dry weight. The volume of the soil pat was determined by mercury displacement and the shrinkage ratio was presented in gm/cc. Tests were also run up to the peak for all normal pressures, and the shrinkage ratio at the peak stage was also determined. They found an increase in the rate of shear reduced the shrinkage ratio, also the shrinkage ratio determined at peak strength increases with the degree of particle orientation caused by increases in normal pressure during consolidation. At the residual strain, the degree of orientation. will be high and, consequently, a high shrinkage ratio is observed. This is illustrated in Figure 3.6. It seems that the findings of Ramiah are in accordance with those of Lambe (1958), who found that a clay with oriented particles will shrink more than a clay which has a random arrangement of particles, and consequently the former will show a higher shrinkage ratio than the latter.

3.2 Effect of clay fraction

Skempton (1964) concluded that during the shearing process a continuous band was formed within which the clay particles were so strongly orientated, in the direction of shearing, that they formed a domain exhibiting sharp extinction when viewed between crossed nicols. The domain comprised the main slip " surface", which had a thickness of the order 20μm. Associated with it were several secondary slip domains, within a matrix of clay showing moderate orientation, not necessary parallel to the slip surface, and having a thickness up to about 25.4 mm. This is the softened zone often observed in the immediate vicinity of the slip plane. On either side of this zone, the clay was found to exhibit scarcely any orientation.

He presented a relationship between residual strength and clay fraction (Figure 3.7) in which the residual angles of shearing resistance of a number of normally and overconsolidated clays are plotted against the clay fraction (defined as percentage of particles, by weight, smaller than 2μm). All the points indicate a most definite tendency for ϕ'_r to decrease with increasing content of clay particles. Domains of strongly orientated particles have also been observed when quite soft remoulded clay is subjected to large strains (Astbury, 1960). Borowicka (1965) reported reversal shearbox tests on different clay soils produced artificially by mixing in the laboratory. He found that brittleness increased and residual shearing angle decreased with increasing clay fraction.

Furthermore Chandler (1966,1969) studied the residual strength of Keuper Marl, which is of low plasticity, and found that the clay fraction in the residual shear surface was higher than in the adjacent soil, indicating break-down of the aggregations during shear. His results were consistent with the relationship between ϕ'_r and clay fraction of Skempton (1964). Chattopadhyay (1972), as reported by Mitchell (1976), related residual strength to both the mode of cleavage of the constituent minerals of soils and to particle shape. He found that low residual friction angles were associated with platey particles, whereas subangular and needle-shaped particles gave high residual friction angles. Blondeau and Josseaume (1976) presented a similar relationship between residual strength and clay fraction to that of Skempton, and this is reproduced in Figure 3.8.

3.3 Effect of rate of shear

It would appear that Petley (1966), using a direct shearbox with reversals of movement, was the first to report a systematic investigation of rate effects on residual shear strength using strain-controlled conditions. Petley found that for pre-cut samples of brown London clay, the effects of varying the rate of displacement, once residual conditions are established, are small. He investigated a range of shear rates between 4 $\times 10^{-5}$ and 1.0 mm/min and found that throughout that range the residual coefficient of friction only increased by approximately 4%. He was mainly concerned with the discrepancy between laboratory test rates and the observed field rates. Landslide movement on pre-existing shear surfaces is generally slower than the conventional rates of shear used in the laboratory.

Lupini et al (1981) found that residual strength measured at slow drained displacement rates resulted from three types of shearing mechanism. If the proportion of clay-sized particles in a sample is small, the more rotund silt and sand particles present are too closely packed to allow a shear surface to form.Large strain involves rotation of the rotund particles, as in granular soils, and particle orientation has a negligible effect. This mode of deformation was termed turbulent shear. If a high proportion of clay particles is present, a continuously orientated shear surface can form between the rotund particles. This mode of deformation was termed sliding shear.At intermediate proportions of clay particles, orientated shear surfaces can partly form, but are continuously disrupted by the rotund particles present. This mode of shear was termed transitional shear.

Herrman and Wolfskill (1966) reported that shearing rate had a small, but noticeable, effect on the deformations necessary to reach the residual condition for weak-clay shales. Shear rates of the order of 5mm/min were reported to be too rapid for the correct establishment of the residual condition. Ramiah et al (1970) tested a slightly clayey silt (WL = 45%, Ip = 17%, clay fraction< 2μm =8%) using the direct shearbox with resersals.They found that the residual stress ratio τ_R/σ'_n for this clay increases only slightly within a range of shear rates between 0.025mm/min and 10.2 mm/min. Garga(1970) investigated rate effects on the residual strength of brown London clay by means of a strain-controlled ring shear test. He found that residual strength increased only slightly with shear rate.The range of shear rates investigated was between 2.5 x 10^{-5} mm/min and 0.25 mm/min, and the total variation of residual strength across the range was found to be approximately 4%. He also suggested that the shear plane with strong clay particle orientation could act as a 'drainage channel' through which the excess pore water pressures generated on the slip surface could dissipate.

De Beer (1967) investigated rate effects on Boom clay (WL =81%, Ip =52%) by means of a ring shear device using both remoulded and pre-cut samples. Unfortunately most of the tests were not carried out to large enough displacements to ensure that residual parameters were achieved. In addition it would appear that different test samples were used to establish comparisons, he studied rate effects at two displacement rates, 0.395 mm/min and 0.035mm/min. He found that the faster rate gave a lower residual strength. Cullen and Donald (1971) reported results of reversal direct shearbox tests on a Silurian clay, which showed a trend of increasing residual strength with increasing shear rate. In addition they investigated the effect of using hand-winding rates before establishing slow shear and found that this technique reduced somewhat the time for completion of the test.

Townsend and Gilbert (1974), using both a reversal direct shear box and a strain-controlled ring shear apparatus, found that the residual strength of clay shales increased by a small amount with increasing shear rates. They attributed this effect to the generation of new slip surfaces along the shear zone by virtue of the clay platelets being unable to adjust into as perfect a parallel alignment at the fast rates. Butcher (1975), using two strain-controlled ring shear devices of different design (one was an Imperial College/ N.G.I apparatus), found for a clay of meduim plasticity sheared at both 0.0145 mm/min and 0.10 mm/min, the increase in residual stress ratio was only 3% . This increase was more pronounced as faster rates were used. For the whole range investigated between 0.0145 and 14.6 mm/min, the increase amounted to 24%.

Blondeau and Josseaume (1976) investigated rate effects on samples of Lias clay using the reversal shearbox. They found that the residual stress ratio showed no definite trend of variation with rate of shear over the range 0.002 mm/min to 0.960 mm/min. They also pointed out that for residual shear box tests on intact specimens the rate of shearing used was crucial for the quality of the stress-displacement curves.

La Gatta (1971) performed an additional series of tests (beyond those reported in 1970) using the Harvard ring shear apparatus and studied further rate effects on remoulded Bearpaw shale and remoulded blue London clay. He carried out a series of tests on both materials at different rates of shear (0.0056 mm/min, 0.056 mm/min, 0.56 mm/min and 2.8 mm/min). He found that shear rate had a negligible influence on the residual angle of friction for Bearpaw shale, which varied from 3.5 degrees to 4.0 degrees with no consistent trend over the range of shear rates investigated. In contrast, it was found that for London clay the residual friction angle increased with shear rate on average from 7.5 degrees to 9.2 degrees . Rate effects determined on the residual stress ratio (one test only) indicated a total variation of the residual stress ratio of 18% over the range of shear rates investigated. The change in residual stress ratio observed between the slowest rate (0.0056 mm/min) and 0.56 mm/min was 8%. It was concluded that rates of shear as fast as 0.56 mm/min could be used without significant error in the Harvard ring shear apparatus, with 2 mm thick samples to reduce the time for testing.

3.4 Effect of normal stress

In many cases the average normal stress acting on failure planes in the field is low, often less than 70 kPa according to De Lory(1957) and James(1970). Peck(1967) presented results of interesting reversal shearbox tests where it was shown that both the displacement to peak and to residual strength for Lake Agassiz clay were a function of the normal effective stress levels, the larger the normal stress the larger the displacements needed to reach peak and residual strength. Extended testing by Hawkins and Privett (1985) has confirmed that residual failure envelopes are curved, and that the curvature is most pronounced below an effective normal stress of about 200 kPa and in soils with a high clay fraction. Bishop (1965) also concluded that the residual strength of a soil is not a unique parameter, but is dependent upon the normal stress acting on the soil.

Anayi (1990) has modified the Bromhead ring shear apparatus by the addition of vanes to the top and bottom platens so that the slip surface occurs in the middle of the sample. He studied the curvature of residual strength envelopes at low normal stresses, he found that the envelope appear to be straight-line above an effective normal stress of 150 kN/m^2.

3.5 Effect of Placement conditions

Subsequent investigations agreed in general with Skempton's (1964) finding that placement conditions did not affect the measured residual strength. These include Petley(1966), Herrmann and Wolfskill(1966), Garga(1970), Sembenelli and Ramirez(1971), Earl and Skempton(1972), Calabresi and Manfredini(1973), andTownsend and Gilbert(1973,1974,1976).

3.6 Influence of clay mineralogy

Mineralogy has been found by Kenney (1967) to be the single most important factor that affects residual strength. Mineralogy also controls the shape of the particles and therefore the shear behaviour and residual strength. He carried out some drained direct-shear tests on natural soils, pure minerals and mineral mixtures, and showed that residual shear strength is primilary dependent on mineral composition and that it is not related to plasticity or to grain-size characteristics. Many investigators have studied the importance of the relative proportions of clay minerals and of particle shape, (Skempton, 1964; Borowicka, 1965; Petley, 1966; Spears and Taylor, 1972; Vaughan and Walbancke, 1975; Kenney, 1977; Chattopadhyay, 1972).

3.7 Effect of vibrations

If the loads applied to a mass of soil change rapidly enough so that inertia forces become significant in comparison to static forces, special calculations become necessary in order to estimate the deformation of the soil. Typical problems of this type include foundations, slope stability during earthquakes, pile driving, and vibratory compaction. Slopes of stiff clay, weak mudstone and shear surfaces in cohesive soils can be subjected to fast movement during an earthquake and similar phenomena exist, such as the strength of shear zones on the sides of piles which are formed by pile driving (Martins and Potts, 1985). A knowledge of the strength of such surfaces under rapid loading (vibrations) is necessary if stability during and after an earthquake or other phenomena is to be examined. However, only a few investigators have studied the effect of vibrations on cohesive soils. Lemos (1985) has studied the influence of fast uni-directional rates of displacement by using ring shear apparatus because of its ready adaptation to high speed, whereas the shear box has a limited speed.

3.8 Effect of interfaces

It is worth noticing that only a few investigators have studied the shear strength of soil interfaces. Skempton and Petley (1967) showed that the concept of residual strength also applied to the shear strength along structural discontinuities in stiff clays where after very small displacement, the shear strength along these discontinuities drops to a residual value.

The interface tests can be of importance in determining wall or shaft friction for retaining walls and piles and also in the design of soil reinforcement. Kanji(1970) studied the shear strength of soil-interfaces, and found that the drop in strength (after peak strength had been reached) was larger for tests of soil-saw cut rock interfaces than for the tests of soil alone, but smaller than for tests of soil-polished rock interfaces. He concluded also that the shear strength-displacement curves for remolded soils and for soil-rock interfaces show differences in behaviour which in the field should contribute to the mechanism of progressive failure.

3.9 Conclusions

Despite the apparantly wide use of shear testing apparatus for determining residual strength, little has been published on the exact techniques used or the effect of different techniques on the strength parameters obtained. For example, there does not appear to be any information on the possibility of using high strain rates to achieve large displacements quickly, with subsequent low strain rates for much shorter times while drained equilibruim is being established. Only a few investigators have studied the shear strength of soil-structure interfaces, despite the fact that many problems of zones of weakness in rock masses are significant and that there are many engineering projects which involve the shear strength of soil-structure interfaces. In addition there is apparently no information on the effect of distance travelled between reversals, and whether or not this has a minimum acceptable value.

The majority of the methods of measurement used present difficulties to a standard testing laboratory either because the methods and equipment are expensive and complicated, or because they require manpower to be present all the time to take the test results. There is also a lack of consistency between the various tests using different apparatuses, leaving the engineer in a dilemma when deciding which, if any, are the correct results. Most of the shearbox tests suffer from limited speed. Information on the above matters can be of great assistance to investigators in increasing both the productivity of their testing programme and the confidence which they place in their results.

The object of this study is to provide such information, and subsequently define as well as possible the simplest acceptable procedure to overcome these drawbacks. A modified shearbox is to be developed to provide a simple and accurate means of measuring shear strength parameters. The recording of shear strength and the displacement is to be achieved initially by using LVDT transducers.

The question of high speed effects in relation to measured residual strength has been investigated only by a few investigators, and a high speed of up to 53 mm/min will be used in this study. Tests will be conducted by using both the modified shear box and the Bromhead ring shear to provide a basis for comparison with other investigators. The effect of vibrations on the peak and residual strength will also be studied, together with the strength of interfaces using both rock and glass, the glass being used as the smoothest interface on which to study interface effects.

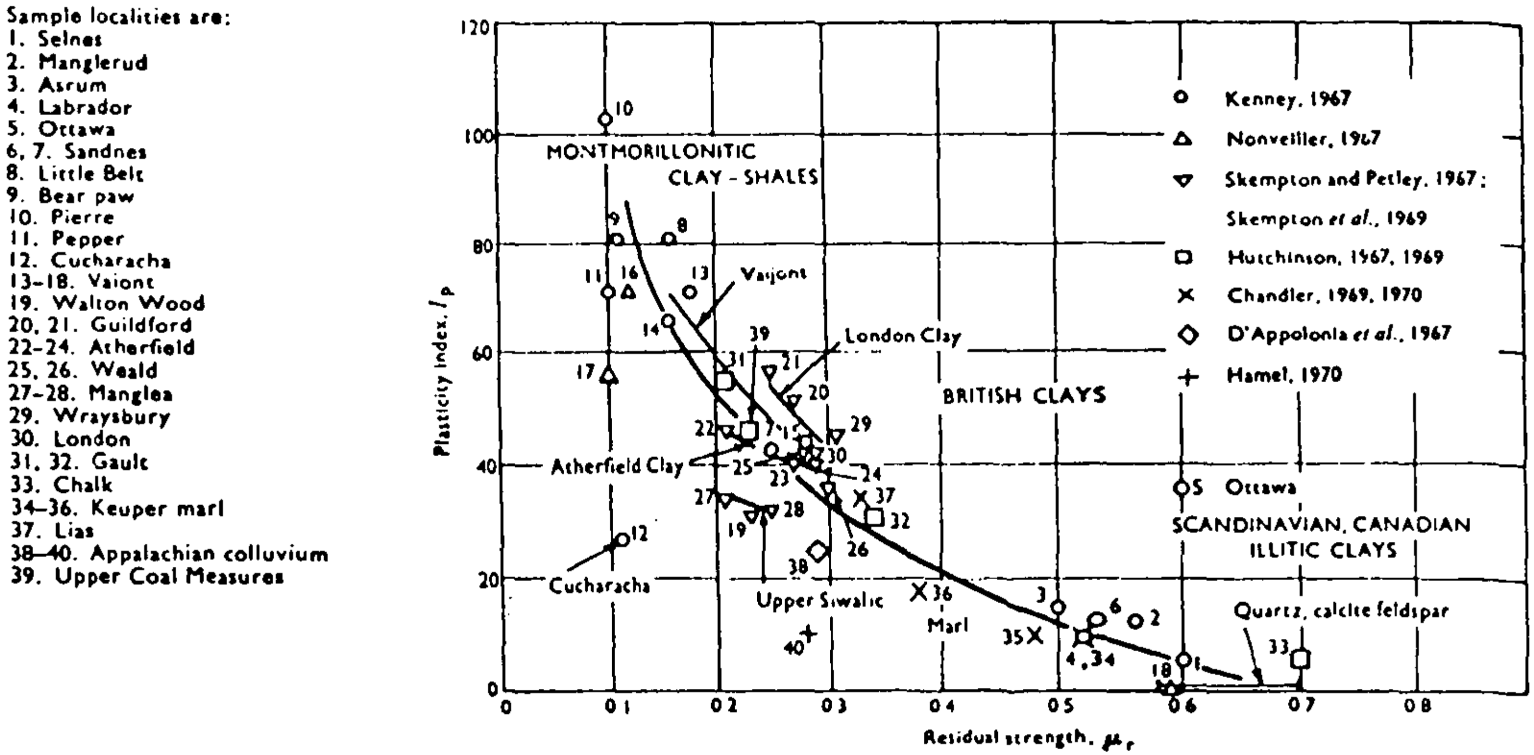


Fig. 3.1 Plasticity index, Ip, plotted against residual coefficient,μ'r (After Voight, 1973).

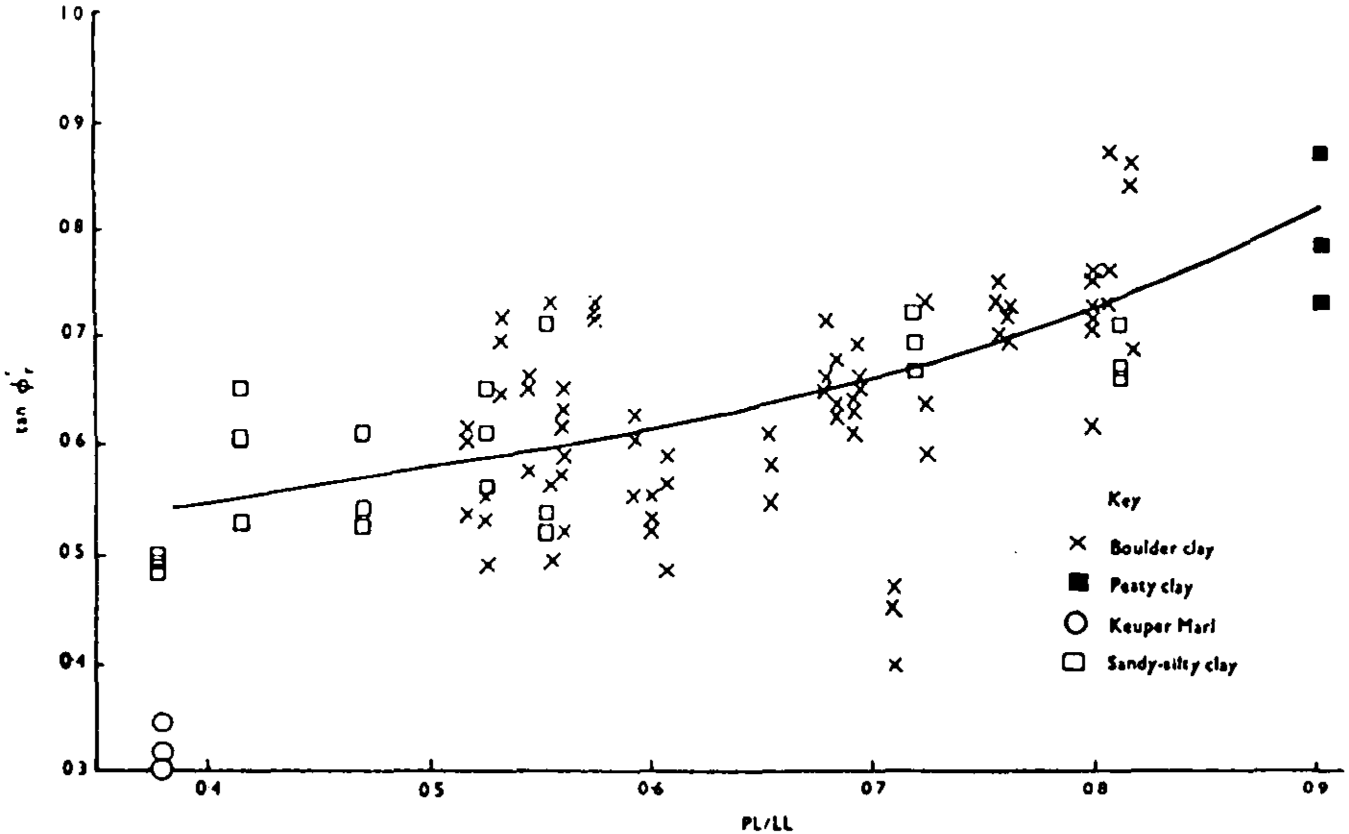


Fig. 3.2 Correlation between tanφ'r and the ratio of plastic limit to liquid limit (After Voight, 1973).

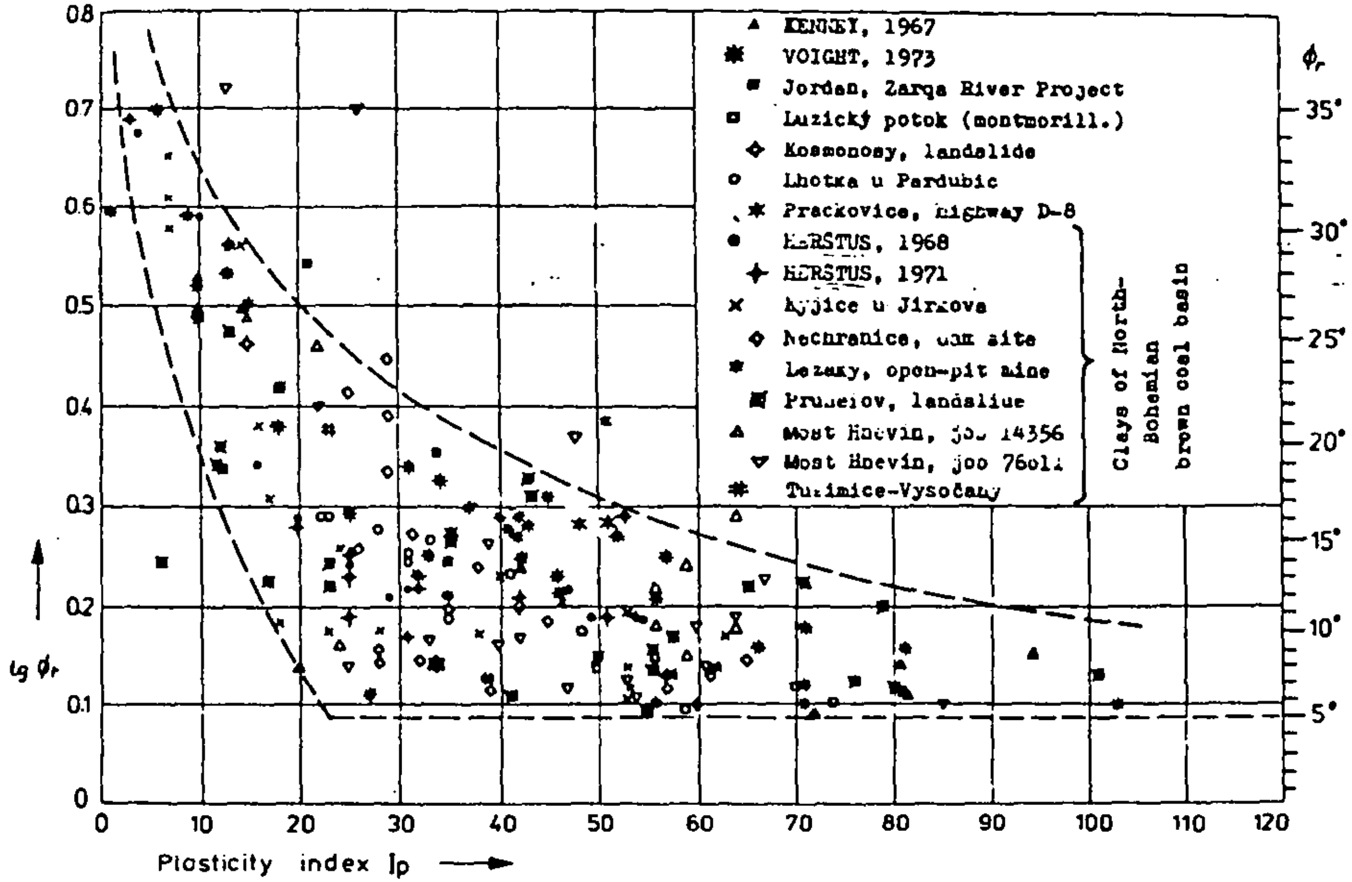


Fig. 3.3 Relation of residual angle of internal friction ϕ'_r to index of plasticity Ip (After Seycek, 1978).

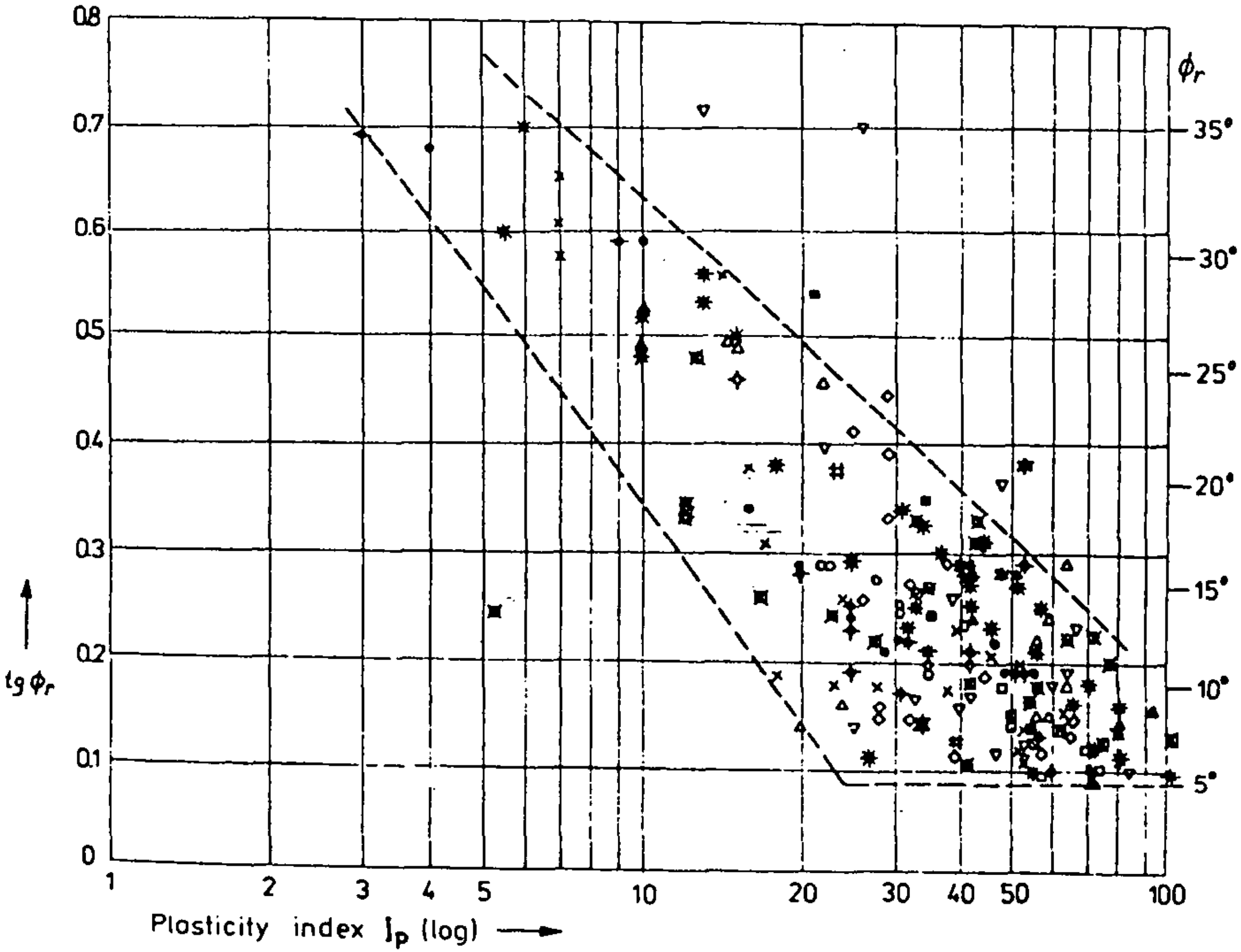


Fig. 3.4 Relation of residual angle of internal friction φ'r to logarithm of plasticity index Ip (After Seycek, 1978).

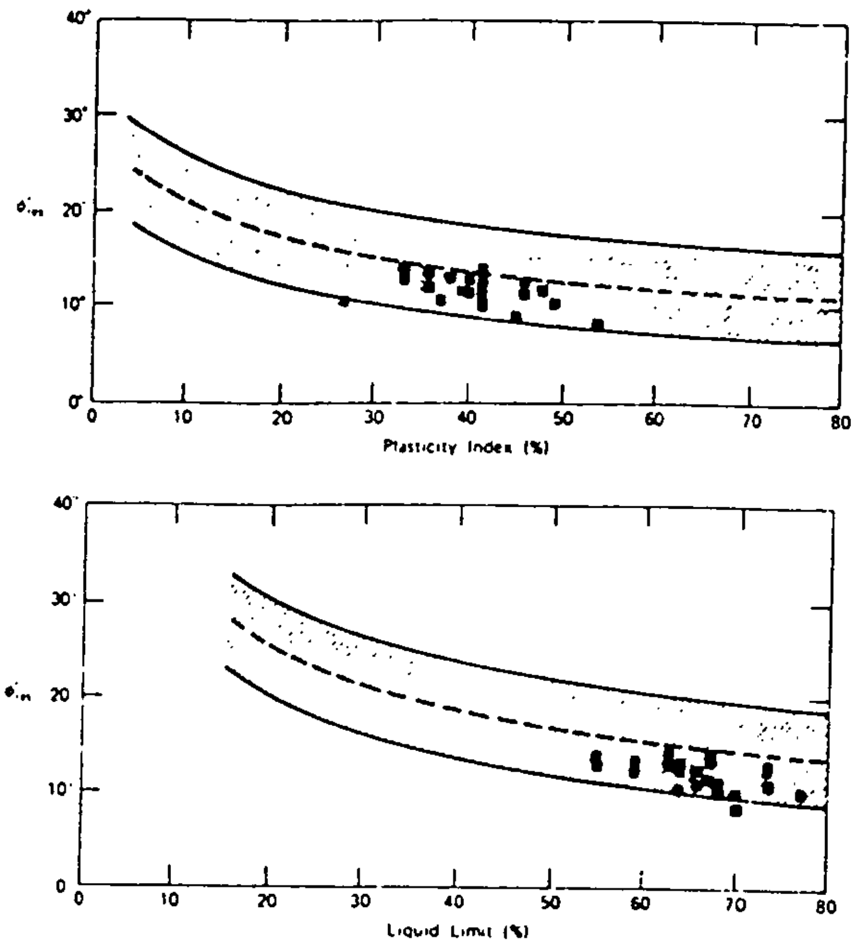


Fig. 3.5 Relation between residual friction angle and plasticity (AFter Deere, 1974).

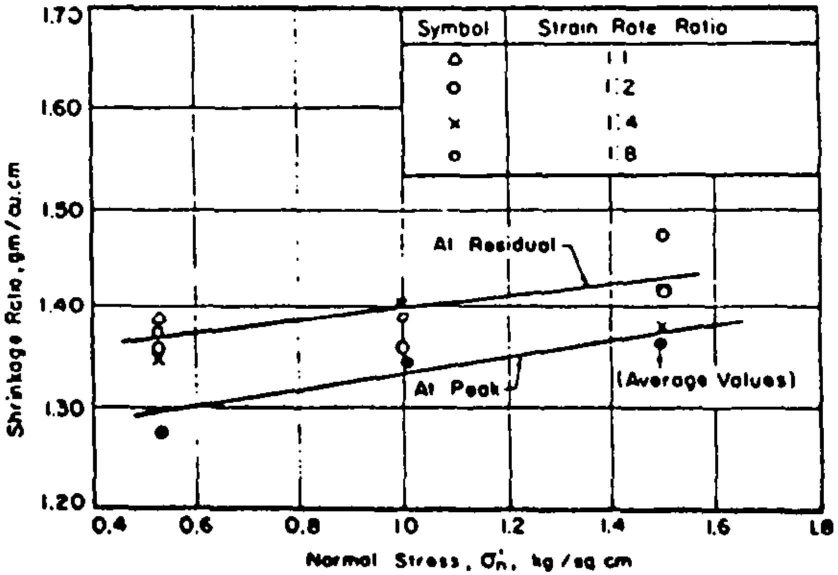


Fig. 3.6 Relationship between tanϕ'_r and normal stress (After Ramiah, 1971).

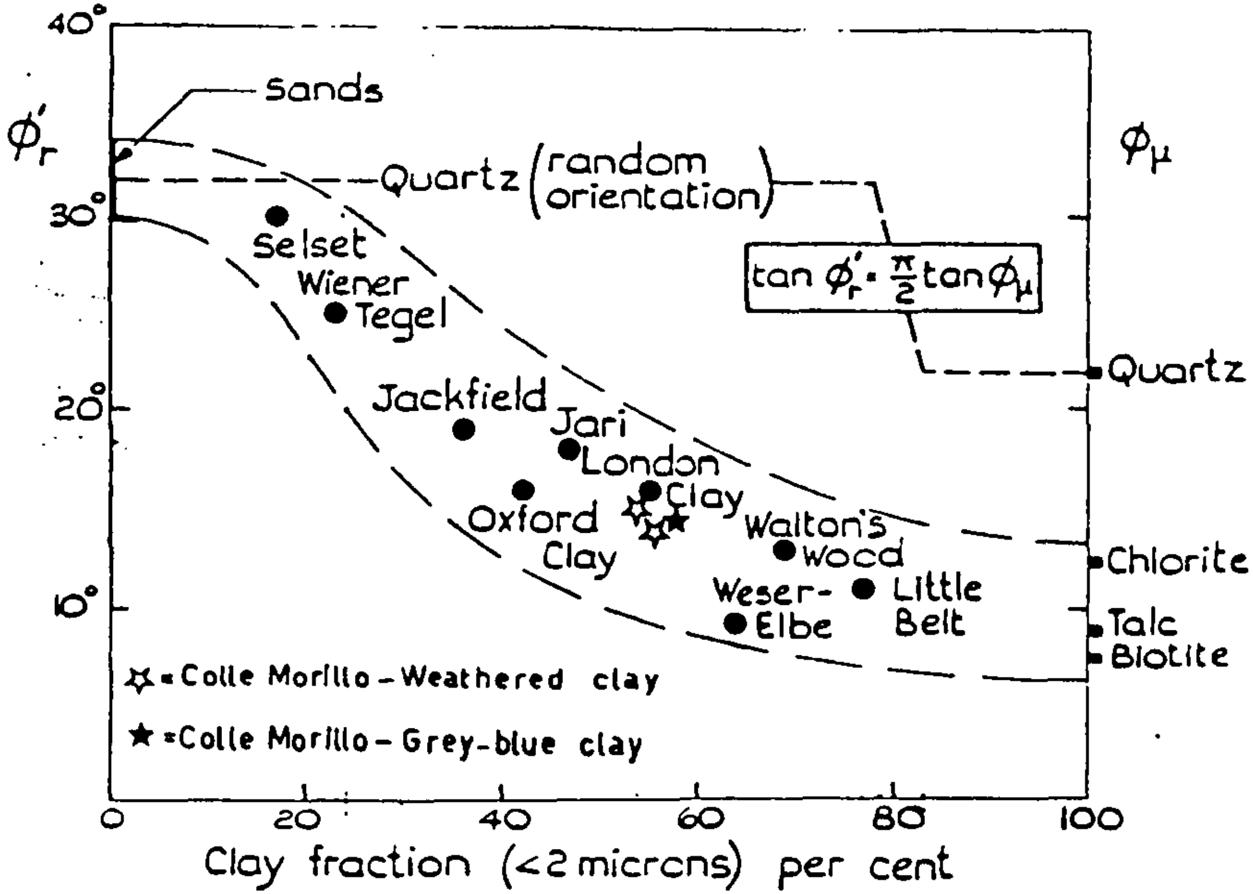


Fig. 3.7 Residual strength angle versus clay fraction
(After Skempton, 1964).

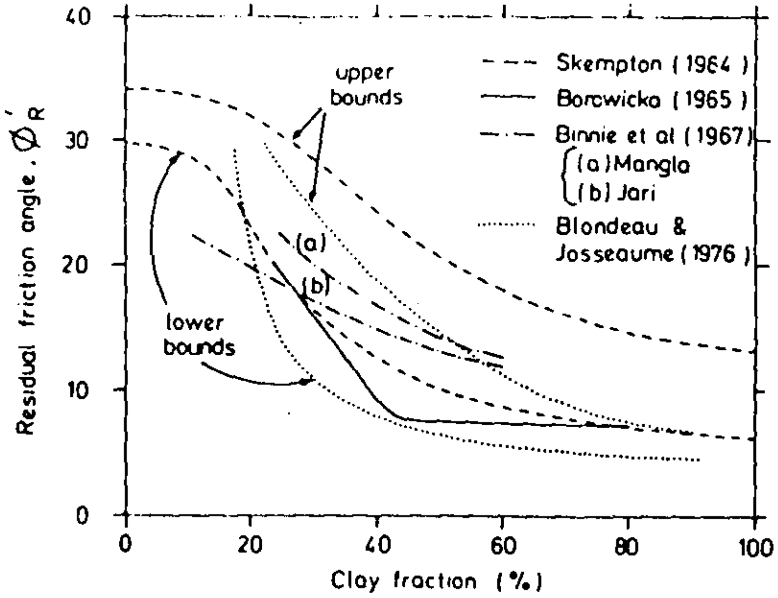


Fig. 3.8 Residual strength correlations with clay fraction (After Blondeau and Josseaume. 1979).

CHAPTER FOUR

REVIEW OF EXISTING METHODS OF RESIDUAL SHEAR STRENGTH MEASUREMENT

4.1 Ring shear apparatus developed by Bromhead (1979)

4.1.1 Description and general principle

Various forms of torsion and ring shear apparatus have been developed to measure the shear strength of soils, as shown in Figure 4.1 . One such device is fully described by Bromhead (1979). In this apparatus an annular specimen of soil 5mm thick with inner and outer diameters of 70mm and 100mm respectively are used. The sample is confined radially between concentric rings and the vertical stress is applied via two porous bronze loading platens by means of a counter balance 10:1 ratio lever loading system (see Figure 4.2 and Figure 4.3). A relative rotary motion is caused to occur between the confining rings (which are fixed to the lower platen) and the upper platen by means of a motor and gearbox driving throughout a worm gear. This causes the sample to shear, the shear surface forming close to the upper platen (which is artificially roughened to prevent slip at the platen/soil interface). A cross arm attached to the upper platen reacts against two matched proving rings which provide a measurement of the torque transmitted through the specimen. Vertical movement of the upper loading platen may be measured by means of a single dial gauge (0.02 mm/div) bearing on top of the loading platen and angular displacement (rotation) by means of a scale fixed to the turret.

4.1.2 Sample Preparation

A remoulded sample is kneaded evenly into the annular cavity between the confining rings using a small spatula. The excess soil should be struck off level with the top of the confining rings and the assembly placed in position, on the locating studs in the turret. The centring pin which locates the upper platen over the specimen should be lightly greased or oiled before filling the upper platen. The upper platen can now be fitted. The loading yoke should be positioned on the upper platten and adjusted such that top of the counter balance lever is horizontal. The vertical dial gauge can now be brought into position to bear on the top of the load hanger assembly. During testing soft clay or when high normal effective stresses are used, it will be necessary to consolidate the soil in several stages up to the required normal effective stress. This is to avoid soil being squeezed through the confining rings and the upper platen. When the consolidation stage is complete the proving rings must be aligned such that a right angle is made between the torque arm of the upper platen and the axis of each proving ring. The torque arm has stops so that the proving ring bears on it at the correct raduis. Two stops are provided each side of the centre. The inner raduis magnifies the proving ring loads relative to the outer raduis and is used for weak soils at low normal stresses. One of the proving rings is aligned by means of the adjustment rod on the proving ring and rotating the torque arm. The second proving ring needs only to be brought into contact with the appropriate stop to achieve alignment. Once the appropriate rate of rotation has been selected the torque arm can be brought into contact with the proving rings and the gear engaged. The vertical dial gauge, the proving ring dial gauges and the rotation scale should be read before switching the motor on and should be read at regular intervals during the tests. When the residual strength has been reached, the motor should be switched off the gear disengaged.

More information about the Bromhead ring shear apparatus, and the interpretation of the results, is given in chapter six.

4.2 Ring shear apparatus developed by Bishop (1971)

4.2.1 General principle

The shear apparatus which was developed by Garga(1970) and then Bishop et al (1971) is shown in Figure 4.4. The apparatus allows measurements of peak and residual strength on a shear surface formed at the mid-height of an annular specimen. The sample, outer diameter 152.4 mm, inner diameter 101.6 mm, initial thickness 19.05 mm, can be subjected to a maximum nominal normal stress of 979 kPa and a maximum nominal shear stress of 490 kPa. The worm gear that rotates the sample assembly is mounted in a housing on the base. The worm gear is chain-driven by an electric motor and variable speed gear box unit, which is fixed to the floor beneath the apparatus to minimise vibration effects. The sample, confined between pairs of upper and lower confining rings, is loaded normally through annular loading platens by a dead-load lever system. The normal load is transmitted by a vertical main shaft mounted in ball bushings to accommodate both linear and rotary motion. The lower half of the sample is carried on a rotating table driven by a worm gear. The upper half of the sample reacts via a torque arm against a pair of fixed proving rings that measure the tangential (shear) load. The gap between the upper and lower confining rings can be controlled and the side friction can be measured by means of a guided linking yoke and a proving ring connected by a screw to the rigid crosshead.

4.2.2 Sample assembly

The annular sample is laterally confined between two pairs of rings and is loaded normally (vertically) through annular platens. Drainage is obtained by means of porous ceramic annuli screwed to the platens. In order to minimise the risk of slip occurring at the soil/ceramic interfaces,12 sharpened radial beryllium copper fins, 0.254 mm thick, projecting 2.032 mm and extending the full width of the sample, were provided on the exposed face of each ceramic annulus. The lower confining rings and the lower platen are screwed to the base plate where a provision for a water bath is given by means of a perspex ring, the water bath serves to prevent the sample from drying out during testing. The confining rings and platens are of brass, plated to minimise corrosion effects in the presence of an aggressive pore fluid.

4.2.3 Normal loading system

The vertical normal load on the sample is maintained by dead weight applied via a 10:1 ratio lever arm, which has a movable fulcrum to accommodate sample thickness variations while maintaining horizontality. The load is transmitted through the main shaft to the torque arm by means of a nut incorporating a spherical seating to accomodate differential settlements of the sample. The load is finally transferred to the upper annular loading platen by two curved segmental spacer blocks screwed to the torque arm.

4.2.4 Torque measuring system

The sample is sheared by steadily rotating the lower half while the upper half reacts against the torque arm. The torque arm transmits the shear load to the two opposed tangential load proving rings mounted on the rigid columns. Each proving ring carries a vertically aligned wheel, which can roll on a hardened steel plate set in the torque arm and which transmits an axial load to the ring while allowing the torque arm to move vertically as the sample dilates or consolidates.

4.2.5 Gap control mechanism

The upper confining rings are connected by means of a yoke to a proving ring, which in turn is connected to a differential screw located in the rigid crosshead. The differential screw permits the proving rings to be raised or lowered. While the side friction is measured on a stiff proving ring which operates either in compression or in tension.

4.2.6 Sample preparation

The samples of clay are placed in the confining rings assembly in a remoulded state at a liquidity index of approximately one half or less, and on some occasions they are placed at the natural water content. The upper loading platen is aligned and gently placed in position on the sample. After the proving ring has been zeroed to balance the weight of the linking, the crosshead carrying the linking yoke is mounted on the rigid columns. Appropriate dead loads are added to the hanger to consolidate the sample and the water bath is filled. After allowing the sample to consolidate (or swell) under a constant normal load. The gap between the upper and lower pairs of confining rings is opened (initially by 0.0254 - 0.0508 mm) by means of the differential screw. The shear load is measured by two devices mounted on the steel columns, while the friction on the sides of the upper confining rings is measured by a proving ring connected to the rigid crosshead. The vertical movement of the sample and the gap opening are monitored by two pairs of dial gauges.

4.2.7 Interpretation of the results

Bishop et al (1971) discuss the influence of a variety of distributions of shear stress across the sample in a ring shear test on the measured torque and hence on the angle of shearing resistance calculated assuming a uniform shear stress distribution. In some cases, errors of about 10% may arise. It is however, much more likely that the distribution is close to being uniform, particularly where the sample is narrow in comparison to its diameter. Conventionally, a uniform shear stress is assumed when the residual strength has been reached. The average normal stress σ'_n is given by equation 4.1.

$$\sigma'_n = W/(3.14\ (r_2^2 - r_1^2)) \qquad (4.1)$$

where :

W = Net normal load on the sample

r_2 = External raduis

r_1 = Internal raduis

The shear stress is computed from equation 4.2.

$$\tau = 3M/(2\text{x}3.14(r_2^3 - r_1^3)) \qquad (4.2)$$

where :

M = Total torque

The coefficient of friction is given by the equation 4.3.

$$\tan\phi' = \tau/\sigma'_n = 3M(r_1 + r_2)/(2W\ (r_1^2 + r_1 r_2 + r_2^2)) \quad (4.3)$$

but $W = 10L + P +/- \Delta W$

and $M = (F_1 + F_2)/2l$

where :

L Load in the hanger

P Weight of the upper loading platen

ΔW Friction load as determined in the upper proving ring

F_1 Force reading of first torque measuring instrument (proving ring)

F_2 Force reading of second torque measuring instrument (proving ring)

l Distance between the two torque measuring instruments.

Therefore the coefficient of friction becomes

$$\tan\phi' = \tau/\sigma'_n = 3.7298\ (F_1 + F_2)/(10L + P +/- \Delta W)$$

where :

$r_1 = 50.8$ mm

$r_2 = 76.2$ mm

$l = 480 +/- 0.2$ mm

4.3 Conclusions

The ring shear apparatus has two main advantages :

a) There is no change in the area of cross-section of the shear plane as the test proceeds and,

b) The sample can be sheared through an uninterrupted displacement of any magnitude.

However, the disadvantages of the ring shear apparatus are that the interpretation of results from torsional tests is not easy and the preparation of ring-shaped samples is difficult.

4.4 Triaxial shear apparatus

4.4.1 General principle

When a soil sample is removed from a soil mass, all of the horizontal and vertical stresses acting on the soil in situ are removed. Thus, when the soil is tested in the laboratory to determine its strength, the test should be conducted under test conditions that resemble the field conditions as closely as possible.

The triaxial compression test is a procedure that permits different horizontal and vertical stresses to be applied to the soil specimen simultaneously and thus closely duplicate the expected field conditions. The concept of the triaxial compression test is that an all-around equal pressure is applied to the soil sample in the form of a confining pressure. The confining pressure, σ_C, is obtained by imposing a compressive stress on a fluid that completely surrounds the soil specimen.

4.4.2 Conclusions

General speaking, It is not practicable to measure the residual strength of intact soil in the triaxial apparatus due to the large displacement necessary to reach the residual condition. However, if the sample already contains a suitably orientated discontinuity, such as a naturally sheared surface, a much closer approach to the residual condition can be obtained within a reasonable axial displacement.

4.5 Conventional Shear box

4.5.1 Description and general principle

The earliest known attempt to measure the shear strength of a soil was made by the French engineer Allexandre Collin in 1846. He used a 350 mm long split box in which a sample of 40 x 40 mm in cross section was subjected to double shear under a load applied by hanging weights (see Figure 4.5). Further work was done by Cooling and Smith (1935) at the Building Research Station, who designed a simple shearbox with a simple plane of shear and in which the load was applied in increments in an attempt to control the increase of stresses (see Figure 4.6). This apparatus required great care in its use and did not give accurate results. In addition the rate of shear was found to be far from controlled. Gilboy (1936) was successful in overcoming the disadvantages of the Building Research Station design by developing a constant rate of shear displacement machine controlled by a fixed speed drive motor.

Furthermore, Cullen and Donald(1971) criticised the standard shearbox as an apparatus which is unable to provide sufficient travel for the determination of residual strength of some soils. With regard to this problem, they modified a shearbox so that when the box reached the limit of its forward travel, the motor reversed automatically.

March(1972) modified the standard shearbox to enable the direction of shear to be reversed so that the sheared specimen may be returned to its initial " in register" position before the commencement of further forward shear. This was achieved by fitting a spring return mechanism to the shearbox trough. The mechanism operates in conjunction with blocking and locating pieces to control the movement of the box and a switching device which automatically reverses the drive motor when the pre-set limit of travel is reached. The important idea behind this modification concerns the spring return devices, which consist of two compression return springs fitted between the front-end of the sample container and the shearbox trough. The position of the trough is adjusted so that at the start of a test the springs are in compression and exerting a force of about 600 N. As the screw-jack pushes the shearbox trough forward the springs are further compressed and this provides the force required to return the box when the jack is reversed. The movement of the box and the shearing force are automatically recorded by a chart-recorder and a punched paper tape.

Obviously the residual shear strength will be best determined by operating the shearbox in continuous cycles of forward and reverse travel. There is a wide discrepency in the results between the standard and the modified shearbox. The latter provides a convenient and accurate method for determining the residual and peak shear strength parameters. The addition of automatic data-recording enables the stress-strain relation for the soil to be examined in great detail without the need for continuous presence of the operator.

Most published measurements of residual strength have been made in the shearbox using the multiple reversal technique. Typical sizes of sample are shown in Table 4.1. In a further development Kanji (1970,1974a and b) and Kanji and Wolle(1977) used a standard Wykeham Farrance direct shearbox to study the shear strength of soil-rock contacts and sandwich specimens. He suggested that no special modifications to the equipment were needed to test the soil-rock or sandwich specimens, but a difficult procedure for sample preparation and set-up was recommended (see Figure 4.7). It is apparent that the majority of shear apparatus have been designed only for soil testing, and have serious limitations when used for rock testing.

Further attempts were made by Franklin(1985) to design a new shear box apparatus which overcome some of these limitations. In this equipment, hydraulic jacks are used for shear and normal stress guages are also used.

4.5.2 Sample preparation

When preparing the specimens for testing in the shear boxes, water was added and mixed throughly. Every attempt was made to remove air bubbles completely by shaking and the sample was then allowed to come to equilibrium for some time. The two halves of the shearbox were then assembled, with porous stones above and below the specimen, and gentle pressure on the upper porous stone forced the sample into the correct location for testing.

The required normal loads were applied by means of the lever system, and the specimen was left to consolidate (or swell) until the equilibruim conditions were reached. In the majority of cases, it was found that very little further change in volume occurred after allowing the equilibruim conditions to be reached, when consolidation was complete, the upper half of the shear box was raised slightly using the two scews provided. The position of the carriage or proving ring was then adjusted until the yoke of the shearbox was just in contact with the proving ring and the gears were then engaged. Frequent readings of the shear load and vertical displacement were taken. After completing the first traverse, with the displacement required, the gears were reversed and by means of tie-bars, the boxes were returned to their initial positions. The procedure followed in the first shear stage was then repeated. The reversal technique was continued until a steady shear stress was recorded on two cosecutive travels, this was then taken as being the ' residual' value.

4.5.3 Interpretation of the results

In principle the shearbox test is an angle of friction test, in which one portion of soil is made to slide along another by the action of a steadily increasing horizontal shearing force while a constant load is applied normal to the plane of relative movement. The box consists of two halves. The lower half of the box can slide relative to the upper half when pushed (or pulled) by a motorised drive unit, while a yoke supporting a load hanger provides the normal pressure. It is assumed that the shearbox is square and that each side is equal to L (see Figure 4.8). The initial area is given by equation 4.4.

$$A_0 = L \times L = L^2 \qquad (4.4)$$

Shearing area at time t is :

$$A = L (L - x)$$

The shear stress τ is given by equation 4.5.

$$\tau = F' / (A_0 - x. L) \quad (4.5)$$

The coefficient of friction :

$$\mu = \tan \phi' \; ; \; F' = F.\mu$$

The normal stress :

$$\sigma'_n = N/A$$

4.6 Swedish Direct Shear Test

The royal S.G.I (Swedish Geotechnical Institute) has developed an apparatus which can be used for consolidation, permeability and direct shear tests (Kjellman, 1951). A short cylindrical sample is confined laterally by a rubber membrane and a series of thin and evenly-spaced rings. The shearing forces are transmitted entirely as tangential forces by means of rough surface ends, while accurate control of drainage to be maintained. The lateral deformations are reasonably uniformly distributed during the test over the height and cylindrical sample of the specimen, and the horizontal cylindrical area remains constant. The disadvantages include difficulty in proper positioning of the membrane and rings so that pinching is not produced at large strains; neither the vertical normal stresses, nor the shearing stresses are uniformly distributed, and the non-uniformity becomes more severe as the displacement increases, making possible only a limited investigation of the shearing characteristics after failure.

4.7 Conclusions

As far as the shear box is concerned, in general some disadvantages have become apparent, such as the shear surface becomes damaged after the first few milimetres of displacement. In addition the stress-displacement curves of reversal shearbox tests are sometimes very difficult to interpret because of renewed peaks on the reversals of shear direction and the shape of the stress-displacement curve. The apparatus is operated manually, as a result of which much time is needed to achieve the required number of reversals. The shear box can be used as a shear technique to determine residual strength, using a soil to hard, polished surface interface (Kanji,1974a,Kanji and Wolle, 1977, Littleton,1976).

Soils	Author	Size of sample
London clay other natural clays	Skempton (1964)	60 mm. square 25 mm. thick
Natural clays Minerals, Clay minerals Treated soils	Kenney (1967)	(a) 80 mm dia. 20 mm thick (b) 80 mm dia. 1 mm thick
Natural clays	Cullen&Donald (1971)	60 mm square 20 mm thick
Blue London clay	Petley (1966)	60 mm square 20 mm thick
Blue London clay	Agarwal (1967)	60 mm square 20 mm thick
Tavium	Chowdhury (1977)	100 mm square 20 mm thick

Table 4.1 Sizes of shear box specimens used for residual strength measurement (After Chowdhury and Bertoldi, 1977).

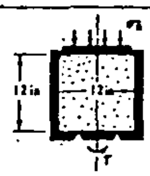
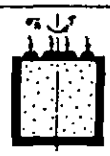
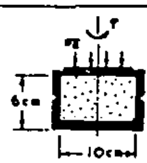
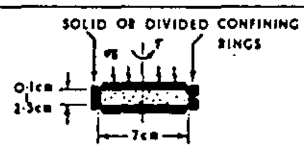
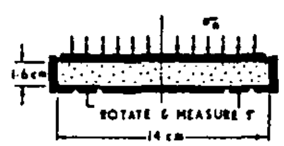
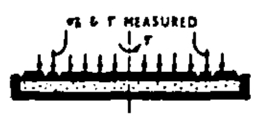
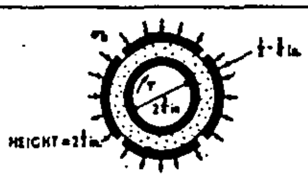
SHAPE OF FAILURE SURFACE	LOADING SYSTEM	SAMPLE TYPE	REFERENCE
CIRCLE		SOLID CYLINDER LOADED NORMALLY, LOWER PLATEN TWISTED	A.S.C.E. (1917)
CIRCLE		SOLID CYLINDER LOADED NORMALLY & TWISTED	STRECK (1928) FRANZIUS ET AL.(1929) (see HVORSLEV, 1939)
CIRCLE		SOLID CYLINDER LOADED NORMALLY & TWISTED	LANGER (1936) (see HVORSLEV, 1939)
CIRCLE		SOLID DISC LOADED NORMALLY & TWISTED	SEMBENELLI & RAMIREZ (1968) LA GATTA 1970
ANNULUS		SOLID DISC LOADED NORMALLY, ANNULUS TWISTED	TIEDEMANN (1937) (see HVORSLEV, 1939)
CIRCLE		SOLID DISC LOADED NORMALLY & TWISTED	GHANI (1966)
CYLINDER		HOLLOW CYLINDER LOADED RADIALLY & TWISTED	CASAGRANDE & U.S. ENGINEER OFFICE, BOSTON, MASS. (see HVORSLEV, 1939)

Fig. 4.1.(a) Principal features of various forms of torsion and ring shear apparatus : Solid cylinder or disc or hollow cylinder (After Bishop et al., 1971).

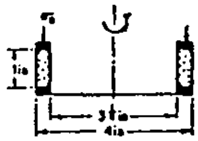
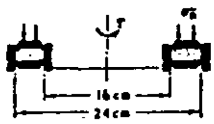
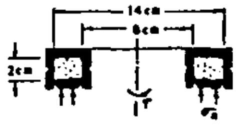
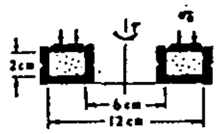
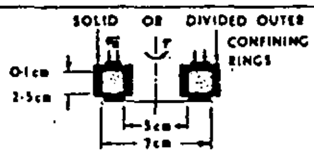
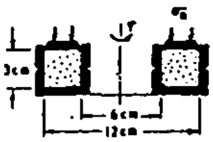
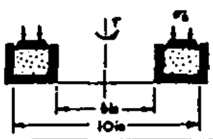
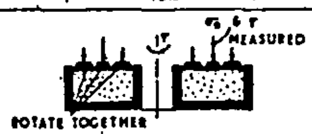
SHAPE OF FAILURE SURFACE	LOADING SYSTEM	SAMPLE TYPE	REFERENCE
ANNULUS		UNCONFINED ANNULAR DISC LOADED NORMALLY & TWISTED	COOLING & SMITH (1935, 1936)
ANNULUS		ANNULAR DISC LOADED NORMALLY & TWISTED	GRUNER & HAEFELI (1934) HAEFELI (1938) (see HVORSLEV, 1939)
ANNULUS		ANNULAR DISC LOADED NORMALLY & TWISTED	TIEDEMANN (1937) (see HVORSLEV, 1939)
ANNULUS		ANNULAR DISC LOADED NORMALLY & TWISTED	HVORSLEV (1937, 1939) HVORSLEV & KAUFMAN (1952) HERRMANN & WOLFSKILL (1966)
ANNULUS		ANNULAR DISC LOADED NORMALLY & TWISTED	LA GATTA (1970)
ANNULUS		ANNULAR DISC LOADED NORMALLY & TWISTED	NOVOSAD (1964)
ANNULUS		ANNULAR DISC LOADED NORMALLY & TWISTED	CARR & WALKER (1968)
ANNULUS		ANNULAR DISC LOADED NORMALLY & TWISTED	SCARLETT & TODD (1968)

Fig. 4.1.(b) Principal features of various forms of torsion and ring shear apparatus : Annular disc —(After Bishop et al., 1971).

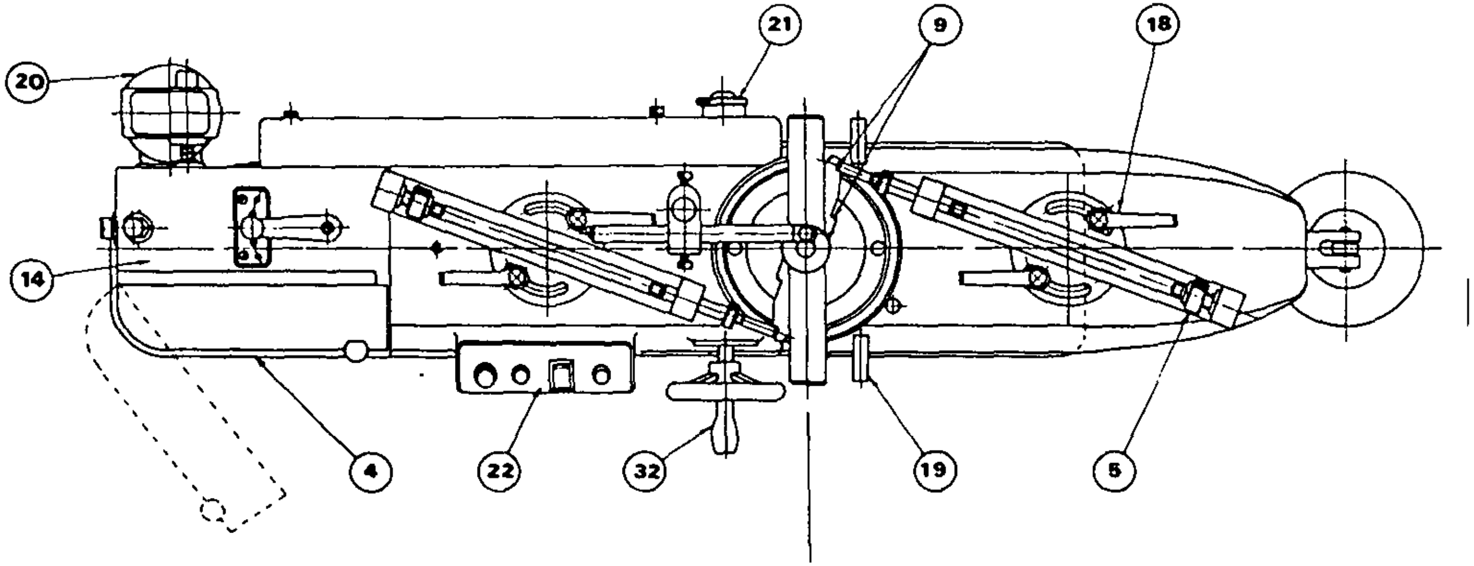


Fig. 4.2 General layout of the Bromhead ring shear : plan view
(After Bromhead, 1979).

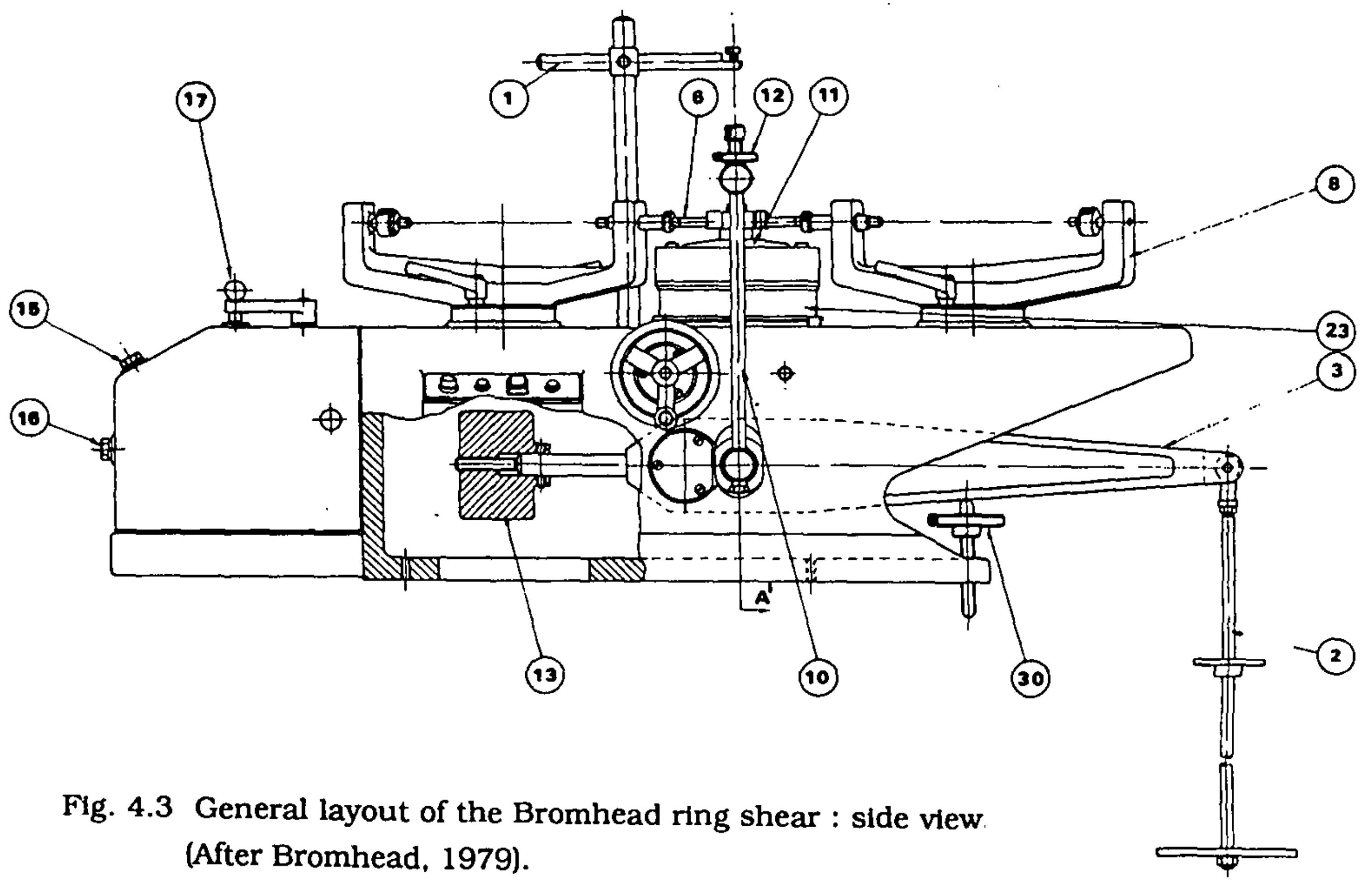


Fig. 4.3 General layout of the Bromhead ring shear : side view (After Bromhead, 1979).

1) Consolidation dial gauge arm
2) Load hanger
3) Counter balanced lever loading arm
4) Hinged gear cover
5) Proving ring adapter
6) Adjustment rod for proving ring
8) Loading restraint
10) Loading yoke
11) Upper ring
12) Loading yoke(working position)
13) Counter-balance weight
14) Gearbox
15) Filler plug
16) Oil level plug
17) Gear change lever
18) Clamps
19) Stops for loading load
20) Motor
21) Clutch
22) Control panel
23) Turret
30) Beam jack
32) Handwheel

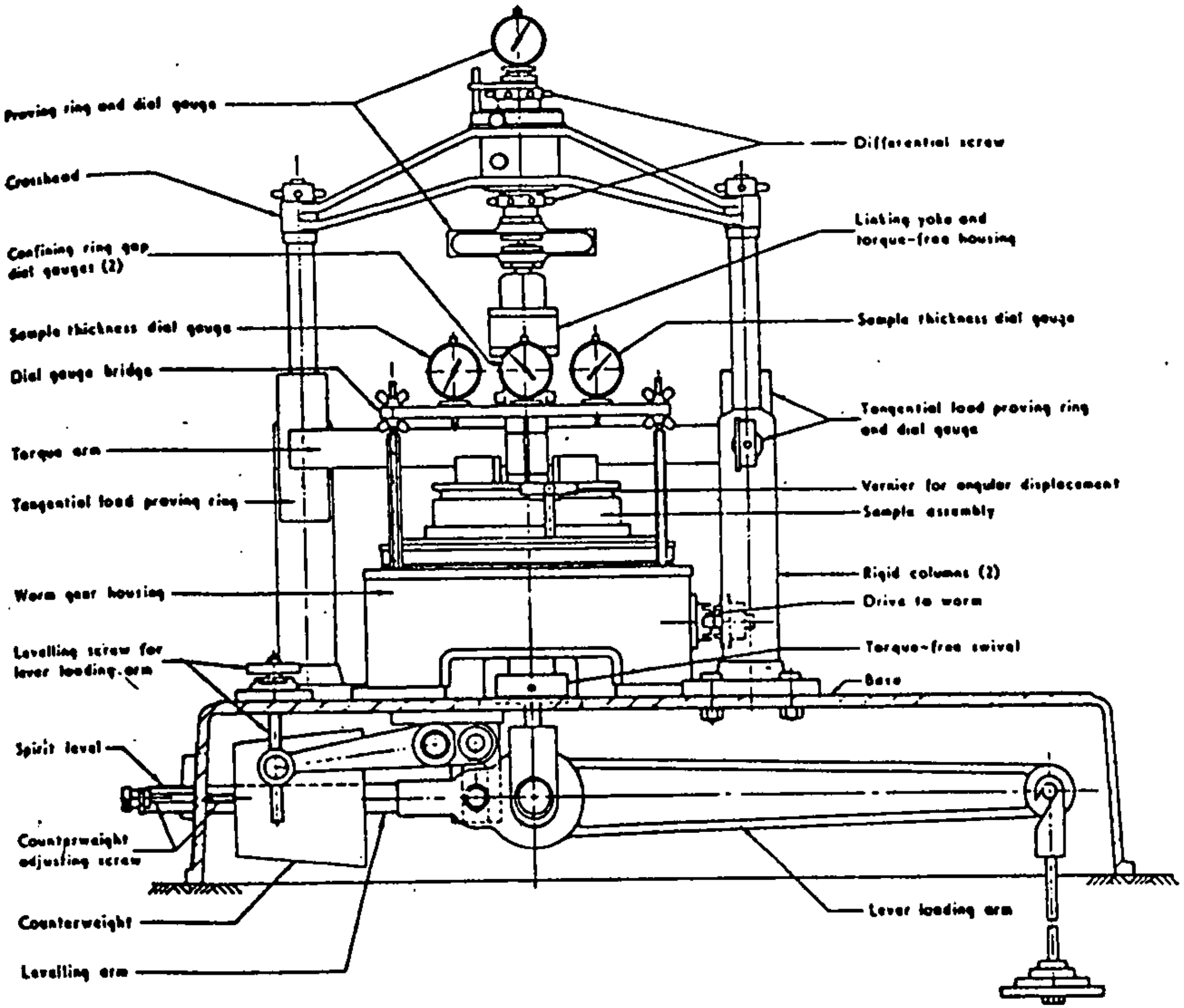


Fig. 4.4 General layout of ring shear apparatus (After Bishop et al, 1971).

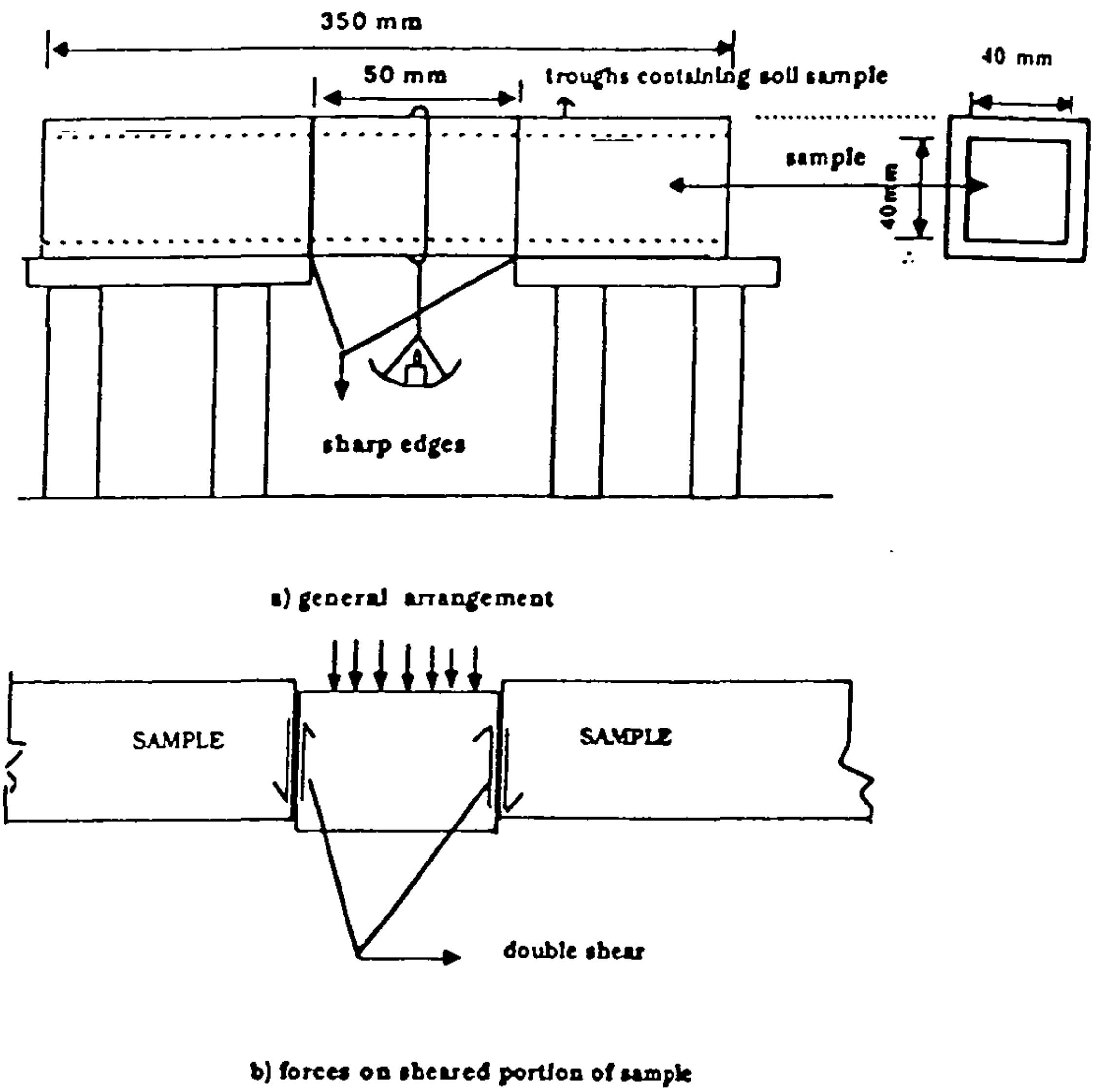


Fig. 4.5 Shearbox apparatus derived by Collin (1846)

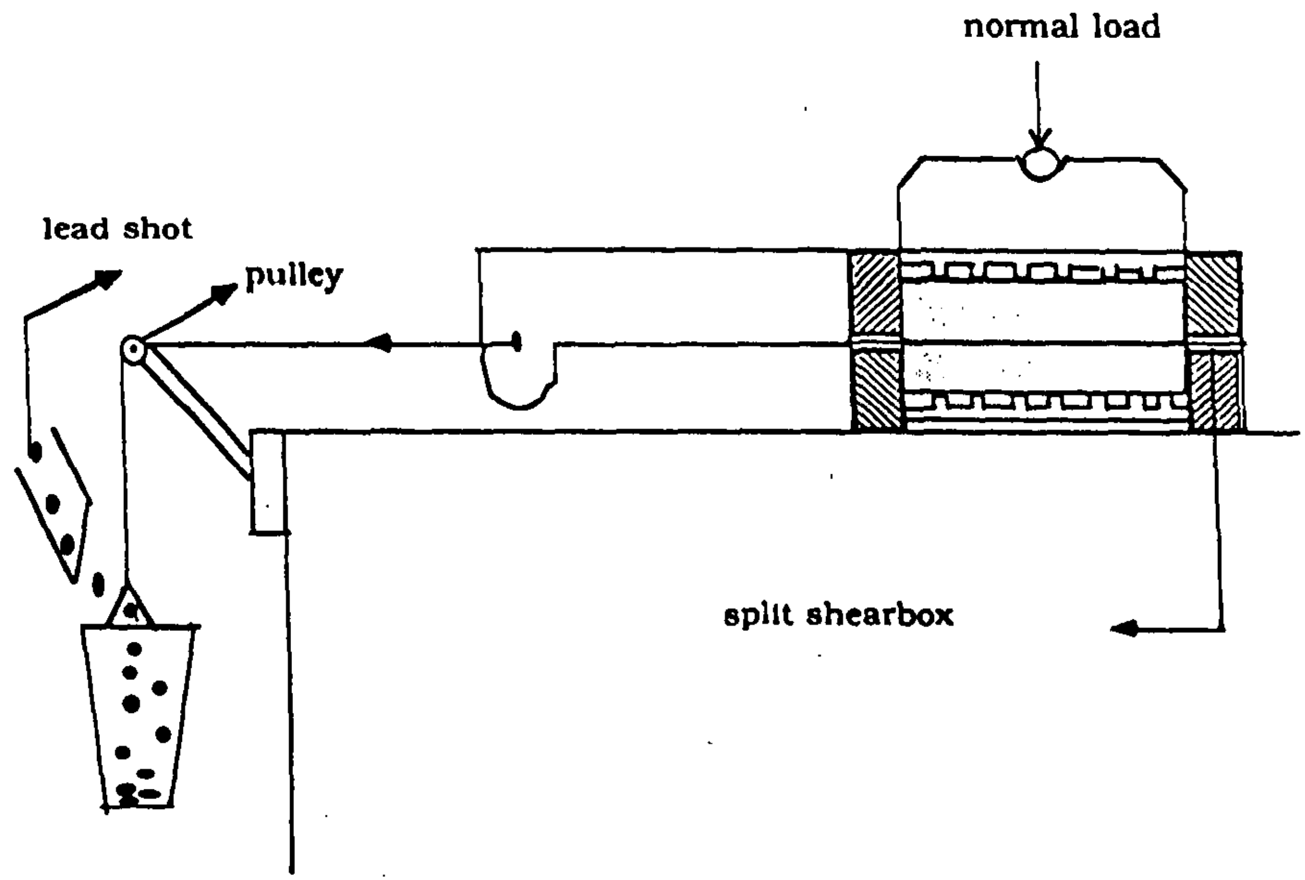
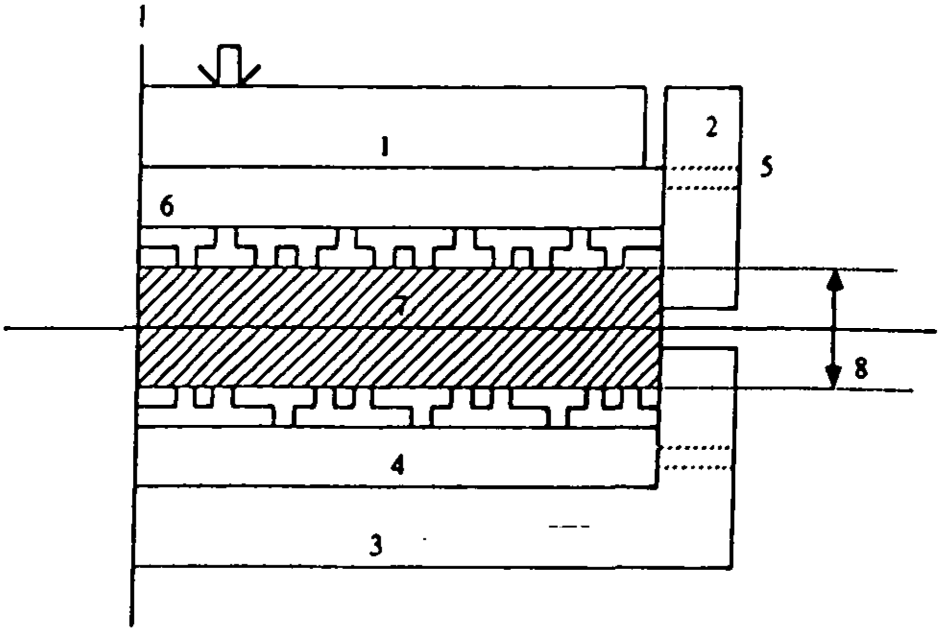
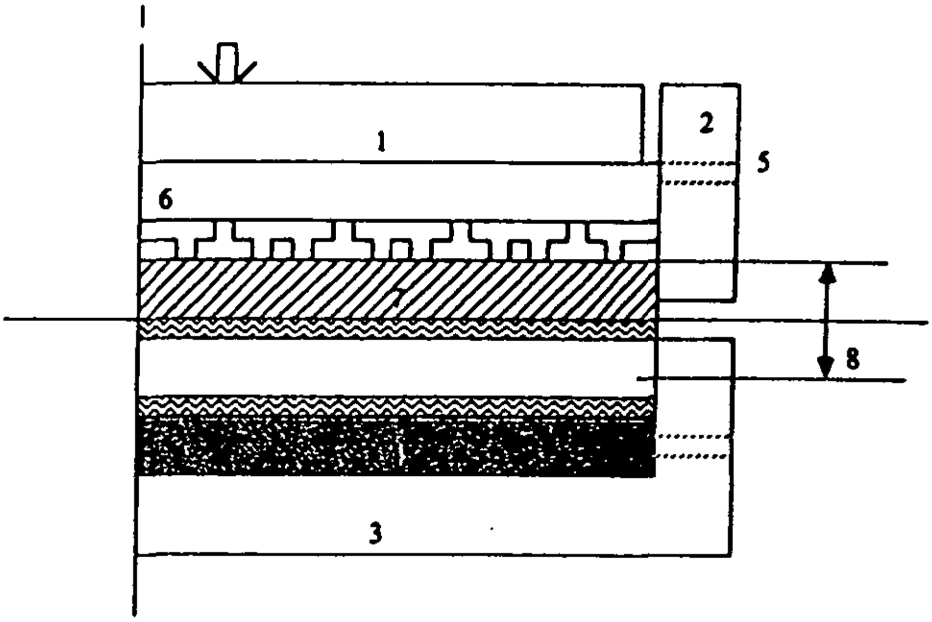


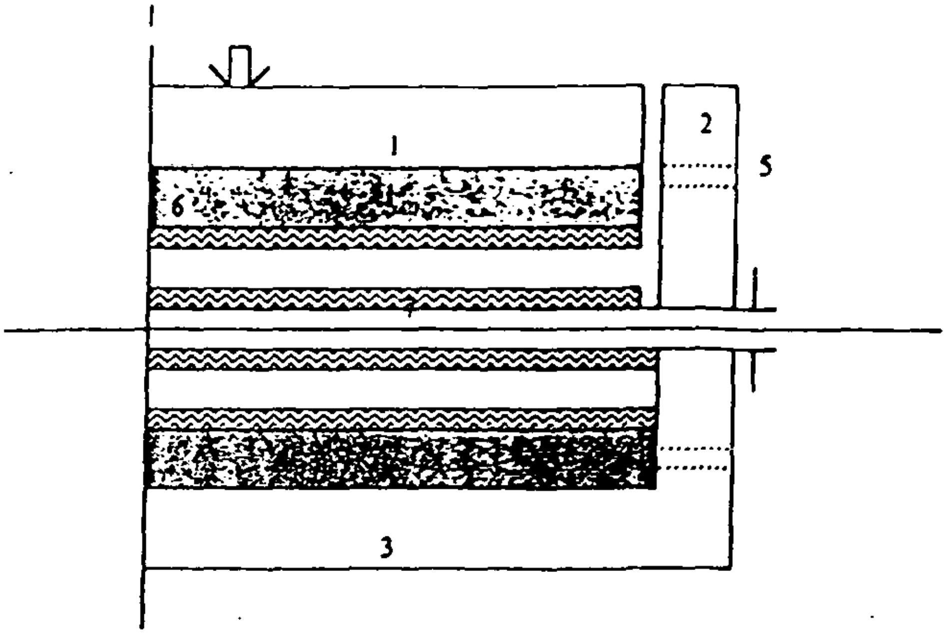
Fig. 4.6 Principle Of the early type of controlled-stress shear



a) The Arrangement for Soil in the Direct Shear Apparatus



b) The Arrangement of Soil-Rock contact in the Direct Shear Apparatus



C) The Arrangement for a "SANDWICH" specimen in the Direct Shear Apparatus

1- Cap of Shear Box 2- Upper half of Shear Box

3 - Lower half of Shear Box 4- Porous plate

5- Drain 6- Perforated metal plate with teeth

7- Soil specimen 8- "FREE" Thickness of soil specimen

9- Rock specimen 10- "CLEARANCE"

11- Filler : Metal plates , Shims , .. etc

12- Spacing between boxes

Fig. 4.7 The arrangement of Soil-Rock contacts and Sandwich specimens (After Kanji, 1974a)

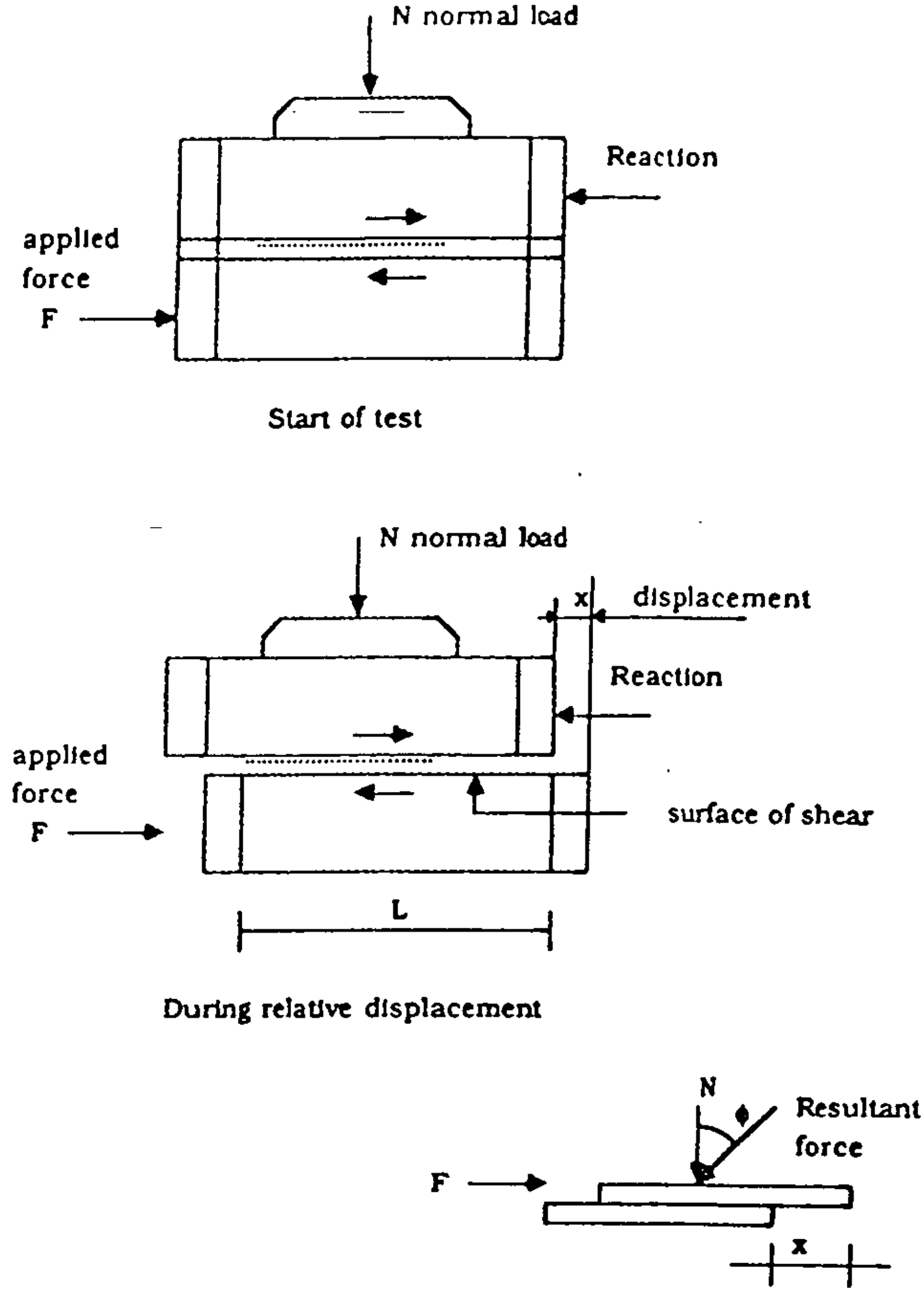


Fig. 4.8 Representation of the concepts of sliding force

CHAPTER FIVE

DEVELOPMENT OF AUTOMATIC SHEARBOX

5-1 Introduction

The use of computerised data logging systems in soil mechanics laboratories is now well established. Tremendous advances have taken place over the past few years in computer technology and electronics, and these have made sophisticated data logging perhaps the only economic solution for laboratory testing. One of the general requirements for automation of the shearbox is then economics, which is a major problem facing testing in most areas and particularly commercial soil mechanics laboratories, in which there is a strong economic justification to reduce laboratory overheads.

Many attempts have been made in the past few years to develop the shearbox such that shearing of soil takes place under similar conditions to those encountered in the field. After the introduction of the concept of residual shear strength by Skempton(1964) in his fourth Rankine Lecture, more interest has been attached to this aspect of shear testing and consequently more serious development has occurred. The need for particular laboratory test techniques, such as those for achieving large strains necessary to measure the residual shear strength, has become apparent.

Despite all the facilities which can be given by computers, only a few investigators have introduced the computer to collect the results from the shearbox. This is a vital step to save technician time and reduce the difficulties of interpretation by obtaining consistent test results.

In general, most direct shear apparatuses used in the laboratory are working manually. At Loughborough University, the standard shearbox has been modified as follows.
The rate of shearing is usually controlled by the steady advancement of a screw jack activated by an electric motor connected by a gear transmission. In such an apparatus it is difficult to change the rate of shear repeatedly because of the need to change the gears. This is especially relevant for this study, which is concerned more with high speed shearing over very short lengths of travel, an operation which is impossible to carry out using the standard shearbox. In this study the gears have been removed and the motor has been replaced by a stepper motor controlled directly from a BBC micro-computer by fixing the number of pulses necessary to drive the motor a certain distance. Instead of measuring the shear stress of the soil or soil-structure interfaces by means of a load ring, which sometimes gives inaccurate results due to the problem of friction of the needle, a transducer is used to allow the measurement of shear stress automatically. Dial gauges which measure the horizontal and vertical movement of the box during consolidation and shear have likewise been replaced by transducers. The normal stresses, which are traditionally applied to the upper half of the specimen by hanging weights on a yoke, are now applied by air pressure controlled by the computer. A load cell is used to measure the normal stress acting on the sample. The data-logging system is used to record measurements obtained from the shearbox. The modifications also

enable the direction of travel to be reversed automatically at a chosen distance of travel. The program, which undertakes all of the communication between the transducers, is written in assembly language and basic and carries out all the calculations necessary to convert the transducer readings from analogue to digital values of stresses and strains.

5.2 Description of the component parts of the modified shearbox

5.2.1 Displacement Transducers

Two linearly variable differential transformers(LVDTs) are used to measure horizontal and vertical displacement of the shearbox. The transformer consists of an electrical coil in a cylindrical casing, through the axis of which a metal rod, the armature, can slide. Movements of the armatures change the inductance of the windings, which is measured electrically by an analogue signal (in volts). It is then converted by the A/D Converter module of a PCI80 Brain Gain micro interface into a digital display having units of displacement (mm).

5.2.2 Submersible load cell Trasducer

Two submersible load cell transducers have been used to measure the shearing force and normal force applied to the soil sample. The load is transmitted directly to a metal web or diaphragm, to which electrical resistance strain gauges are bonded. As a consequence of the resulting strains in the web, changes occur in the electrical resistance of the strain gauges. These are small voltage changes which are amplified and converted by the microinterface into a suitable digital display in force units. The maximum load which can be supported by the two submersible load cell transducers is 450 kgF.

As far as the transducers are concerned, they share the same characteristics and the only difference that exists is in the electrical resistance. Unfortunately, both the load cells work only in compression and not in tension. With regard to this problem, modification has been made to the original prototype of the shearbox shown in Figure 5.1, which shows the first prototype of the modified 100 mm shearbox with strain and load transducers. The horizontal load cell transducer was removed and replaced by a load ring and dial gauge to measure the load manually. A LVDT was fitted in parallel with the dial gauge across the load ring to measure the horizontal load automatically (Figure 5.2). Another LVDT is fitted to the lower base of the shearbox to measure the horizontal displacement of the box during the shearing stage. The vertical displacement of the shearbox is measured by means of a transducer attached directly to the rod of the load cell as shown in Figure 5.3.

5.2.3 Electro-pneumatic converter

An electro-pneumatic converter controls the pressure of the air supply, the output pressure being proportional to the drive current supplied. The converter used is a Westinghouse, which gives a pressure output of 0-690 kPa for a control current 0-500 mA. This is connected to the top port of a 37 mm bore actuator, which was sufficiently large to apply the range of loads required during the testing programme.

5.2.4 Signal conditioning box

This was used to facilitate the operation of all of the transducers. It consisted of six seperate channels, although this study required the use of four channels, three of them being used for the strain transducers and one for the load cell transducer (Figure 5.4).

5.2.5 The Micro-interface (A/D converter)

Measuring analogue quantities using a computer is slightly more difficult and requires a special piece of hardware called an A to D converter (Analogue to Digital converter). It takes an electrical signal and turns it into a number that can be read by the computer (see Figure 5.5). The Brain Gain Microinterface is a PCI series80, 16 bit converter which lies in the range of 0 to 65536, the instrument containing a series of Z80-based intelligent microcomputer circuits. Facilities are available for interfacing of both analogue and digital signals, including eight differential input channels, four output channels and four relays. However, in this study only four channels and one output channel have been used, the electronic devices used for this modified shearbox are shown in Figure 5.4.

5.3 Calibration of the Equipment

5.3.1 Introduction

Measuring devices are precision-made instruments and should be treated with respect and protected against damage, dirt, dust and damp. Calibration is a vital factor in the use of instruments and needs to be carried out from time to time, in order to maintain a high standard of accuracy of test results.

5.3.2 Calibration of Transducers

The procedure consists of adjusting the voltage and the digitized values output from each transducer to provide a direct indication of the movement or strain of the transducer. Both horizontal and vertical displacement transducers were calibrated in the same way. A digital voltmeter (D.V.M) was adjusted to zero, or near zero, and connected to the conditioning box at the position of the transducer lead. The B.B.C microcomputer was programmed to record the variation of the transducer in digitized values via the micro interface, whose role was to convert the analogue variation of the transducer into a digitized value which could then be monitored on the screen and printed out.

The displacement transducer is placed into a simple device, as shown in Figures 5.6 and 5.7, in which the head of the armature of the transducer contacts the point of the standard calibration device. One rotation of the device pushes the armature of the transducer by 0.5 mm. Simultaneously, both the D.V.M and the computer are monitering the values of the voltages and the digitized values exclusively. A graph was drawn relating every point from the standard calibration device in (mm) to the digitized values from the computer(for example see Figures 5.8). A linear graph was obtained and the tangent of the angle formed by the straight line was calculated. The displacement corresponding to any transducer reading can thus be calculated accurately by multiplying the reading of the digitized values by the corresponding values of calibration coefficient(CR) that are taken from the graph.

The load cell was calibrated in a similar manner by placing the cell in series with a cell of known calibration as shown in Figures 5.9 and 5.10. The load was changed in increments, and subsequently decrements, and a graph of linear calibration was once more produced (see Figure 5.11). The load measured by the load ring was calculated by cross calibration of the dial gauge and the displacement transducer.

5.3.3 The effect of Temperature on the stability of the Equipment

The data-recording system, which was developed for laboratory use, will normally be operated in a temperature- controlled laboratory and small variations of the order 2°C are to be expected. To check the effect on the measurements of small variations in the ambient temperature (up to 1.5°C) , both temperature and transducer readings were measured. Four channels were scanned every 3 minutes for a period of 24 hours, and a thermometer, connected to a multi-channel recorder, measured the temperature at various points in the room. In all of these calibration tests, all of the transducers showed sensitivity, proved to be very stable and proved to have linear outputs. However, the vertical load cell against the signal generater gave a non-linear curve especially at low pressures, and this was taken into account in the test programme.

5.4 Computer Automation

5.4.1 Introduction

Automatic data-logging for laboratory testing has been described by Irwin(1968), Prince(1981, 1985) and Prince & Callenran(1985). A computer was introduced into the experimental arrangement , to act as a data-logger on one hand and to control the application of normal and shear stress on the other hand. In this way complex loading regimes can be pre-programmed and the test could run fully automatically. The arrangement of the computer control and data-logging equipment is shown in Figures 5.12 and 5.13.

The heart of any computer,the part that actually does all the processing, is the control processor unit (CPU). The only language that the CPU understands is machine code, or assembly language, which is a set of ones and zeroes. In this study the program is written in assembly language and Basic, rather than Basic language alone, despite the fact that Basic is easy to learn and easy to use.

However, it has got the one major drawback that it is very slow to operate compared to assembly language. In addition, the only language that the computer can obey is assembly language. In other words, the execution of a Basic program involves the use of another program which is called an interpreter. When the Basic program is run, the interpreter looks at the first line of the program and carries out all of the instructions. It is worth noting that the Basic program does not directly control what the machine is doing. In contrast assembly language is executed by the heart of the BBC micro-computer without any intervening programs, and in particular there is no searching for the specified line number since assembly language does not work in terms of line numbers. Whenever an assembly language instruction refers to a position in a program, it uses memory addresses.

There are a number of special places inside the control processor unit called registers where the contents of memory location can be stored and these are the places where the work gets done. These registers are:

A Register or accumulator,it does things like arithmetic.

X Index register.

Y Index register.

PC Programme counter register.

S Stack pointer register.

P Processor status register.

Each register has a different role to play and the program devised in this study is characterised by many features .

5.4.2 Tasks

The control program can consist of up to four tasks. Each task is treated as a seperate control sequence and can either be executed in isolation from the other tasks or can interact with the other tasks. Only one task may be associated with one timer.
The command used to the source program is :

TASKn where n- is task number (n=1,2,3,4)

Although the program has four tasks available, this study is concerned only with two tasks. One task is used to define the delay for the converter to scan the results during the consolidation stage. The second task is used to control the motor by defining the rate of shearing required.

5-4-3 Timers

The control program is driven by three timers. Two timers are used for the two tasks. The third timer is concerned with the speed of the motor and uses a specially devised electronic chip, which was built in an attempt to increase the speed of the motor

and to drive the plotter at the same time from the 1 Mhz user port on the computer.
The motor receives a number of pulses following the formula below:

1/(2xN) = Timer3

where

N	Number of pulses required
Timer3	Time in microseconds

For example if Timer3 is required to have a value of 400 microseconds then :

1/ (2xN) = (400 x 0.000001)

N = 1250 pulses/seconds

If the program is driven by timer1, then the delay must be multiplied by the basic delay of timer1 (default value 50 ms), which can be altered to any integer value of time in microseconds. In contrast if the program is driven by Timer2, then the delay is in multiples of seconds and the time interval associated with timer2 cannot be changed.

5.4.4 Scanlist [MAX or MID or MIN]

This command selects for scanning one or more channels. Up to eight channels may be scanned in one go. The full scale deflection is defined by :

MAX = 10 V
MID = 1 V
MIN = 100 mV

Only one voltage may be specified per list of channels to be scanned. This study is concerned only with four channels.

CH0 Vertical displacement
CH1 Horizontal displacement
CH2 Horizontal load
CH3 Vertical load

5.4.5 Set VOLn [value]

This command sets the output channel n to a particular voltage. In this case a voltage of +/- 10V was used for channel 3 to control the electro-pneumatic converter. The output from the converter is 15 bit, and hence a value of 32767 in the selected register will produce +10V, 0 will result in 0V and -32768 will result in -10V.
If the required voltage is specified directly in the command line, then the numeric value must be followed immediately by the appropriate multiplier mV or V. This study is concerned only with one output channel which is called VOL 0

5.4.6 Set Delay [value REGm]

This command defines the interval between clock ticks of the task required. It is the only instruction which has parameters that depend on which timer is driving the control program.

5.4.7 Macros

Including macros in the command sequence allows the control program to be written in a way that is both more understandable and less likely to contain mistakes. The keywords MACRO and ENDMACRO denote the limits of the MACRO. Only the first six letters are stored and used in comparisons/expansion. The compiler does not allow one MACRO to be defined within another, thus, the keyword ENDMACRO must appear before the next MACRO.

5.4.8 Function Keys

Eight function keys have been programmed, each key having a different function. These functions are :

f0 help
f1 enable timers
f2 call task from basic
f3 show values
f4 show page 0
f5 switch to graphics
f8 disable timers
f9 end

5.4.9 Automation of normal load application to the shearbox

First of all, the calibration of the load cell must be known prior to the execution of the program. Thus, each value of the vertical load will be known to correspond to an appropriate voltage value. A suitable digital voltage value should be sent from the computer to the analogue output of the converter by this command, for example

```
SET VOL0  300 mV
```

then, the multiplier mV must be defined as macro, as follows

```
MACRO mV
(param x 3.2767)
ENDMACRO
```

Because a value of 32767 in the selected register will produce +10V the digital value supplied by the computer is 300x3.2767= 983.01 and this value will be converted to an analogue value of 0.3V by the A/D converter.

The electro-pneumatic converter has got two inputs. The first is current and the second is an analogue high pressure. These give the advantage of combining the current with the high pressure to an analogue high pressure pneumatic output,which allows the air pressure from the electro-pneumatic converter to the piston.

Finally, the vertical stress is applied using only one analogue output(the only digital to analogue signal operation), which is represented by VOL 0 in the program.

5.4.10 Automatic driving of the motor

The number of pulses required to drive the motor is ensured by timer3, which is created from the new electronic chip. Therefore the speed of the motor depends on the value given to timer3. An example is presented below, with say

Timer3 = 400 microseconds

Then, the number of pulses is :

1/(2xN) = Timer3

N = 1/800 pulses/microseconds

hence

N = 1250 pulses/seconds

With the introduction of the reduction gear and other equipment, the number of pulses required to drive the shearbox by 1mm is 3780000 pulses. Therefore, the speed required for timer3 = 400 microseconds is 0.0198 mm/min.

5.4.11 Getting the reading from the transducers

The transducer is connected to the signal conditioning box, such that a change in the resistance from the transducer generates a voltage into the signal conditioning box. This analogue voltage value is transmitted to the computer as a digital value through the converter.

5.4.12 Driving the Printer and the Plotter through the source program

The program "prog" (see Appendix 1) contains some procedures which are written in Basic language. To make the printer work instantaneously, two command numbers should be given to the source program through the task commamd. The first command number gives the time and the second gives the output of the channels,see the example below :

```
TASK 1

    SET DELAY 5 :  REM it scans each 5s by using timer2
    LOOP SCANLIST MAX CH3
    SCAN
    SET REG3 CH3
    BASIC 37  :  REM it gives the time interval
    BASIC 38  :  REM it gives the output of  channel 3
    GOTO LOOP :  REM it repeats the operation
```

An electronic chip, built in the laboratory to ensure the workability of both the printer and the plotter simultaneously in parallel, has been incorporated in the 1 MHz port. Note that this chip also alters the speed of the motor. The source program for the plotter is similar to the program for the printer, the only difference being the basic command number,as shown in the source programme below :

TASK 1

```
SET DELAY 5
LOOP SCANLIST MAX CH2 CH3
SCAN
 SET REG2 CH2
 SET REG3 CH3
BASIC 42
GOTO LOOP
```

5.4.13 Procedures of the program

There are many procedures in the program. Each procedure is defined by its specific basic command number. The data-logger system consists of a B.B.C micro-computer, disc drive, printer, plotter, stabilised voltage box, A/D converter, drive current, motor generator, motor and electro-pneumatic converter. To run the program, it is necessary first to type the program called 'source' which is very simple and very short. Each command in the source program is replaced by a single numeric code, followed by one or more parameter values. The interpreter is a program written in machine code. It performs all of the data-logging functions and consists of two parts.

1) The task controller. This piece of software responds to interruptions from the timer, or from the keyboard, and then executes the coded instructions.

2) The largest part of interpreter is a collection of subroutines which perform the individual instructions corresponding to the numeric codes. Figure 5.14 shows the text program instructions between the main parts of the program. The steps used to run the program are shown in Appendix 1 and the list of the three main parts of the program are shown in Appendices 2,3 and 4.

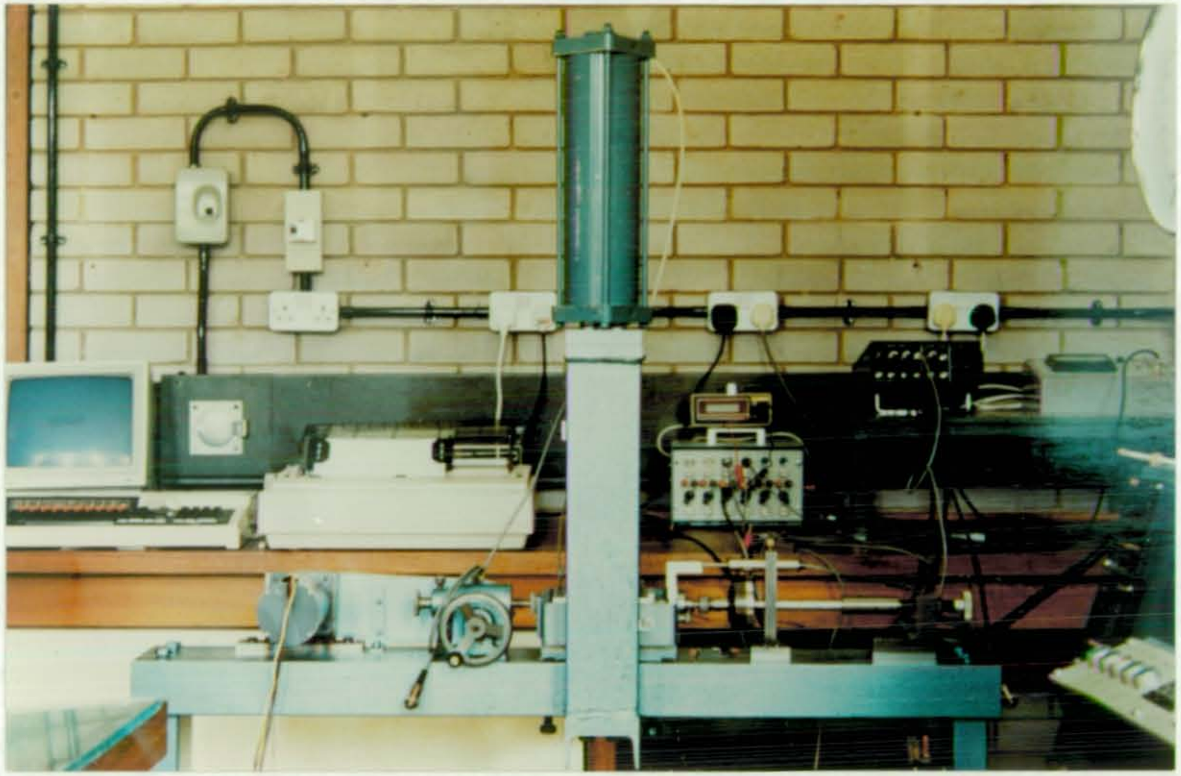


Fig. 5.1 Prototype of the modified shearbox

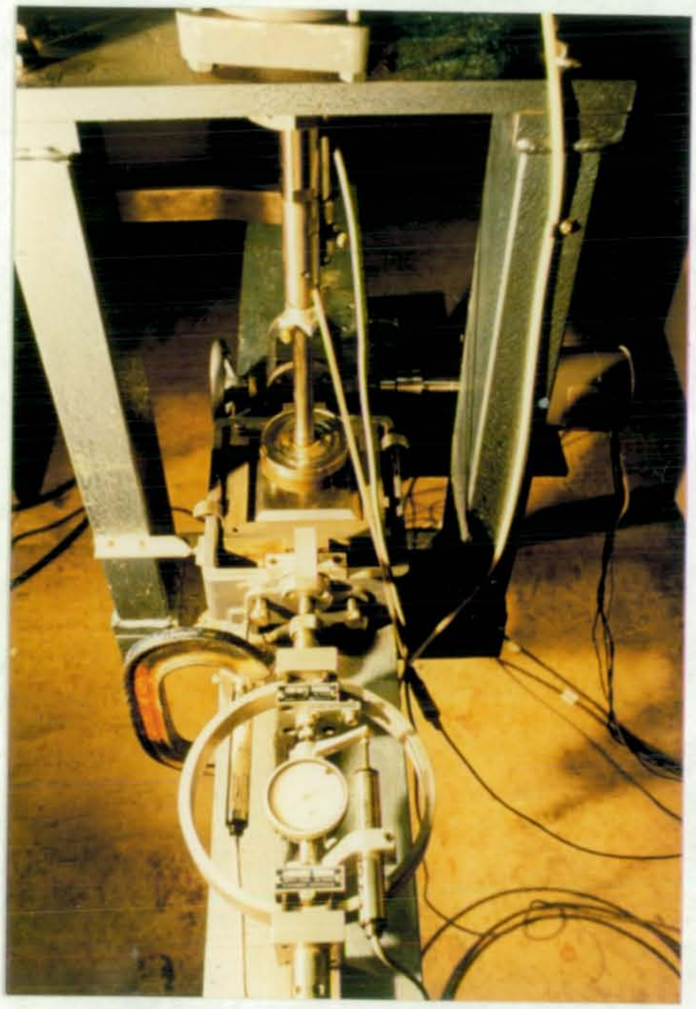


Figure 5.2 Replacement of the load cell by displacement transducer

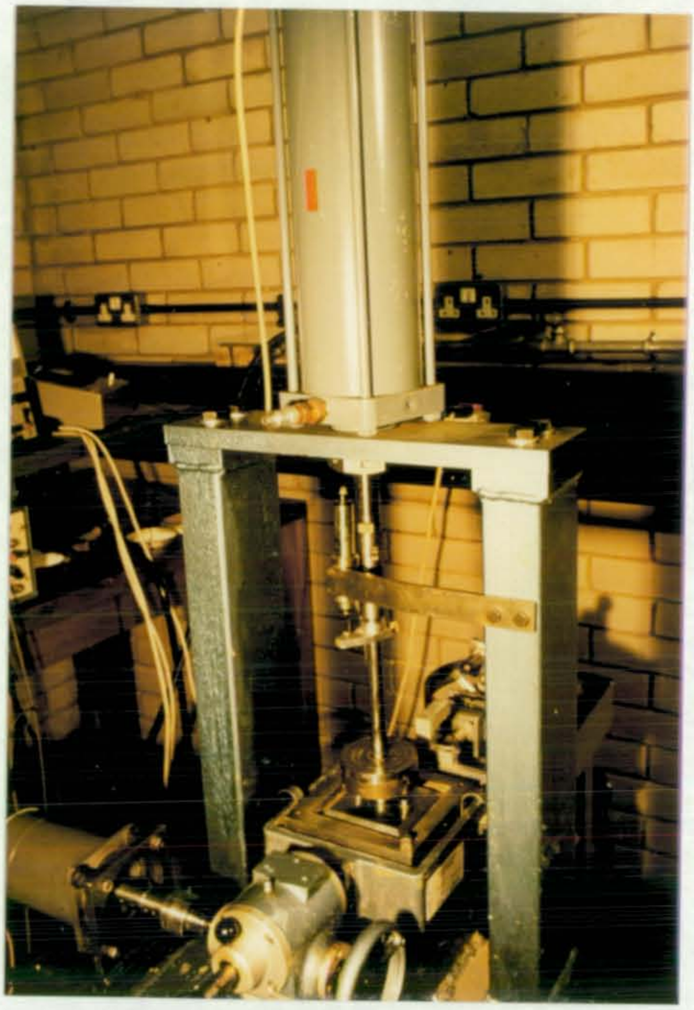


Fig.5.3 Alignment of the vertical displacement transducer and the load cell.

Fig. 5.4 The electronic devices used for the modified shearbox

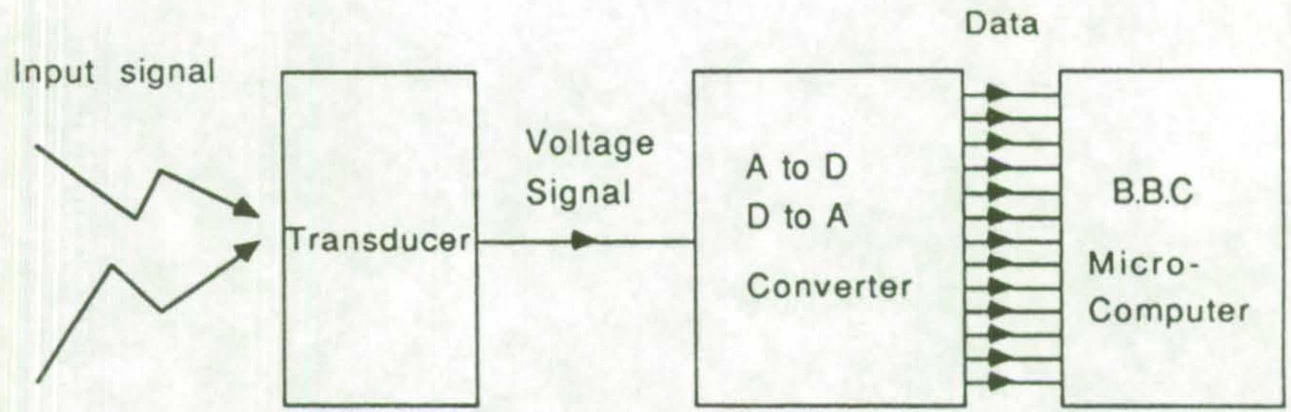
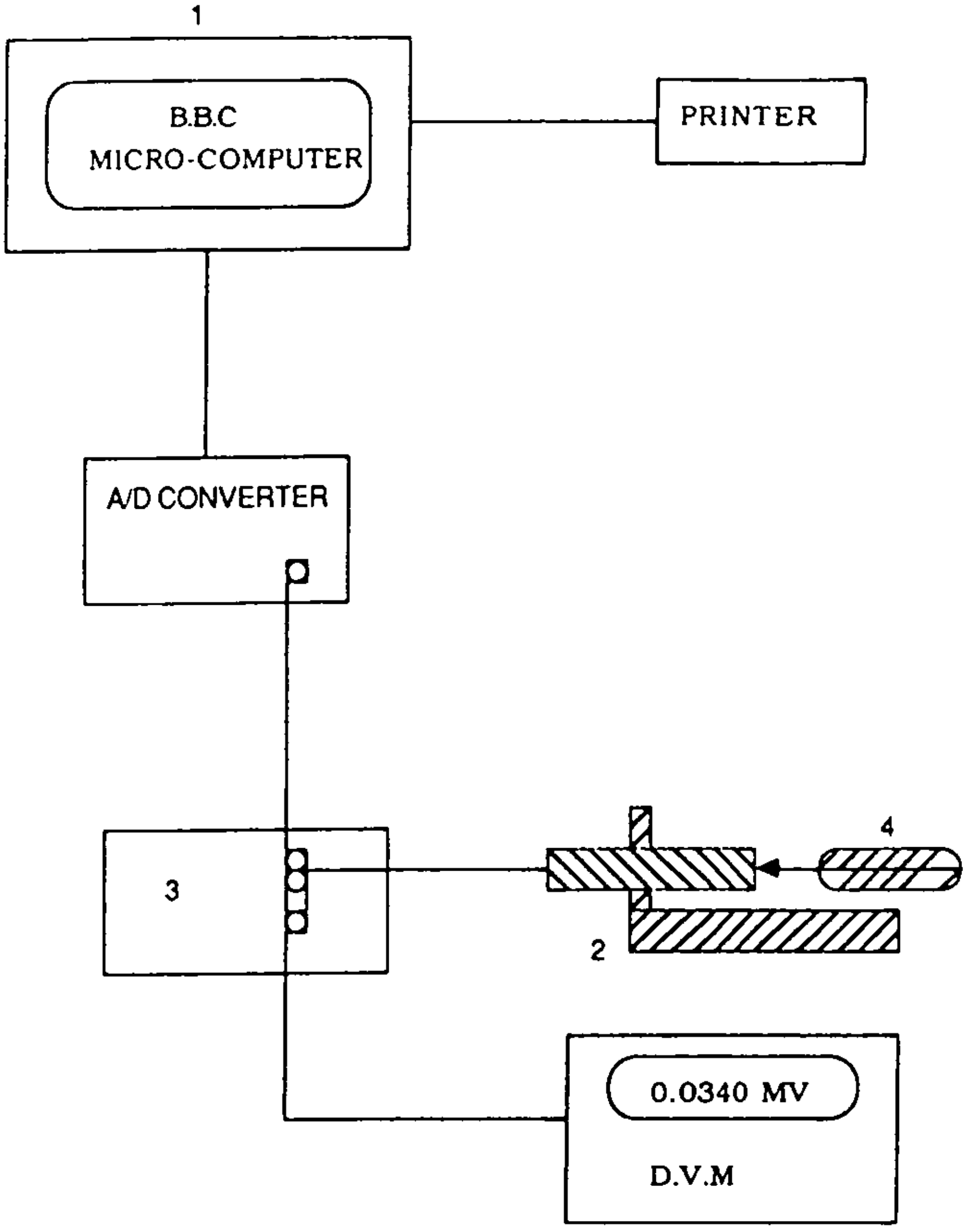


Fig. 5.5 B.B.C Micro-Computer measuring system

Fig. 5.6 Calibration of the displacement transducer



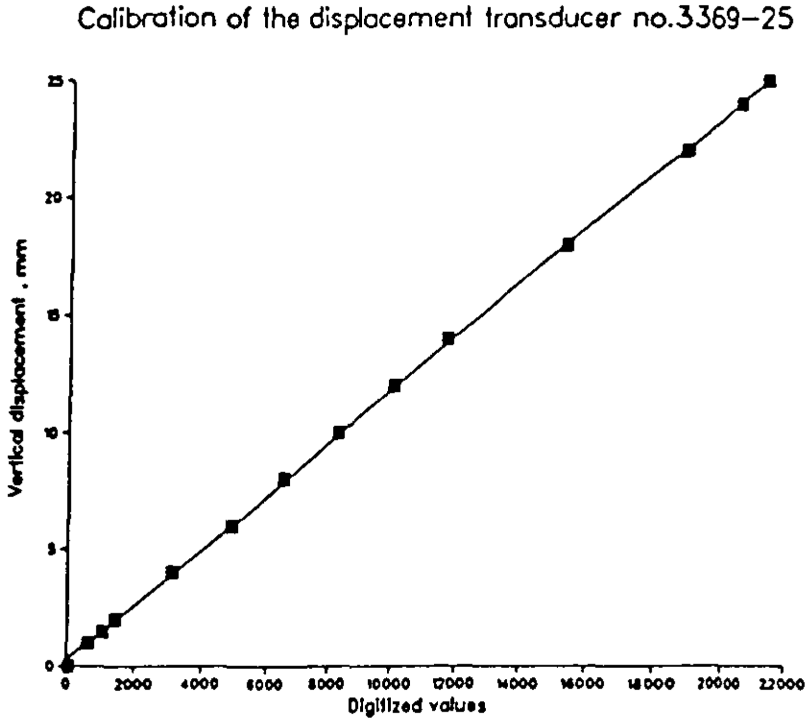
1 B.B.C MICRO-COMPUTER (indicates the digitized values)

2 STANDARD CALIBRATION TRANSDUCERS
(indicates the displacement in mm)

3 D.V.M (indicates the values in MV).

4 TRANDUCER

Fig. 5.7 Procedure used for the calibration of the displacement transducer



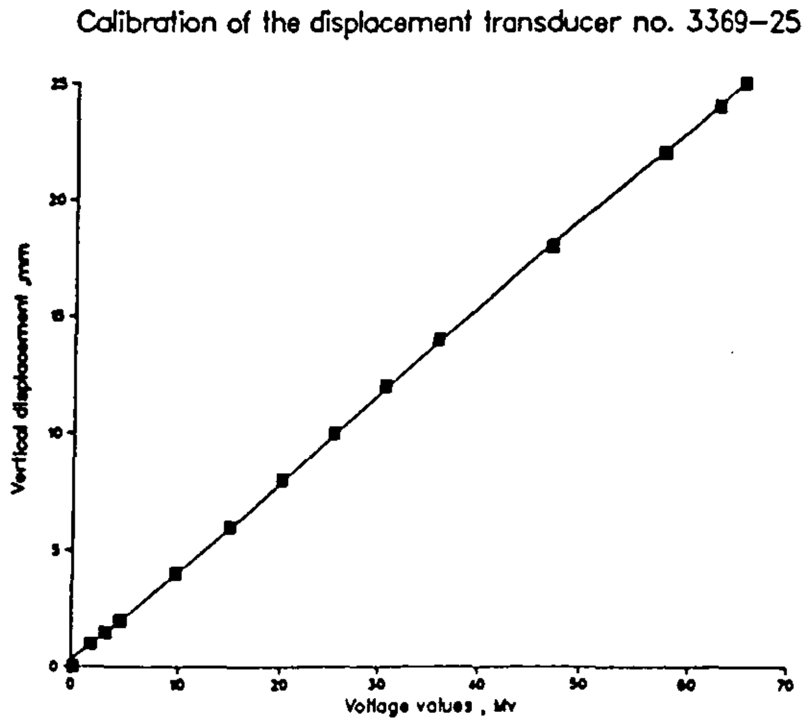
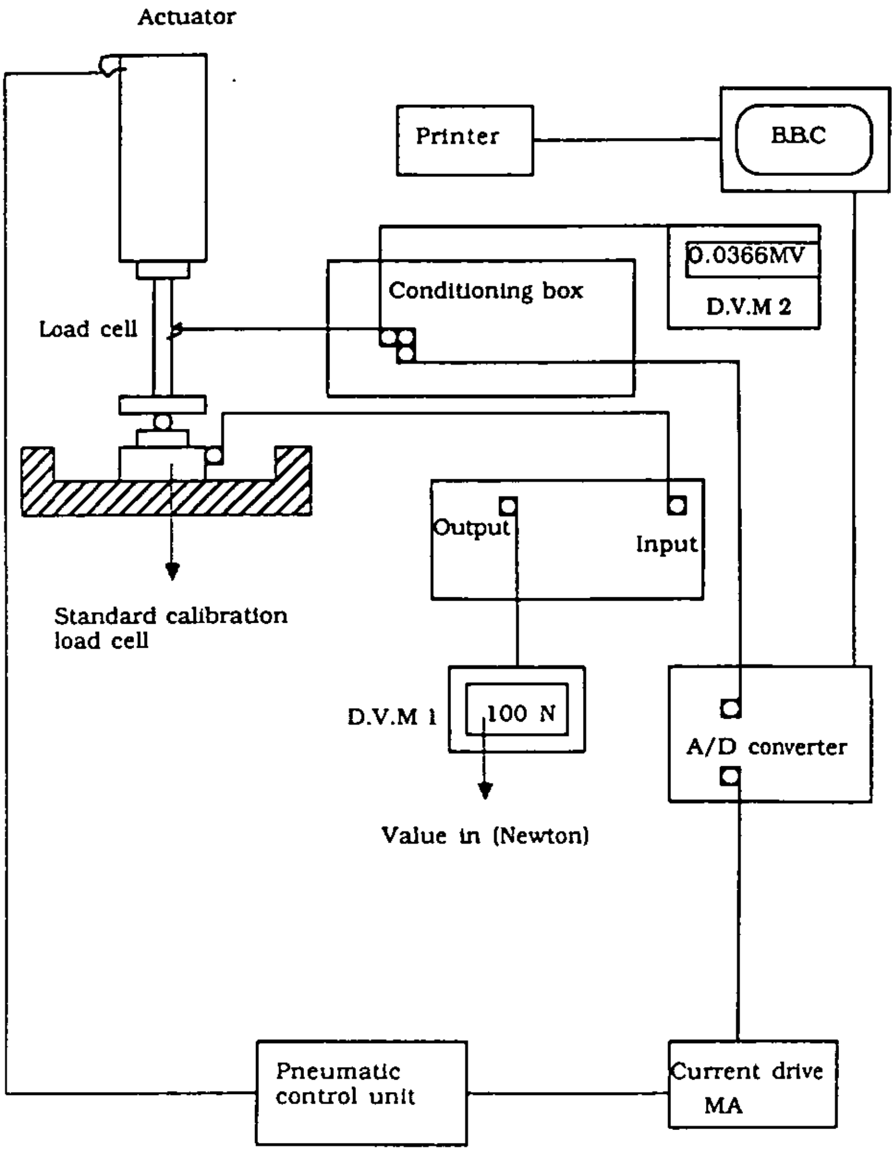


Fig. 5.8 Vertical displacement plotted against digitized values and voltage values.



D.V.M1 indicates the value in(Newton).
D.V.M2 indicates the value in(Millivolt).

B.B.C sends the values in Millivolt and records the digitized values.

Fig. 5.9 Calibration of the load cell.

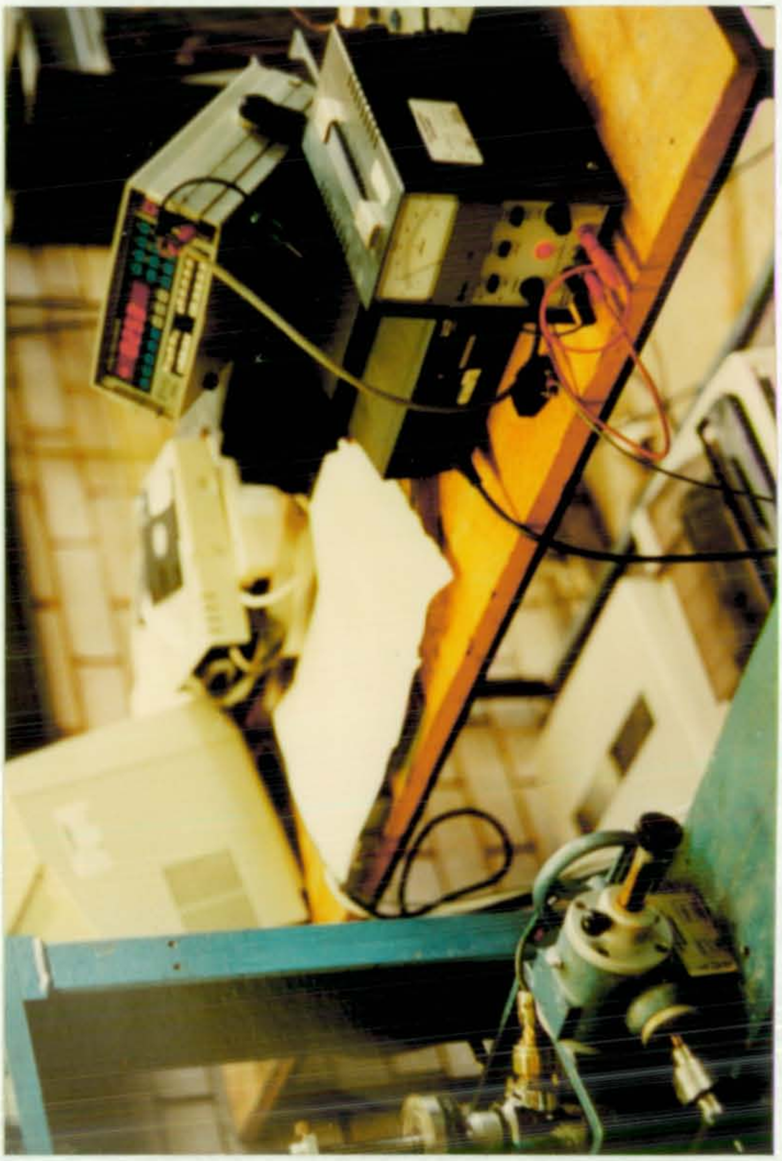
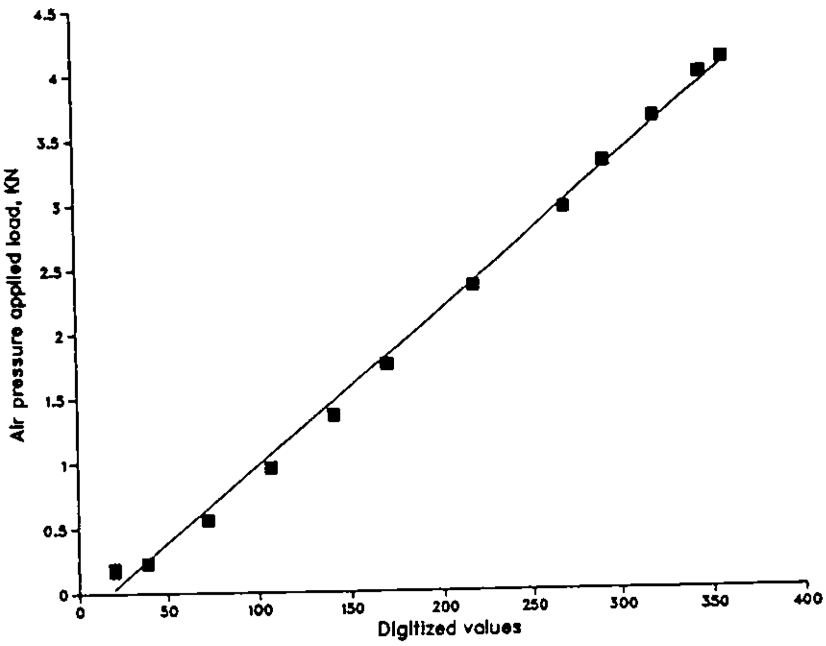


Fig. 5.10 Calibration of the load cell

Calibration of the load cell no.420/450 kgf



Calibration of the load cell no.420/450 kgf

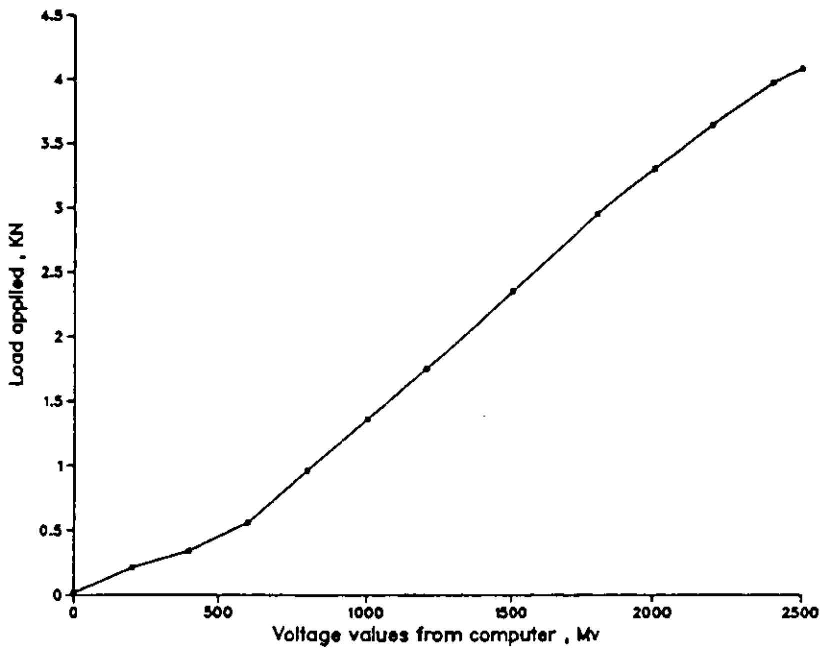


Fig. 5.11 The load plotted against voltage values and digitized values

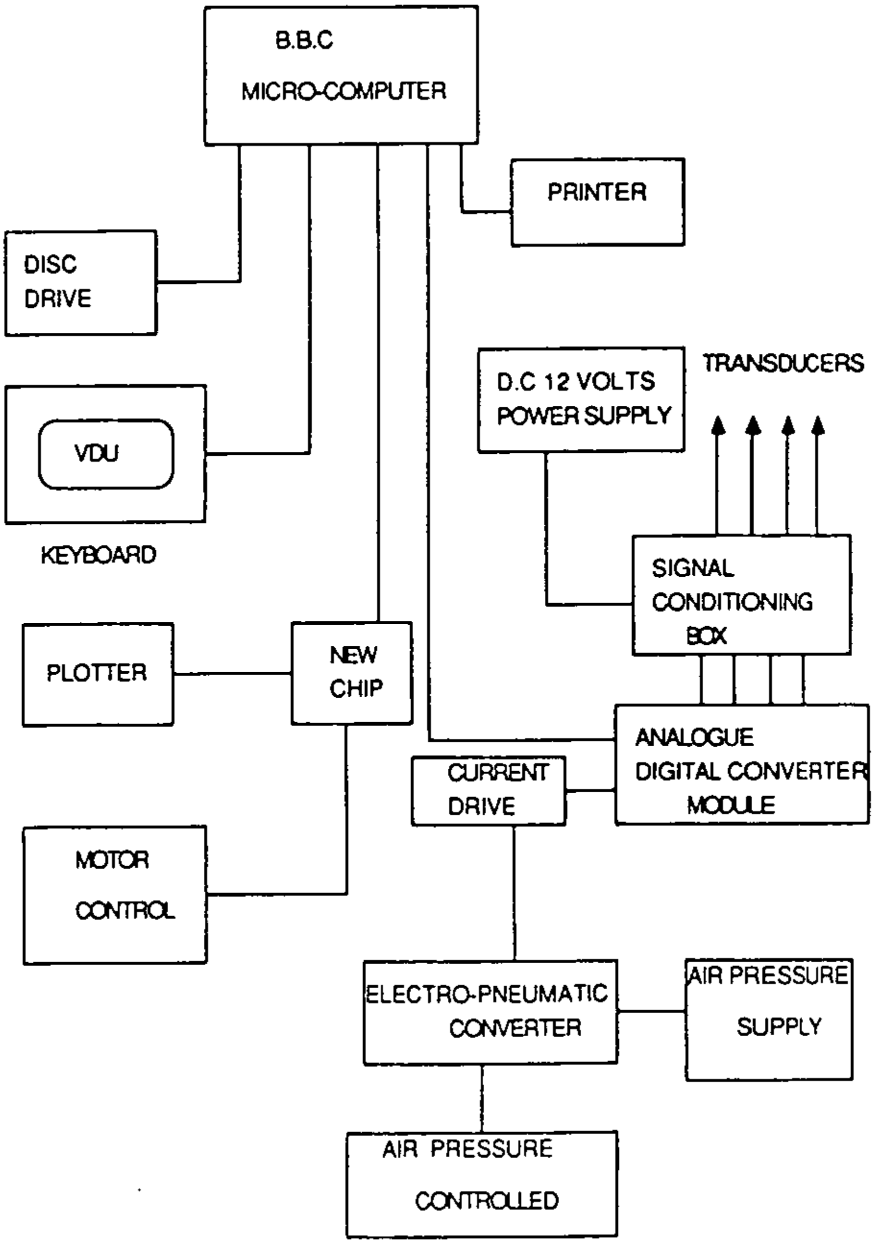
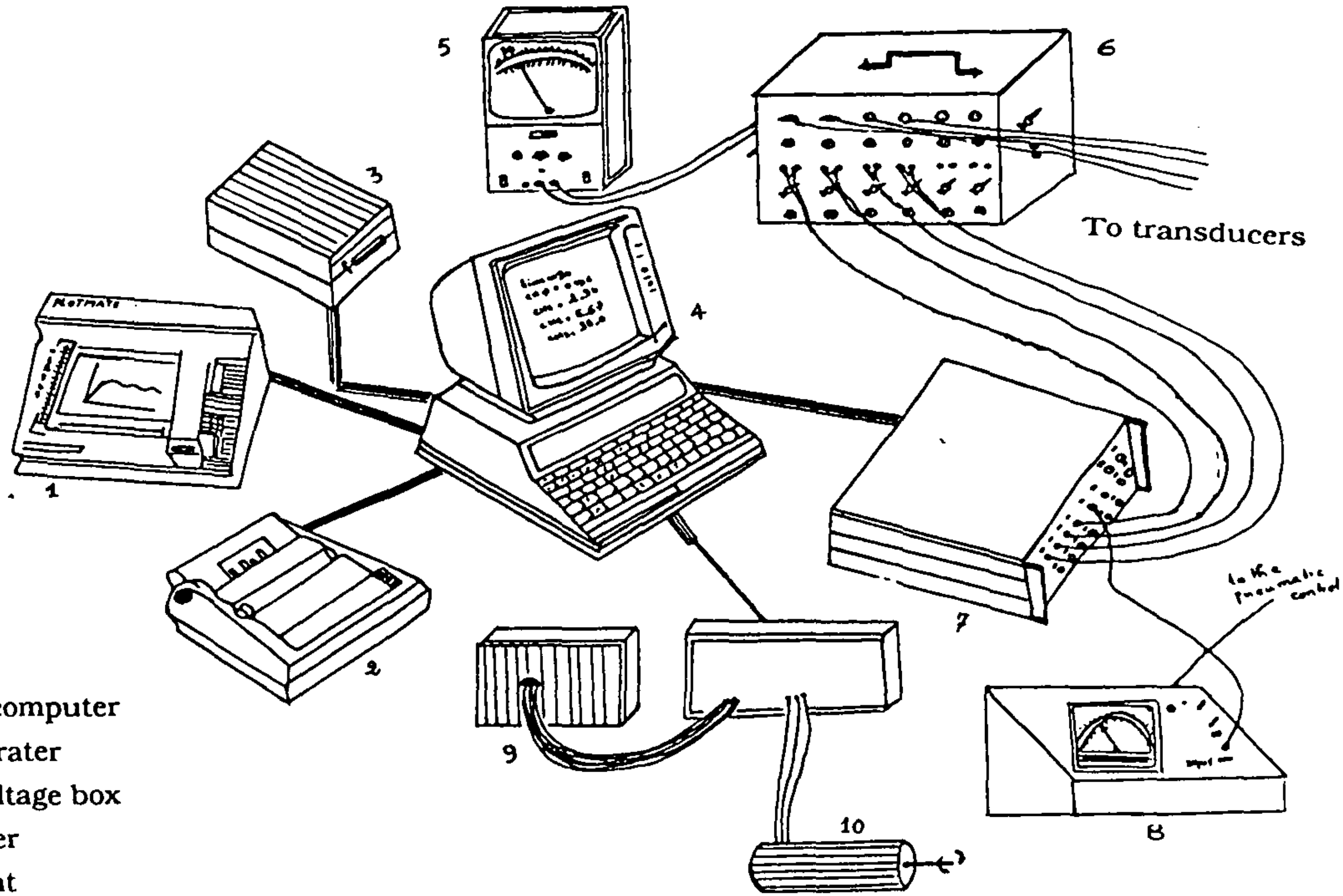


Fig. 5.12 Schematic layout of computer control and data logging equipment.



1 - Plotter
2 - Printer
3 - Disc drive
4 - B.B.C microcomputer
5 - Voltage generater
6 - Stabilised voltage box
7 - A/D converter
8 - Drive current
9 - Motor generater
10 - Motor

Fig. 5.13 General layout of the automated shearbox

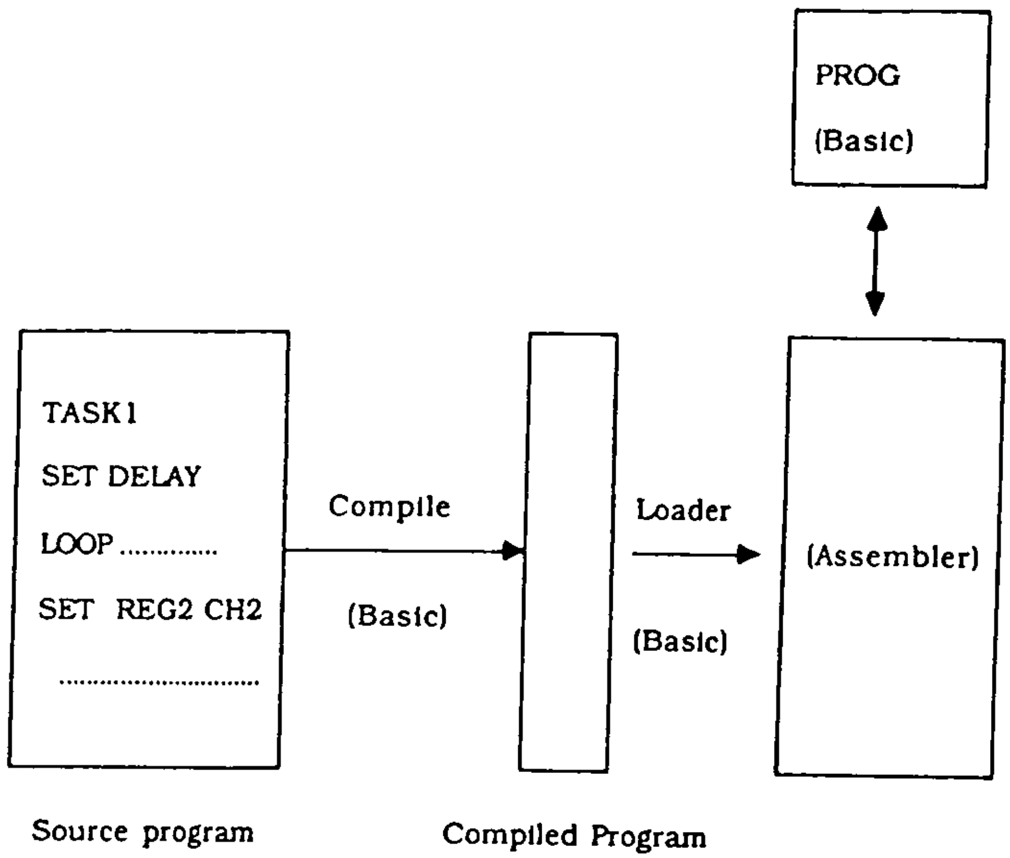


Fig. 5.14 Text instructions between the main parts of the program

CHAPTER SIX

EXPERIMENTAL PROGRAMME

6.1 Description of the materials used

The soil samples used in this investigation were three Algerian clays, termed Kaolin1, Kaolin2 and Kaolin3, and three British clays, London clay, Lias clay and Keuper Marl. These soils are described in the following sections. Two interfaces are used in this study (see Figure 6.1). The normal load during consolidation for all the tests was applied in stages to avoid squeezing of the relatively liquid sample through the gap between the two halves of the box.

6.1.1 London clay

The London clay was deposited under marine conditions during the Eocene period about 30 million years ago, and was overlain by the Claygate Beds, and the Bagshot, Brachlisham and Barton Beds. Since mid-Tetiary times, up-lift and erosion have removed these overlying deposits together with the upper layers of the London clay Skempton(1961).

In some localities, the London clay has been covered by the flood plain gravels of the River Thames or by March clays of postglacial Age. The London clay has a characteristic dark blue-grey colour, but the upper 6 to 9 metres has been oxidised and has a typical brown colour. No sharp junction between the weathered and unweathered clay exists, and no abrupt change in mechanical properties has been observed. The tendency is for the strength to decrease, water content to increase and intensity of fissuring to increase as ground level is approached.

The London clay used in this investigation was obtained from a site in Essex. Block samples were taken from the base of a trench at depths of between 2 and 3 metres, and consisted of a brown, firm clay. The soil classification and properties of London clay are given in Table 6.1. The clay mineralogy of the London clay was dominated by Smectite, Illite, Mica and Chlorite see Table 6.7.

6.1.2 Lias clay

The block sample of blue-grey Lias clay were taken from a limestone quarry near Southam in southern Warwickshire. The blue-grey deposit was very hard, and extreme difficulty has been encountered in preparing satisfactory undisturbed samples for testing due to the tendency for the material to "open" along the bedding planes. It consists mainly of clays and shales with occasional bands of limestone and irronstone. Block samples were taken from depths of between 12 and 15 metres below ground level. The soil classification and properties of this Lias clay are given in Table 6.2. The clay mineralogy consists of Illite, Mica, Kaolinite and Chlorite, the most dominant being Illite and Mica (see Table 6.7).

6.1.3 Keuper Marl

Keuper Marl is the name given to a particular series of rocks laid down in north west Europe and the British Isles in the late Triassic period. There are a variety of rock types encountered in the Keuper Marl series these include :

1) The evaporites - precipitated mineral salts such as rock salt, Gypsum and Anhydrite.

2) The sandstones - occasional beds varying in thickness from a few millimetres to several tens of metres.

3) The calcareous mudstones.

4) The red-brown to green shales and mudstones traditionally known as the "true" Keuper Marl (through only rarely possessing enough calcium to merit the name of Marl, which is by definition a calcareous shale or mudstone).

The Marl is a heavily over-consolidated deposit with a total thickness of over 600 metres and a cover of Jurassic and cretaceous sediments which perhaps reached another 1200 metres in some areas prior to the pre-Tertiary erosion period. The Marl now exposed in central England must have been subject to a pressure from between 1200 and 1800 metres of overburden. The Marl is usually massively-bedded, breaking along joints and fissure-planes with a stachy fracture. The Keuper Marl used in this study was originally obtained in powdered form from a local supplier. It was fed through a rotary classifier to seperate out all particles larger than silt size (0.063mm). These were discarded and the residual material was stored in plastic bins until required. The material is red-brown in colour. The classification and properties of Keuper Marl are given in Table 6.3. Despite the clay mineralogy observed in Keuper Marl deposits, it has been found, in a survey of samples taken from locations scattered over England and Wales, that over 95% of these samples occur in the mineral suite Illite, Corrensite, carbonates, Quartz and Haematite, with a trace of Chlorite. Samples falling within this suite have been shown to obey the Gibbs's phase rule, suggesting chemical equilibruim. The clay mineralogy compositions using X-ray diffraction shows that the Keuper marl used in this study has Chlorite as the dominant mineral with traces of Illite and Mica (see Table 6.7).

6.1.4 Kaolin1, Kaolin2 and Kaolin3

These three kaolin samples were obtained from an area which is situated in the east of Algeria, north Africa.

They were obtained from the same general area, with a distance of approximately between 700 and 800 metres seperating each sample site. These materials are used for the manufacture of pottery and were removed from a kaolin quarry. Kaolin1 and Kaolin 2 are similar, both being white in colour, soft and smooth. However, kaolin3 is between blue and black in colour, is hard and it looks as though it was formed from residual rocks and silts. The soil classification and properties are given in Tables 6.4,6.5 and 6.6. The clay mineralogy of all the Algerian clays was dominated by Kaolinite with few traces of Illite and Mica(see Table 6.7). Figure 6.1 shows the six clays used in this study. The standard soil classification tests were carried out in accordance with B.S 1377 : 1975, the pipette method being used to determine the particle size distribution.

6.1.5 X-ray diffraction laboratory test

In order to identify the mineralogy of the clay samples, investigation of clay materials by X-ray diffraction has been carried out in the Geology Department of Leicester University. The procedure used was as follows.

The sample was disaggregated and the < 2 micon clay component was seperated off by gravity sedimentation in a solution of soduim hexametaphosphate. A 20g sample of the clay material was placed in a 250 ml beaker, approximately 200 ml of de-ionised water was added and 5% Na-hexametaphosphate solution was added using a dropping pipette. After stirring well to disaggregate the clay, the material was left for 15 minutes before being stirred again and allowed to settle for 4 hours. 5 cm of the top layer of the suspension, which should contain the <2 micron clay fraction, was removed. The clay fraction was centrifuged for 10 minutes at 3000 rpm and the excess water was decanted to recover a slurry. Just sufficient de-ionised water was then added to allow the transfer of a layer of slurry to surface of a glass slide with a dropping pipette. The glass slides were allowed to air dry at room temperature. Three diffractometer traces were obtained from the material on the same slide to allow for complete identification of the clay components. The three traces were obtained from the following samples.

a) Air-dried slide, as prepared above.

b) Glycolated sample. The air-dried slide was placed in a desiccator with ethylene glycol and held at 70 degrees Centigrade overnight (or at 100 degrees Centigrade for 2 hours).

c) Heat-treated sample. The previously glycolated slide should be held a 55 degrees Centigrade for 2 hours.

Traces were drawn with different coloured pens and superimposed on one another by rewinding the chart. From the peaks shown on the graph, determination of the clay minerals was obtained, see Figures 6.2 and 6. 3.

6.2 Tests on the six clays using the modified shearbox

The first tests were carried out on the six clays using the modified shearbox under normally consolidated conditions. When preparing the specimens for testing in the modified shearbox, the samples were first sieved through a 425 micron sieve and then mixed with water to a value near the liquid limit. After mixing the sample and leaving it for a few minutes to come to equilibrium, it was placed into the 100 mm square mould of the box. The two halves of the shearbox were then assembled as shown in Figure 6.6, with porous stones above and below the specimen.

A gentle pressure on the upper porous stone forced the sample into the correct location for testing. The required normal stress was applied using the computer control and the specimen was left to consolidate until equilibruim conditions were reached. During the consolidation period, measurement of vertical displacement with time were made at time intervals specified by the BBC micro-computer.

In the majority of cases, it was found that very little further change in volume occurred after an interval of 24 hours. The normal stresses applied to each clay were 100, 150, 200 and 400 kPa, each test being carried out on a fresh sample. The shearing stage was not usually commenced until an interval of 16 hours had elapsed.

When consolidation was complete, the upper half of the shear box was raised slightly using the two screws provided. The position of the transducers were then adjusted until the arms of the transducers were just in contact with the shearbox. The motor was then engaged, the rate of shear was fixed to 0.01588 mm/min, a value that was found by preliminary tests to ensure drained conditions throughout the test. Frequent readings of the shear load, horizontal displacement and vertical displacement were recorded simultaneously with the time. After completing the first cycle with a displacement of approximately 10 mm, the box returned automatically to its starting position at the same rate of shear and the procedure of forward shearing was repeated. The reversal technique was continued until a steady shear stress was recorded on two consecutive travels. This was taken as being the residual value. Generally the shearing was stopped after 5 cycles. These tests were carried out to determine the peak and residual strength parameters for each sample and to define the Mohr-Coulomb failure envelope.

6.3 Interface tests

An extensive programme of tests was conducted to examine the peak and residual strength, and to study the stress-displacement behaviour, of the six clays when sheared alone and against two plane interfaces. Every clay was sheared against Rock(sandstone) and against glass. The test procedure followed the standard technique described above with slight modifications. The shearbox was assembled in the testing machine, with the rock in the bottom half and the clay placed in the top half of the box. A porous stone was placed above the specimen and below the rock and gentle pressure on the upper porous stone forced the specimen into the correct position for testing. The loading head was then assembled. Figure 6.7 shows the assembly of the 100 mm shearbox for clay-rock tests. The normal stress was applied throughout the test using the BBC micro-computer and the sample was sheared with the rate of shear fixed to 0.015873 mm/min for both forward or backward shear cycles. For the tests against glass, the procedure of testing was the same except that smooth plate glass instead of rock was located in the bottom half of the box. Figure 6.8 shows the assembly of 100 mm shearbox for clay-glass interface tests. After five complete cycles of shear, the drive was dismantled and the surrounding water in the water bath was drained. The normal stress was removed automatically by the computer, the shearbox was disassembled and excess moisture removed prior to studying the shear surface.

A primary purpose of this study was to investigate the residual strength of the interfaces and their relative residual strength compared to the clay alone. For this reason the tests were carried out using the same rate of shear and the same normal stresses. These tests have an application in the study of the intercallation between hard rock layers, where the problem of zones of weakness in rock masses is significant. Such a problem can occur in natural and artificial slopes, open cuts and excavations, foundations and abutments of dams, and underground openings.

6.4 Bromhead ring shear tests

In this study , tests were carried out using both the Bromhead ring shear and the modified shearbox, to study the shear strength of soils at large strains on the one hand, and the shear strength of interfaces on the other hand. The shear strength measured in all tests is discussed in terms of effective stresses. Accordingly tests were made using the Bromhead ring shear apparatus to examine the residual shear strength and stress-displacement behaviour of these six clays. The apparatus has got two major advantages. There is no change in the area of cross-section of the shearbox plane as the test proceeds and the sample can be sheared through an uninterrupted displacement of any magnitude.

A remoulded sample of the clay being tested was kneaded evenly into the annular cavity between the confining rings using a small spatula. The moisture content of the sample tested was near to its liquid limit. The excess soil was struck off level with the top of the confining rings and the loading assembly was placed in position using the locating studs in the turret. The centring pin, which locates the upper platen over the specimen, was lightly greased or oiled before fitting the upper platen onto the apparatus.

The confining rings were designed to be small enough to prevent loss of soil by squeezing. The loading yoke was then positioned on the upper platen and adjusted such that top of the counter balance lever was horizontal. The vertical dial gauge was then brought into position to bear on the top of the load hanger assembly.

The normal effective stress under which the sample was to be consolidated was then applied using the load hanger. The weight necessary to produce the required normal stress was found from the following equation.

$$\sigma'_n \ (KN/m^2) = (98.1W \ X \ 981000)/(R_2^2 - R_1^2)$$

where

W Hanger load (Kg)

R_1 Inside raduis sample (mm)

R_2 Outside raduis of sample (mm)

The water bath was completely filled, which served to prevent the sample from drying out during testing, and the vertical dial gauge read. The lower arm stop was then lowered and a stop clock was started. The proving rings were aligned such that a right angle is made between the torque arm of the upper platen and the axis of each proving ring. A rate of displacement of 0.17808 mm/min was used for all of these tests. The average shear stress (KN/m^2) was found using

$$\tau \ (KN/m^2) = (3(A+B).L.P_f X10^3)/(12.56(R_2^2 - R_1^2))$$

where

A Proving ring A dial gauge reading

B Proving ring B dial gauge reading

L distance between proving rings

R_1 Inside sample raduis (mm)

R2 Outside sample raduis (mm)

P_f Proving ring factor (N/Div.)

6.5 Tests on London clay and Lias clay to investigate the effect of normal stress

A series of tests was carried out to investigate the effect of the normal stress on the residual shear strength. The shearbox has been criticized in the literature because of the problem of disturbing the shear zone during the reverse travel of the box. To investigate this London clay and Lias clay have been used.

One of the objective of these tests was to minimise the effect of sample disturbance on the residual shear strength. The sample was prepared in a wet state for both London clay and Lias clay. The sample was placed in the carriage and was consolidated to a normal effective stress of 200 kPa. The time allowed for consolidation was roughly 48 hours. A slow shearing rate of 0.00881 mm/min was used for the first backward cycle following which the normal load was reduced to zero without causing any disturbance to the sample. The upper half of the shearbox was quickly returned to its original position using a rate of shear of 0.03968 mm/min. Prior to being sheared again at a speed of 0.00881 mm/min, the normal stress was then applied again, the sample was left for 4 hours to reconsolidate. These operations were repeated until sufficient displacement had accumulated to reach the residual conditions.
The variation of the rate of shear and normal stress for each cycle is presented in Table6.8.

6.6 Tests on London clay and Lias clay to investigate the effect of rate of shear on residual shear strength

The rate of shear plays a great role in the explanation of slope movement and the mechanism which occurs during any failure or instability problem. In this study two modified shearbox tests have been carried out to study the influence of rate of shear on London clay and Lias clay. Rate effects were investigated by varying displacement rates for every backward cycle, by increasing the rate of shear during each subsequent cycle, with a slow constant rate of shear for every forward cycle until residual conditions were established. The clay was prepared in a wet state near the liquid limit. It was placed in the box in the conventional way with a thickness of 20 mm. It was first consolidated at a normal stress of 50 kPa before two more consolidation stages were carried out to reach normal stresses of 100 kPa and then 200 kPa. The time between these normal stress applications was about 30 minutes. It was decided not to apply the normal stress of 200 kPa directly to avoid squeezing of the relatively liquid sample through the gap between the two halves of the box. In addition the particles were allowed to adjust themselves and the dissipation of water was allowed to take its normal course. After the consolidation stage was complete, a slow shear rate was applied of 0.00881 mm/min for a shear displacement of 10 mm for the first backward cycle. For the first forward cycle the box was returned with the same rate of shear of 0.00881 mm/min. (The various stages of the test can be followed in Table 6.3). For the second cycle of the test, the rate of shear was changed to 0.01321 mm/min for the backward cycle, a higher rate than the previous backward cycle. For the second forward cycle the rate of shear was unchanged at 0.00881 mm/min. This rate was maintained for every forward cycle, this slow rate of shear being applied in order to re-establish residual conditions. The rate for subsequent backward cycles was increased to 0.019822 mm/min for the third, 0.029733 mm/min for the fourth and 0.039680 mm/min for the final five cycles. The variation of the rate of shear for each cycle is presented in Table 6.9.

6.7 Vibrationary loading tests

The influence of fast rates of displacement, in which vibrations are created during the tests, must be considered in the study of seismic slope stability, machine foundations and other phenomena such as the strength of shear zones on the sides of piles which are formed by pile driving (Martins and Potts, 1985). In this study, tests were carried out using rapid undrained shearing, before the samples were subjected to slow displacement rates in the modified shearbox. In each case the clays were sheared against a plane sandstone rock surface. These tests were divided into two parts.

6.7.1 Vibrationary loading tests for 200 cycles of vibration

The aim of these tests was to provide preliminary information and subsequently to define as well as possible the effect of vibrations. The question of speed effects in relation to the measurement of both peak and residual shear strength was investigated. In order to apply this very fast shear rate, the reduction gear was disconnected, the cogs were removed, and the motor was directly attached to the shaft of the worm drive (see figure 6.5). No results were recorded during high speed shearing. The idea behind the high speed is just to shake the sample before slow shearing takes place. These tests have been carried out on all six clays. The samples were prepared in a wet, remolded state. The 100 x100x15 mm sandstone rock was placed in the bottom half of the shearbox and the clay sample was placed in the upper half over the sandstone rock block following the standard procedure. After the assembly of the shearbox, the sample was consolidated at a normal effective stress of 50 kPa, followed by further consolidation stages under normal stresses of 100 kPa and 200 kPa . Consolidation took 48 hours, which was enough to bring the pore pressure into equilibruim. After this the sample was sheared at a rate of 53 mm/min for 200 cycles(both forward and backward) with a travel of 10 mm. The test was then stopped for a period of 4 hours before a slow rate of shear of 0.00881 mm/min was applied. This rate of shear was comparatively very slow to ensure fully drained conditions. This rate of shear was mainained until the residual condition was established, generally after 5 cycles.

6.7.2 Vibrationary loading tests for 2000 cycles of vibration

In nature, residual shear strength conditions are reached as a result of large uni-directional deformations. In the shearbox large deformations can only be achieved by cumulative small deformations in opposite directions. The object of these tests are to provide information on the effects of quick vibrations. For this purpose six tests were carried out using the same method as for the tests shown in section 6.7.1. After the consolidation stage, the shearing rate was fixed to 53 mm/min for 2000 cycles, which is 10 times more than the previous tests, but with a length of travel of the shearbox fixed to 1mm instead of 10mm. The tests were stopped for a period of 4 hours and the rate of shear was changed to 0.00881 mm/min as before, for which the reduction gear and the cogs were replaced again (see Figure 6.4). This rate was maintained until 5 cycles had been accomplished. All the tests carried out in this study are summarized in Table 6.8.

London clay

Specific Gravity		2.75
Liquid Limit		87%
Plastic Limit		31%
Plasticity Index		56%
Activity (PI/CF)		1.43
Organic Content		
Classification	**%**	**Particle size (μm)**
Sand	4	> 63
Coarse Silt	15	20 - 63
Meduim Silt	4	6 - 20
Fine Silt	38	2 - 6
Clay	39	< 2

Table 6.1 Properties of London clay

Lias clay

Specific Gravity		2.50
Liquid Limit		45%
Plastic Limit		27%
Plasticity Index		18%
Activity (PI/CF)		0.54
Organic Content		
Classification	%	Particle size (μm)
Sand	1	> 63
Coarse Silt	26	20 - 63
Meduim Silt	8	6 - 20
Fine Silt	32	2 - 6
Clay	33	< 2

Table 6.2 Properties of Lias clay

Keuper Marl

Specific Gravity		2.80
Liquid Limit		35%
Plastic Limit		17%
Plasticity Index		18%
Activity (PI/CF)		0.66
Organic Content		
Classification	%	Particle size (μm)
Sand	12	> 63
Coarse Silt	26	20 - 63
Meduim Silt	12	6 - 20
Fine Silt	23	2 - 6
Clay	27	< 2

Table 6.3 Properties of Keuper Marl

Kaolin 1

Specific Gravity		3.20
Liquid Limit		104%
Plastic Limit		48%
Plasticity Index		56%
Activity (PI/CF)		0.98
Organic Content		
Classification	%	Particle size (μm)
Sand	2	> 63
Coarse Silt	9	20 - 63
Meduim Silt	11	6 - 20
Fine Silt	21	2 - 6
Clay	57	< 2

Table 6.4 Properties of Kaolin 1

Kaolin 2

Specific Gravity	2.69
Liquid Limit	86%
Plastic Limit	49%
Plasticity Index	37%
Activity (PI/CF)	1.60
Organic Content	

Classification	%	Particle size (μm)
Sand	35	> 63
Coarse Silt	2	20 - 63
Meduim Silt	28	6 - 20
Fine Silt	12	2 - 6
Clay	23	< 2

Table 6.5 Properties of Kaolin 2

Kaolin 3

Specific Gravity	2.60
Liquid Limit	57%
Plastic Limit	36%
Plasticity Index	21%
Activity (PI/CF)	1.61
Organic Content	

Classification	%	Particle size (μm)
Sand	42	> 63
Coarse Silt	26	20 - 63
Meduim Silt	10	6 - 20
Fine Silt	9	2 - 6
Clay	13	< 2

Table 6.6 Properties of Kaolin 3

Sample	Mineralogy composition in dominant order
Kaolin 1	Kaolinite (ordered layers) Illite/Mica (very little)
Kaolin 2	Kaolinite (better ordered layers) Illite/Mica (very little)
Kaolin 3	Kaolinite (poorly ordered layers) Illite/Mica (more in comparison to Kaolin 1 and Kaolin2)
London clay	Smectite Illite/Mica Chlorite
Lias clay	Illite/Mica Kaolinite Chlorite
Keuper Marl	Chlorite Illite/Mica

Table 6.7 Clay mineralogy compositions using X-ray diffraction

	Rate of shear forward (mm/min)	Rate of shear backward (mm/min)	Normal stress forward kPa	Normal stress backward kPa
1) Cycle	0.00881	0.03968	200	0
2) Cycle	0.00881	0.03968	200	0
3) Cycle	0.00881	0.03968	200	0
4) Cycle	0.00881	0.03968	200	0
5) Cycle	0.00881	0.03968	200	0

Table 6.8 The variation of rate of shear and normal stress for each cycle

	Rate of shrear backward (mm/min)	Rate of shear forward (mm/min)
First cycle	0.00881	0.00881
Second cycle	0.01321	0.00881
Third cycle	0.019822	0.00881
Fourth cycle	0.029733	0.00881
Fifth cycle	0.039680	0.00881

Table 6.9 The rate of shear for each cycle

Test No	Normal stress Kpa	Interface type	Rate of shear mm/min	Duration of test Days
Lo Lo	100,150 200,400	London clay London clay	0.015873	20
Li Li	100,150 200,400	Lias clay Lias clay	0.015873	20
Ke Ke	100,150 200,400	Keuper marl Keuper marl	0.015873	20
K1 K1	100,150 200,400	Kaolin 1 Kaolin 1	0.015873	20
K2 K2	100,150 200,400	Kaolin 2 Kaolin 2	0.015873	20
K3 K3	100,150 200,400	Kaolin 3 Kaolin 3	0.015873	20
Lo R	100,150 200,400	London clay Rock	0.015873	20
Li R	100,150 200,400	Lias clay Rock	0.015873	20
Ke R	100,150 200,400	Keuper Marl Rock	0.015873	20
K1 R	100,150 200,400	Kaolin 1 Rock	0.015873	20
K2 R	100,150 200,400	Kaolin 2 Rock	0.015873	20
K3 R	100,150 200,400	Kaolin 3 Rock	0.015873	20
Lo G	100,150 200,400	London clay Glass	0.015873	20
Li G	100,150 200,400	Lias clay Glass	0.015873	20
Ke G	100,150 200,400	Keuper Marl Glass	0.015873	20
K1 G	100,150 200,400	Kaolin1 Glass	0.015873	20

Table 6.10 Plan of tests

Test No	Normal stress kPa	Interface type	Rate of shear (mm/min)	Duration of test Days
K2 G	100,150 200,400	Kaolin 2 Kaolin 2	0.015873	20
K3 G	100,150 200,400	Kaolin 3 Kaolin 3	0.015873	20
BRS Lo	100,150 200,400	London clay London clay	0.17808	5
BRS Li	100,150 200,400	Lias clay Lias clay	0.17808	5
BRS Ke	100,150 200,400	Keuper Marl Keuper Marl	0.017808	5
BRS K1	100,150 200,400	Kaolin 1 Kaolin 1	0.017808	5
BRS K2	100,150 200,400	Kaolin 2 Kaolin 2	0.017808	5
BRS K3	100,150 200,400	Kaolin 3 Kaolin 3	0.017808	5
Lo Lo	200	London clay London clay	Forward: 0.00881, 0.01321, 0.019822, 0.029733, 0.039680 Backward : 0.00881	6
Li Li	200	Lias clay Lias clay	Forward: 0.00881, 0.01321, 0.019822, 0.029733, 0.039680 Backward : 0.00881	6
Lo Lo	Forward 0 kPa Backward 200 kPa	London clay London clay	Forward 0.03968 Backward 0.00881	8
Li Li	Forward 0 kPa Backward 200 kPa	Lias clay Lias clay	Forward 0.03968 Backward 0.00881	8

Test No	Normal stress kPa	Interface type	Rate of shear (mm/min)	Duration of test Days
Lo R	200	London clay Rock	53 mm/min for 200 cycles and then fixed to 0.00881	9
Li R	200	Lias clay Rock	53 mm/min for 200 cycles and then fixed to 0.00881	9
Ke R	200	Keuper Marl Rock	53 mm/min for 200 cycles and then fixed to 0.00881	9
K1 R	200	Kaolin1 Rock	53 mm/min for 200 cycles and then fixed to 0.00881	9
K2 R	200	Kaolin2 Rock	53 mm/min for 200 cycles and then fixed to 0.00881	9
K3 R	200	Kaolin3 Rock	53 mm/min for 200 cycles and then fixed to 0.00881	9
Lo R	200	Rock London clay	53 mm/min for 2000 cycles and then fixed to 0.00881	9
Li R	200	Lias clay Rock	53 mm/min for 2000 cycles and then fixed to 0.00881	9
Ke R	200	Keuper Marl Rock	53 mm/min for 2000 cycles and then fixed to 0.00881	9
K1 R	200	Kaolin 1 Rock	53 mm/min for 2000 cycles and then fixed to 0.00881	9
K2 R	200	Kaolin 2 Rock	53 mm/min for 2000 cycles and then fixed to 0.00881	9
K3 R	200	Kaolin 3 Rock	53 mm/min for 2000 cycles and then fixed to 0.00881	9

Test Abbreviations :

Li Li	Lias clay sheared alone
Li R	Lias clay sheared against rock
Li G	Lias clay sheared against glass
BRS	Bromhead ring shear tests

Material Abbreviations :

Li	Lias clay
Lo	London clay
Ke	Keuper Marl
K1	Kaolin1
K2	Kaolin2
K3	Kaolin3

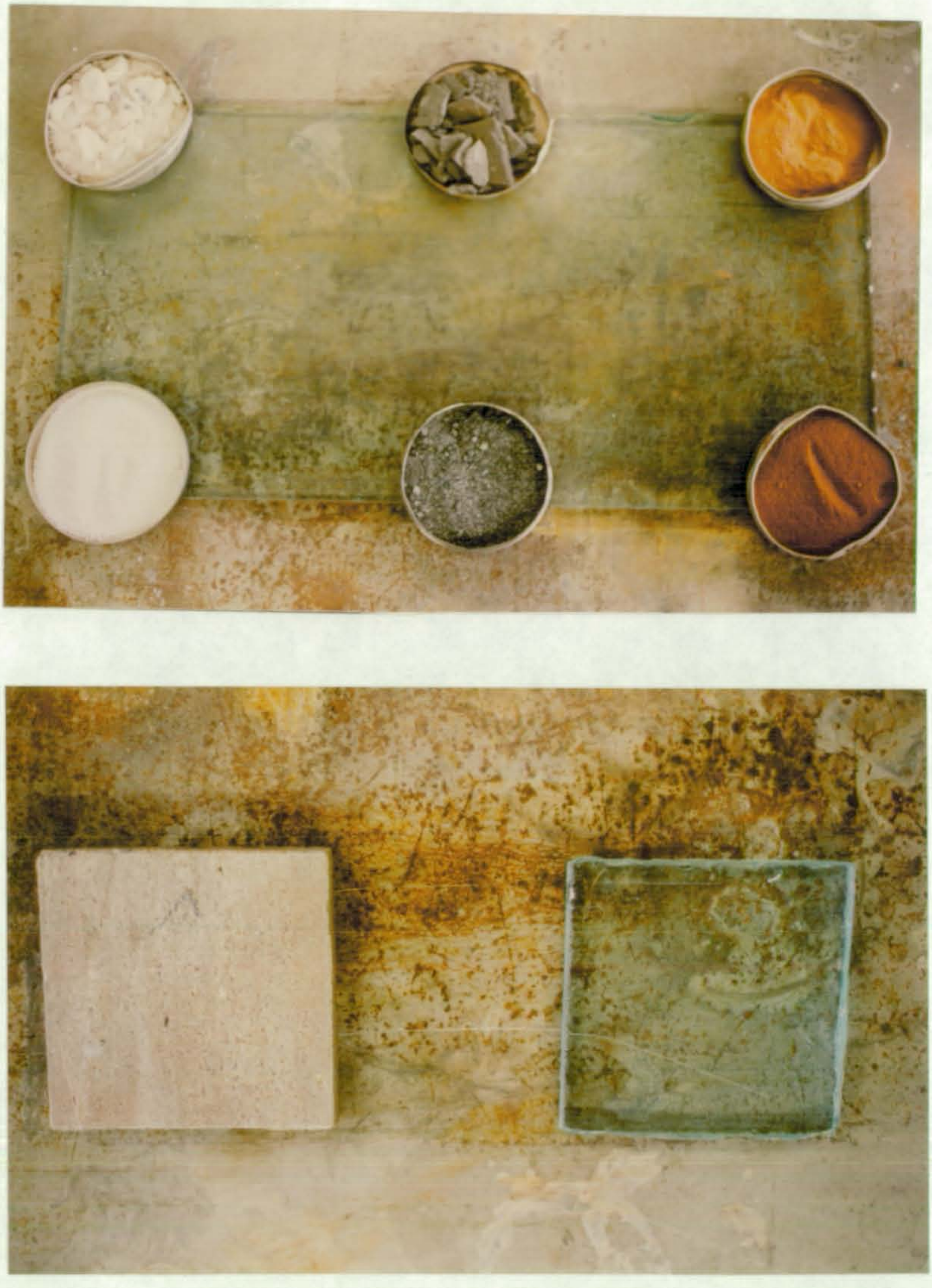


Fig. 6.1 Sample and interfaces used in this study

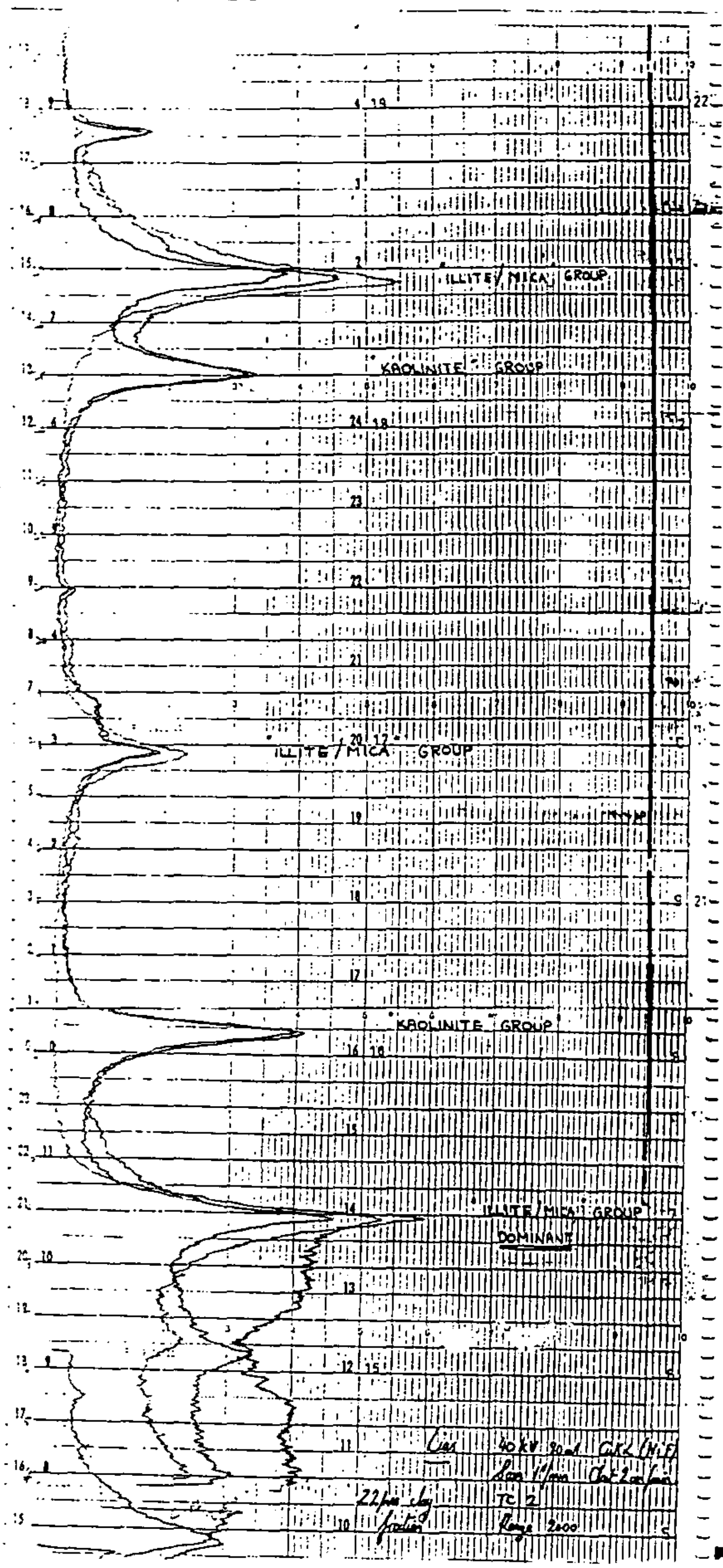


Fig. 6.2 X-ray diffraction mineralogy test for Lias clay

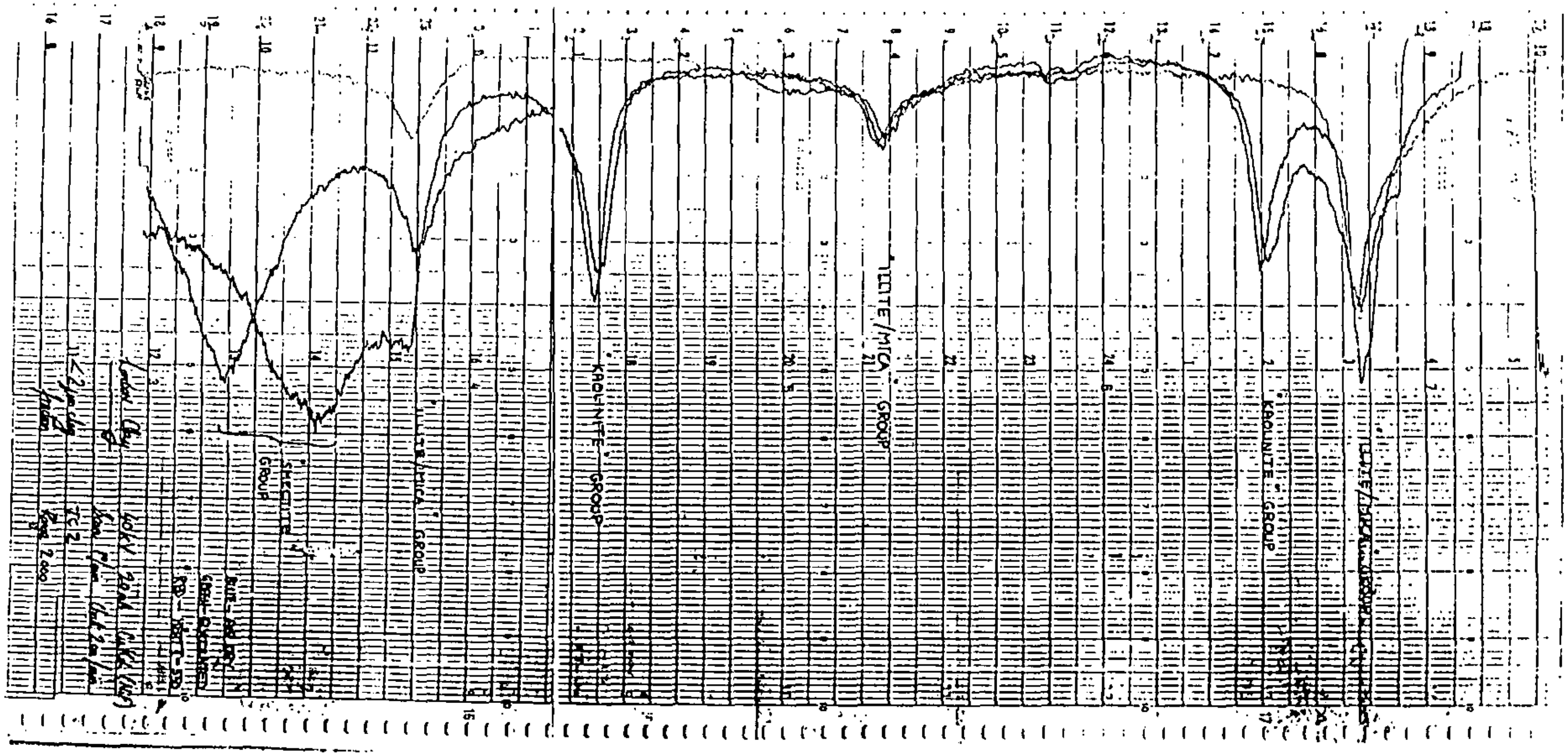


Fig. 6.3 X-ray diffraction mineralogy test for London clay

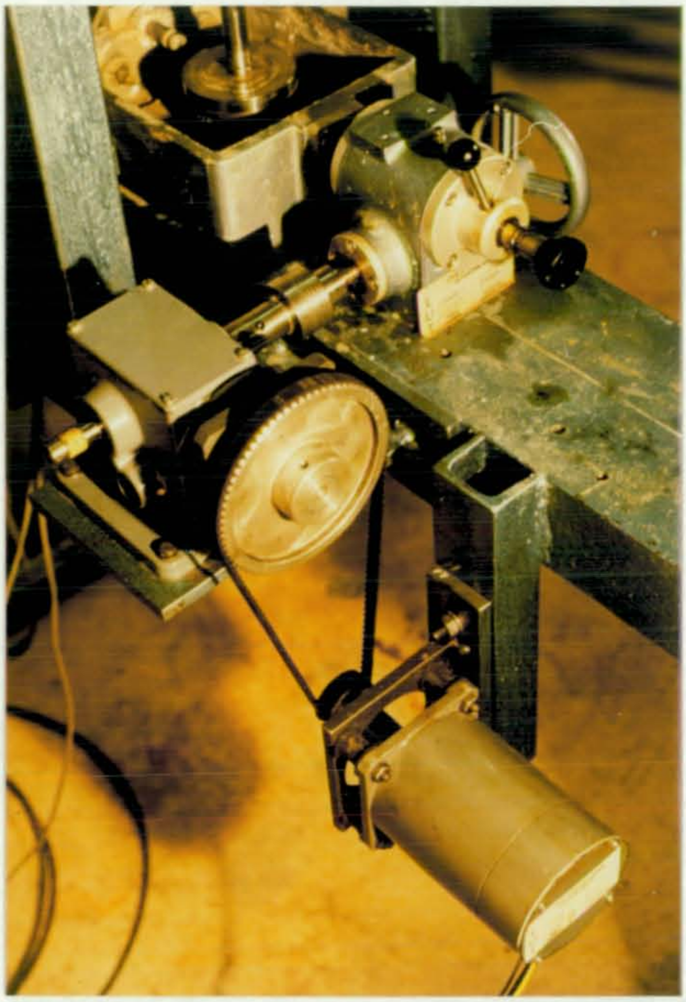


Fig. 6.4 Introduction of the reduction gear and cogs to reduce the vibrations

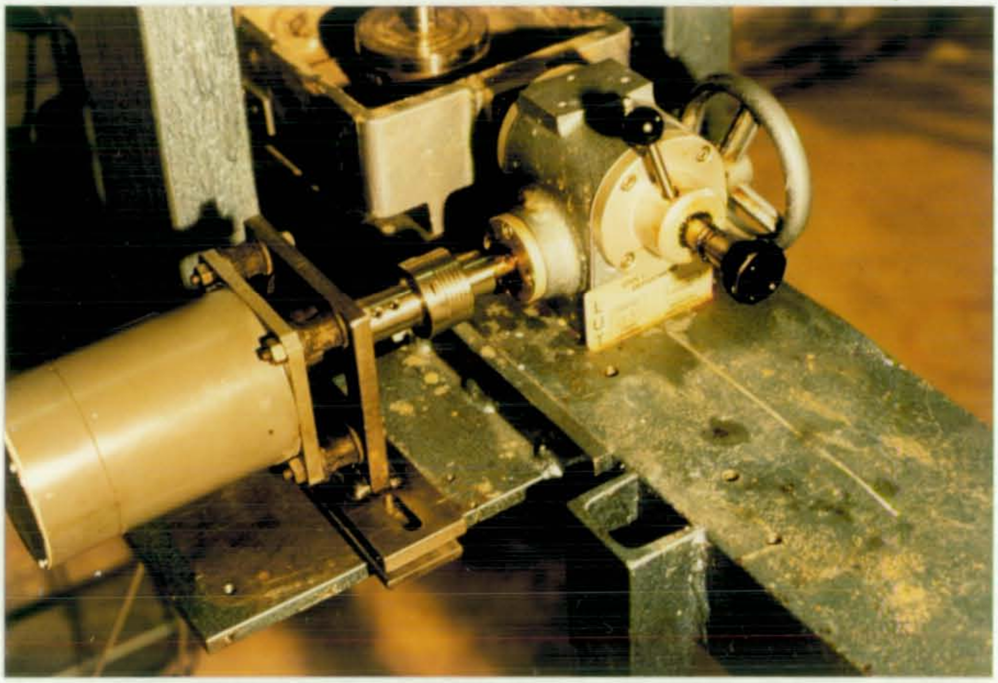


Fig. 6.5 Direct connection between the motor and drive unit

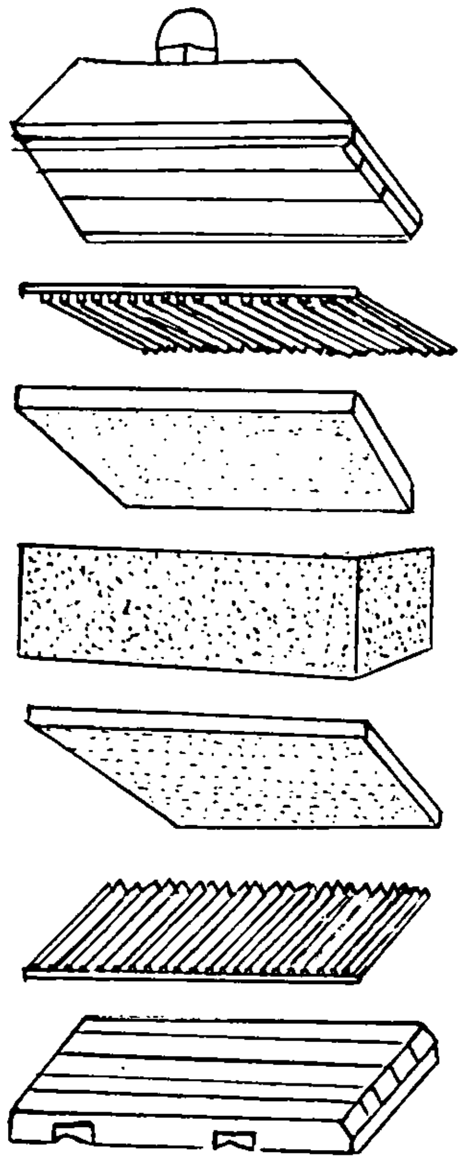


Fig. 6.6 Assembly of 100 mm shear box for clay-clay

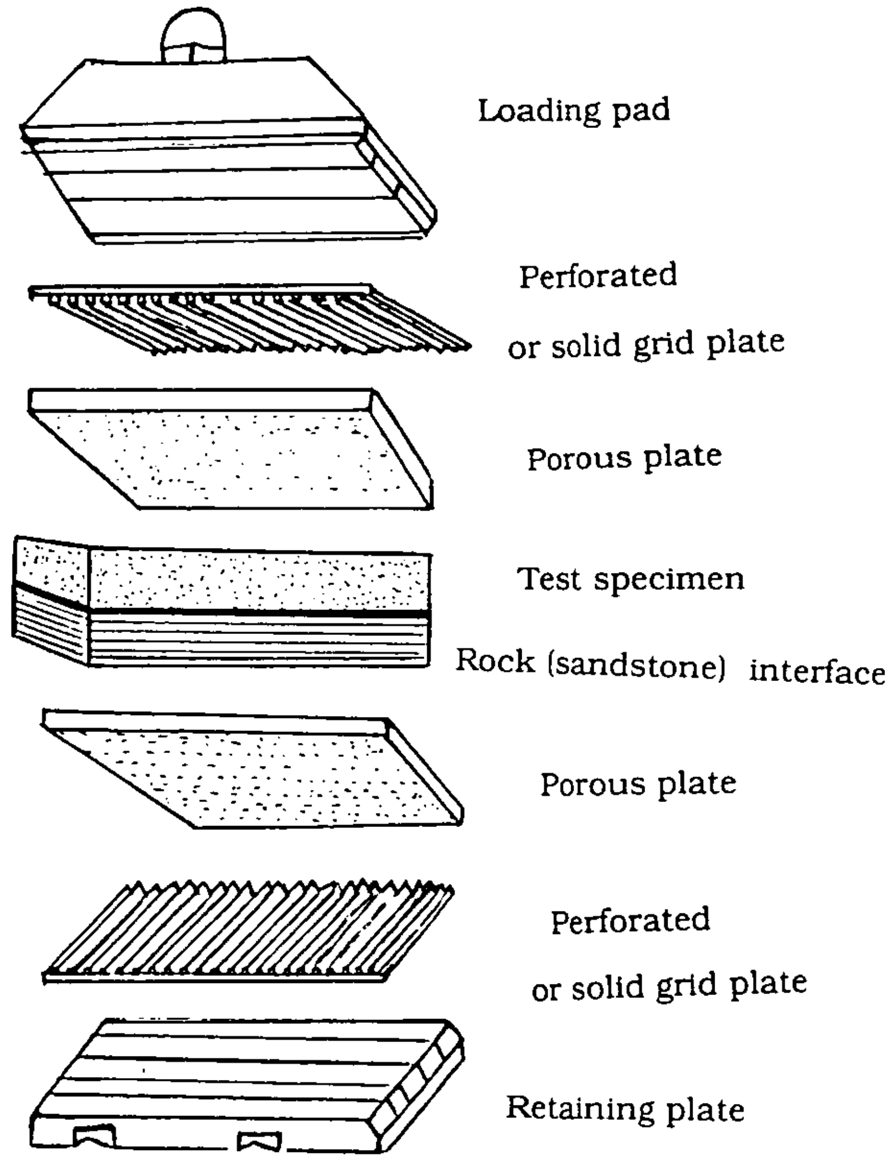


Fig. 6.7 Assembly of 100 mm shear box for clay-rock

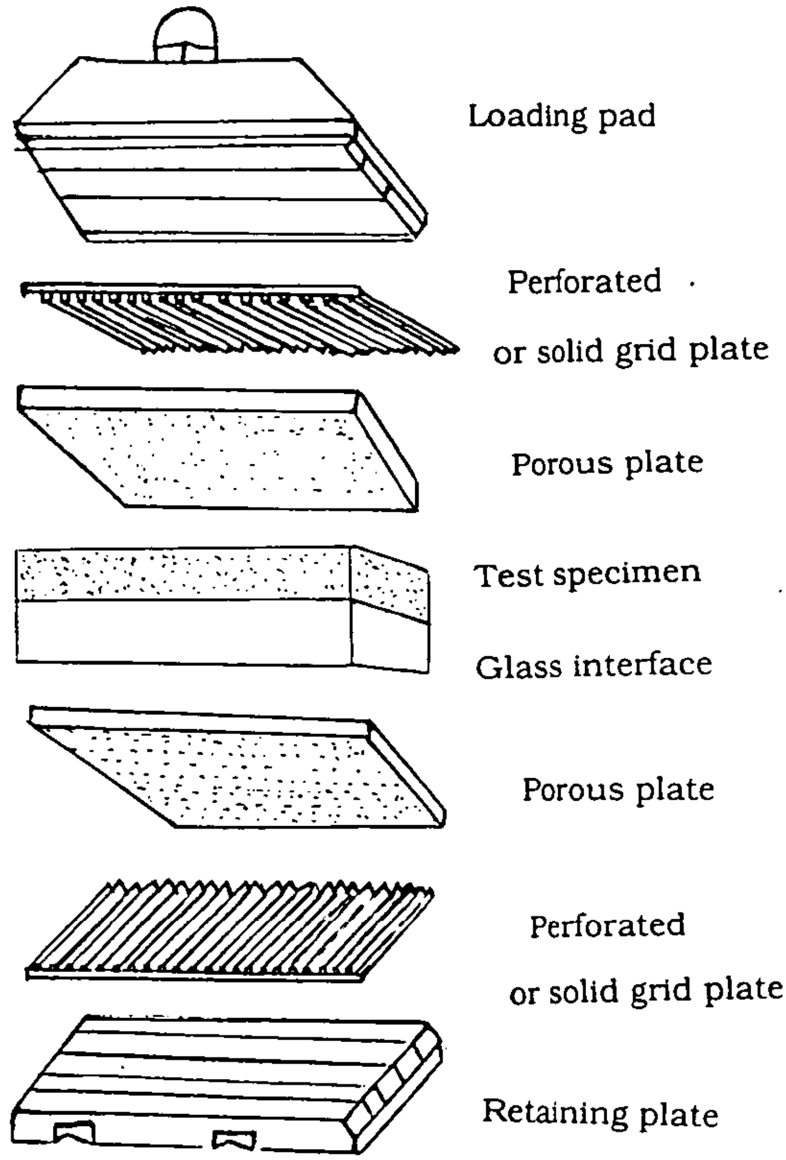


Fig. 6.8 Assembly of 100 mm shear box for clay-glass

CHAPTER SEVEN

EXPERIMENTAL RESULTS

7.1 Introduction

All tests were carried out under normally consolidated conditions, since it has been demonstrated by Bishop et al (1971) that the ultimate residual angle of shearing resistance is not significantly affected by the initial structure of the soil. The results from both the modified shearbox and the Bromhead ring shear tests are described in this chapter. The preliminary tests showed that the strain rate used ensured the drained conditions. As far as the repeatability concerned, some tests have been repeated twice with keeping the same conditions, only slight differences of the order of 4% was found.

7.2 Results of standard modified shearbox tests

The index properties of the six clays and their clay mineralogy are presented in chapter six. A summary of the results obtained from the standard modified shearbox tests is presented in Figures 7.1 to Figure 7.6. Typical stress-displacement curves, for Kaolin1 sheared alone, are shown in Figure 7.7. These results demonstrate the value of the modified shearbox in enabling the peak and residual strengths to be measured accurately. In Figure 7.7, it can be seen that on the first cycle the strength rises to the peak value at about 1.9 mm displacement and then gradually decreases with increasing displacement. During the second and third subsequent cycles the strength rises to a smaller peak and then falls rapidly after small displacements, with the fourth and fifth cycles indicating the approach and establishment of the residual conditions.

The value at the fifth cycle is taken therefore as the residual strength of Kaolin1 when sheared alone at the applied normal stress. The results of these tests are summarised in Tables 7.1 to 7.6.

7.3 Results of Bromhead Ring Shear Tests

The results of the Bromhead ring shear tests on the six remoulded clays are presented in Figure 7.8 to 7.13. The stress-displacement relationship for the test on Kaolin1 is shown in Figure 7.14, which clearly shows a marked drop from the peak strength at a displacement of less than 1.8 mm. However continued shearing results in a reduction of the shear strength until a displacement of approximately 140 mm, after which the strength remains constant up to 200 mm. Similar behaviour was observed in the other five tests, as shown in Figure 7.15, although the displacement at which ϕ'_p and ϕ'_r were established varied from one sample to another. The results of these tests are summarised in Tables 7.1 to 7.6.

7.4 Results of Interface tests

The results of the modified shearbox tests, in which the six clays were sheared against plane rock and plate glass surfaces, are presented in Figures 7.16 to 7.21. Figure 7.22 shows typical results of the tests with a rock interface, in this case for Kaolin1. It can be seen clearly from the figure that the values of peak and residual shear strengths are lower than the previous values shown in Figure 7.7. The curves are similar in shape, except for the drop in strength which occurs quickly after the peak strength has been reached. Figure 7.23 shows the results of the test of Kaolin1 sheared against glass, which were likewise typical, in which the recorded peak and residual strengths were smallest in comparison with the previous tests.

For good comparison between the results of all of these tests, it was decided to present all of the results for each clay tested using both the Bromhead ring shear and the modified shearbox on the same axes and these are shown in Figures 7.24 to 7.29 for peak strengths and 7.30 to 7.35 for residual strengths. The parameters defining the strength envelopes indicate that a difference exists between the strengths measured using the Bromhead ring shear and the modified shearbox techniques. Tests on Kaolin1 sheared alone showed the following peak and residual strengths expressed by parameters from the modified shearbox

$c' = 0.2$ kPa ; $\phi' = 15.4$ Degrees

$c'_r = 0$ kPa ; $\phi'_r = 11.8$ Degrees

whereas for Kaolin1 sheared in the Bromhead ring shear Bromhead

$c' = 2$ kPa ; $\phi' = 13.4$ Degrees

$c'_r = 0.3$ kPa ; $\phi'_r = 8.5$ Degrees

In the same way, different values were obtained from the interface tests. The parameters for Kaolin1 sheared against rock were found to be

$c' = 4$ kPa ; $\phi' = 13.6$ Degrees

$c'_r = 0.1$ kPa ; $\phi'_r = 9.1$ Degrees

and for Kaolin1 sheared against glass the following parameters were found

$c' = 4$ kPa ; $\phi' = 10.2$ Degrees

$c'_r = 0$ kPa ; $\phi'_r = 7.5$ Degrees

The envelopes in each case have been drawn as best fit straight lines using a least squares regression analysis program and some degree of change would be possible by subjective interpretation. The majority of clay rich engineering soils tested by Privett(1980) were found to have curved residual failure envelopes, the maximum deflection occurring below 200 Kpa effective normal stress. The curved envelopes could account for some variation of Atterberg limits where the scattering was more dense for the clays of plasticity Index between 40% and 60% as shown in Figures 3.1 and 3.2. In particular it is known that the linearity of the envelope at normal stress below approximately 150 to 200 kPa is questionable and research is being carried out at Loughborough (Anayi, 1990) to better define the envelope in this region. Neverthless there are some clear trends apparent from these parameters, such as that the smoothness of the failure plane greatly influences the results, and these will be discussed in detail in chapter eight.

The results of the interface tests are summarised in Tables 7.1 to 7.6, from which can be seen the trends in peak and residual strengths for each of tests carried out.

7.5 The effect of Normal Stress

In this study two modified shearbox tests were carried out to investigate the disturbance caused by the reversal of the shearbox during the test. In these tests, the normal stress was relieved every forward cycle while keeping the same normal stress (σ'_n = 200 kPa) for backward cycles. The rate of shear for backward cycles was fixed to 0.00881 mm/min, whereas the rate for the forward cycles was 0.03968 mm/min.

The stress-displacement relationships for both London clay and Lias clay are shown in Figures 7.36 and 7.37, and the results are summarised in Table 7.7. The stress-displacement curves show clearly a decrease in strength, after the peak shear strength has been reached, with increasing displacement and the strength ultimately reduces to the residual value.

There are small peaks at the beginning of each cycle, although with further small displacements the strength quickly falls towards a lower strength than that of the former cycle. It can seen from the tabulated results that relieving the normal stress during the forward cycles causes a reduction in the residual strength of both London clay and Lias clay of 0.30 Degrees and 0.27 Degrees respectively compared with those results obtained without relieving the normal stress.

7.6 Results of Vibrationary Loading Tests

The influence of fast rates of displacement on the strength of shear surfaces in cohesive soils must be considered in the study of seismic slope stability. A series of undrained vibrationary loading tests was carried out using 200 cycles with 10 mm length of travel and 2000 cycles using 1 mm length of travel.

The purpose of these tests was to investigate the behaviour of the material sheared against rock after a given number of cycles. The stress-displacement curves for London clay and Lias clay after 200 cycles of 10 mm undrained displacement are shown in Figures 7.38 and 7.39, and for Kaolin1 after 2000 cycles of 1mm undrained displacement in Figure 7.40. Tables 7.8 and 7.9 present the values of peak and residual strength for all six clays, both with and without vibrations using both methods of application. These Tables indicate some general trends in behaviour.

For 200 cycles of 10 mm (Table 7.8), both the peak and residual strengths were significantly affected by the vibrationary loading, giving lower values in comparison with the values obtained without vibrationary loading. A similar tendency was noticed with 2000 cycles of 1 mm travel (Table7.9) for the peak strengths, whereas the residual strengths are roughly the same and in two cases show an increase.

7.7 Results of Tests to investigate Rate Effects on Residual Shear Strength

In this study two modified shearbox tests were carried out to study the influence of increasing shear displacement rates every backward cycle while keeping the same slow rate of shear for forward cycles (0.00881 mm/min). The results of the tests on London clay and Lias clay are presented in Figures 7.41 and 7.42 respectively.

In general there is a discrepancy between the stress-displacement curves for the forward and backward cycles. There seems to be a clear trend towards an increase of peak shear strength with increasing displacement rate for the first three forward cycles with little reduction in the strengths at the end of each cycle. There is, however, a drop in strength for the two last forward cycles, in which the residual shear strength was approached and, in the case of Lias clay, perhaps established . However for the backward cycles where the rate of shear was unchanged there is a drop in strength immediately after the peak shear strength was reached in the first cycle. The values of peak and residual shear strength for both tests are given in Table 7.10.

7.8 Moisture Content Measurements

At the end of each of the modified reversal shearbox tests, five water content determinations were made on each sample. These water content determinations were made on a specimen of approximately 1.0 mm in thickness containing the shear plane. Precise determination of the water content in the shear zone is difficult to obtain due to the small thickness of the shear zone.

In addition the water bath surrounding the shear zone could affect the final moisture content and care was taken during dismantling of the shearbox. For these reasons the average value of the five moisture contents was taken. In general, however, more sensible results are likely from tests on samples prepared in the laboratory than the values taken in situ. Tables 7.6 and 7.7 give the final moisture contents for the modified shearbox tests and Bromhead ring shear tests, together with those from the interface tests using the modified shearbox. Figure 7.43 shows a summary of the final moisture contents for every sample. The clay sheared against clay using the modified shearbox gave the lowest values of moisture content in shear zone, followed by the clay sheared against glass. However, there is a discrepancy between the values of the moisture content for the Algerian and the British samples. For example, the Algerian samples sheared against rock gave higher moisture contents whereas the British clays gave higher moisture contents with clay sheared against clay in the Bromhead ring shear.

7.9 Structure Formed by Shearing

Visual inspection on dismantling the test showed a change in structure of failure zone in all the tests, which matches the changes in behaviour predicted from the results of the shear tests. Figure 7.44, for example, shows the formation of the shear zone between the two halves of the shearbox for Lias clay.

Strength Parameters		SB test K1 Vs K1	SB test K1 Vs Rock	SB test K1Vs Glass	RS test K1 Vs K1
σ'_n = 100 kPa	τ_p (kPa)	26	30	16	26
	τ_r (kPa)	18	14	12	16
σ'_n =150 kPa	τ_p (kPa)	36	33	28	36
	τ_r (kPa)	28	20	18	21
σ'_n =200 kPa	τ_p (kPa)	54	48	34	46
	τ_r (kPa)	42	32	26	29.8
σ'_n = 400 kPa	τ_p (kPa)	103	84	70	94
	τ_r (kPa)	84	60	48	52
ϕ'_p peak (Degrees)		15.4	13.6	10.2	13.4
ϕ'_r residual (Degrees)		11.8	9.1	7.5	8.4
c' peak (kPa)		0.2	4	0	2.5 2
c'r residual (kPa)		0	0.1	0	0.3

Table 7.1 Peak and residual strength parameters for Kaolin1

Strength Parameters		SB test K2 Vs K2	SB test K2 Vs Rock	SB test K2Vs Glass	RS test K2 Vs K2
σ'_n = 100 kPa	τ_p (kPa) τ_r (kPa)	46 30	38 24	32 22	34 22
σ'_n =150 kPa	τ_p (kPa) τ_r (kPa)	62 46	51 42	44 29	46 34
σ'_n =200 kPa	τ_p (kPa) τ_r (kPa)	76 63	62 50	56 41	58 46
σ'_n = 400 kPa	τ_p (kPa) τ_r (kPa)	150 124	120 95	112 80	118 90
ϕ'_p peak (Degrees) ϕ'_r residual (Degrees) c' peak (kPa) c'r residual (kPa)		20.9 17.6 2 0.3	17.5 14.2 3 0.1	16 11.6 0 0	17.1 13 2.5 0

Table 7.2 Peak and residual strength parameters for Kaolin2

Strength Parameters		SB test K3 Vs K3	SB test K3 Vs Rock	SB test K3Vs Glass	RS test K3 Vs K3
σ'_n = 100 kPa	τ_p (kPa)	60	46	38	46
	τ_r (kPa)	42	34	28	31
σ'_n =150 kPa	τ_p (kPa)	84	60	58	64
	τ_r (kPa)	60	52	42	44
σ'_n =200 kPa	τ_p (kPa)	103	84	76	80
	τ_r (kPa)	84	73	58	60
σ'_n = 400 kPa	τ_p (kPa)	196	160	148	157
	τ_r (kPa)	165	146	118	117
ϕ'_p peak (Degrees)		27.3	22.6	20.5	22.4
ϕ'_r residual (Degrees)		22.8	20.0	16.7	18.5
c' peak (kPa)		5	1	0.5	4
c'r residual (kPa)		0.3	0	0	1.25

Table 7.3 Peak and residual strength parameters for Kaolin3

Strength Parameters		SB test Lo Vs Lo	SB test Lo Vs Rock	SB test LoVs Glass	RS test Lo Vs Lo
σ'_n = 100 kPa	τ_p (kPa)	30	34	26	30
	τ_r (kPa)	14	12	10	11
σ'_n =150 kPa	τ_p (kPa)	54	48	34	42
	τ_r (kPa)	20	22	14	20
σ'_n =200 kPa	τ_p (kPa)	62	60	48	53
	τ_r (kPa)	30	26	20	24
σ'_n = 400 kPa	τ_p (kPa)	124	110	94	108
	τ_r (kPa)	50	52	36	40
ϕ'_p peak (Degrees)		16.9	16.6	13.7	15.6
ϕ'_r residual (Degrees)		8.2	7.4	5.8	7.0
c' peak (kPa)		2	4	0.5	1.20
c'r residual (kPa)		0.7	0.2	0.2	0

Table 7.4 Peak and residual strength parameters for London clay

Strength Parameters		SB test Li Vs Li	SB test Li Vs Rock	SB test LiVs Glass	RS test Li Vs Li
σ'_n = 100 kPa	τ_p (kPa) τ_r (kPa)	42 24	30 22	28 18	36 18
σ'_n =150 kPa	τ_p (kPa) τ_r (kPa)	50 28	54 24	46 24	47 22
σ'_n =200 kPa	τ_p (kPa) τ_r (kPa)	71 42	66 36	58 30	62 32
σ'_n = 400 kPa	τ_p (kPa) τ_r (kPa)	144 85	133 68	116 58	120 60
ϕ'_p peak (Degrees) ϕ'_r residual (Degrees) c' peak (kPa) c'r residual (kPa)		19.5 12.1 0.3 0	18.0 10.2 0.1 0	16.3 8.4 0 0	17.7 9.5 3 1

Table 7.5 Peak and residual strength parameters for Lias clay

Strength Parameters		SB test Ke Vs Ke	SB test Ke Vs Rock	SB test KeVs Glass	RS test Ke Vs Ke
σ'_n = 100 kPa	τ_p (kPa) τ_r (kPa)	54 40	48 36	38 30	44 30
σ'_n =150 kPa	τ_p (kPa) τ_r (kPa)	74 60	66 54	54 42	60 46
σ'_n =200 kPa	τ_p (kPa) τ_r (kPa)	98 82	92 74	73 54	80 62
σ'_n = 400 kPa	τ_p (kPa) τ_r (kPa)	172 150	172 143	138 110	158 123
ϕ'_p peak (Degrees) ϕ'_r residual (Degrees) c' peak (kPa) c'r residual (kPa)		26.1 22.4 5 2	25.2 20.3 1 0.3	20.1 15.5 0.2 0.2	22.5 19 0 0

Table 7.6 Peak and residual strength parameters for Keuper Marl

	Peak shear strength kPa	Residual shear strength kPa	Peak shear angle Degrees	Residual shear angle Degrees
London clay London clay	61.3	27.8	17.0	7.9
Lias clay Lias clay	73.0	41.9	20.1	11.8

Table 7.7 Peak and residual shear strengths with varying normal stress for London and Lias clays.

	Residual angle with vibrations ϕ'_{rv}	Residual angle without vibrations ϕ'_{r}	Peak angle with vibrations ϕ'_{pv}	Peak angle without vibrations ϕ'_{p}
K1 - Rock	8.4	9.1	12.3	13.6
K2 - Rock	13.0	14.2	16.5	17.5
K3 - Rock	18.5	20.0	21.0	22.6
Lon - Rock	7.0	7.4	15.3	16.6
Lia - Rock	9.5	10.2	16.5	18.0
Keu - Rock	19.0	20.3	23.0	25.2

Table 7.8 Shear strength values for both with and without vibrations (200 cycles, 10 mm length of travel).

	Residual angle with vibrations ϕ'_{rv}	Residual angle without vibrations ϕ'_{r}	Peak angle with vibrations ϕ'_{pv}	Peak angle without vibrations ϕ'_{p}
K1 - Rock	8.8	9.1	12.5	13.6
K2 - Rock	13.4	14.2	16.2	17.5
K3 - Rock	20.5	20.0	21.3	22.6
Lon - Rock	9.0	7.4	13.5	16.6
Lia - Rock	10.0	10.2	15.5	18.0
Keu - Rock	21.0	20.3	23.0	25.2

Table 7.9 Shear strength values for both with and without vibrations (2000 cycles, 1 mm length of travel).

Test/stage no.		Peak stresses		Residual stresses		Clay fraction %
		Shear τ' kpa	ϕ' Degrees	Shear τ'_r kpa	ϕ'_r Degrees	
London clay	Forward	62	17.2	34	9.6	39
	Backward	64	17.7	36	10.2	
Lias clay	Forward	74	20.3	46	13.0	33
	Backward	76	20.8	47	13.2	

Table 7.10 Results of the Modified shearbox test on the variation of rate of shear

	Modified shear box tests		Bromhead ring shear tests	
	ϕ'_r	Wf	ϕ'_r	Wf
Kaolin1 - Kaolin1	15.4	43%	13.4	45.5%
Kaolin2 - Kaolin2	20.9	45%	17.1	49%
Kaolin3 - Kaolin3	27.3	34%	22.4	37%
(London-London) clay	16.9	32%	15.6	35%
Lias clay - Lias clay	19.5	33.5%	17.7	36%
(Keuper - Keuper) Marl	26.1	22.8%	22.5	26%

Table 7.11 Values of the residual shear angle and fianl moisture content for both Modified shearbox and Bromhead ring shear.

	Modified shear box tests	
	Residual angle ϕ'_r (Degrees)	Final moisture content Wf (%)
Kaolin1 - Rock	13.6	46
Kaolin2 - Rock	17.5	48
Kaolin3 - Rock	22.6	36.8
London clay - Rock	16.6	36.5
Lias clay - Rock	18	38
Keuper Marl - Rock	25.2	27.5
Kaolin1 - Glass	10.2	44.5
Kaolin2 - Glass	16	46
Kaolin3 - Glass	20.5	36
London clay - Glass	13.7	33
Lias clay - Glass	16.3	36
Keuper Marl - Glass	20.1	24.5

Table 7.12 Values of the residual shear angle and final moisture content for interfaces using the modified shear box.

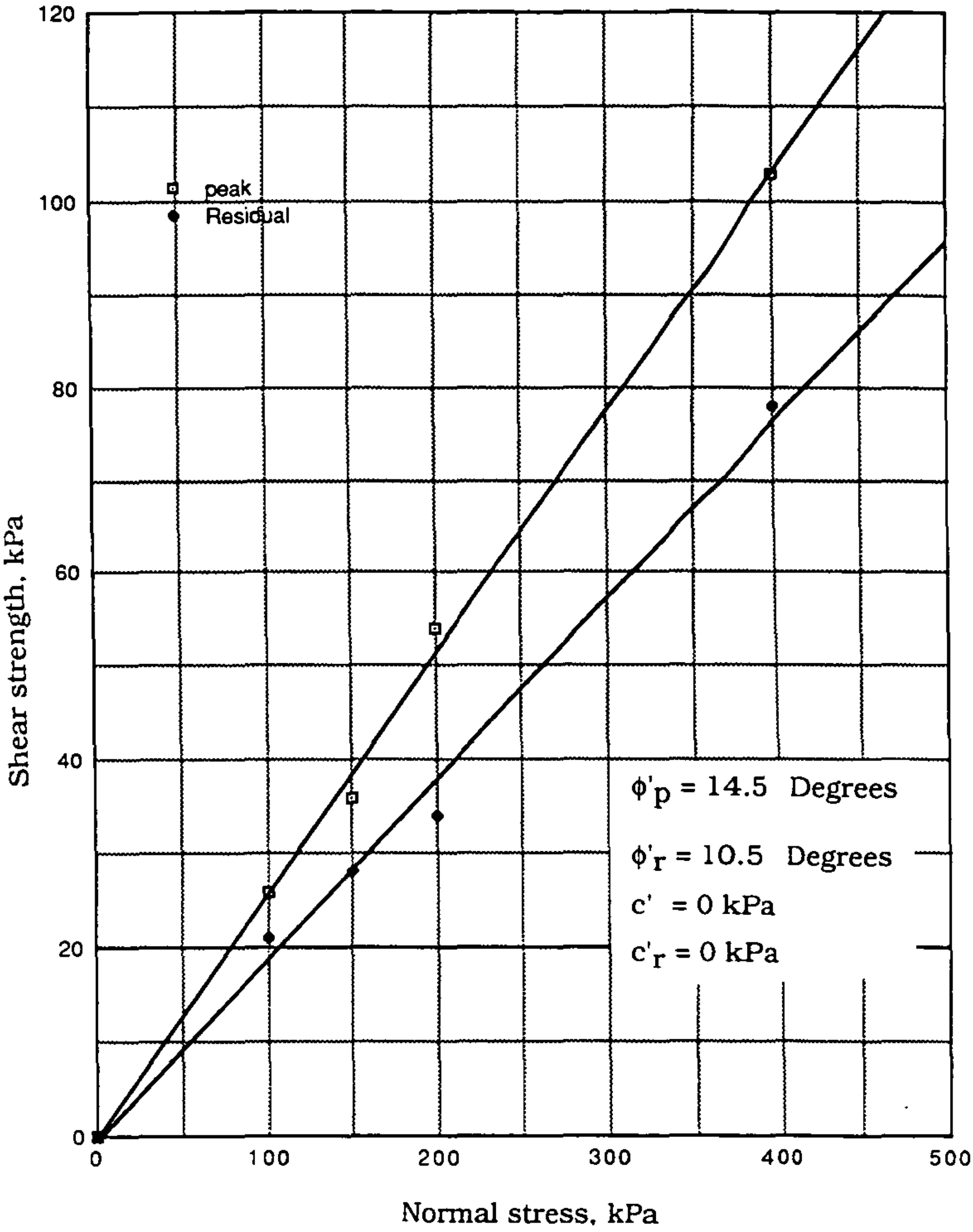


Fig. 7.1 Peak and residual shear strength values for Kaolin1 alone using the modified shearbox.

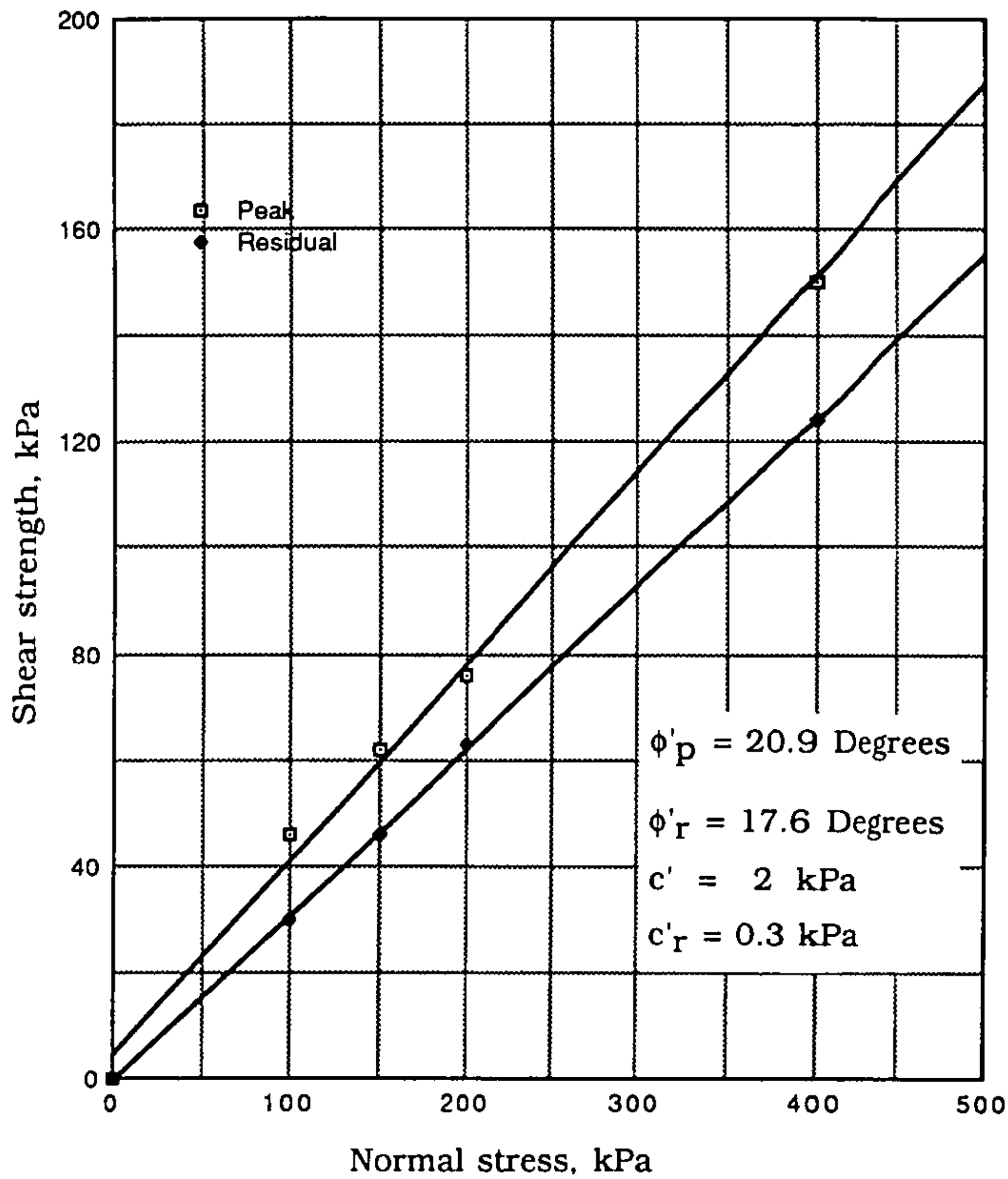


Fig. 7.2 Peak and residual shear strength values for Kaolin2 alone using the modified shearbox.

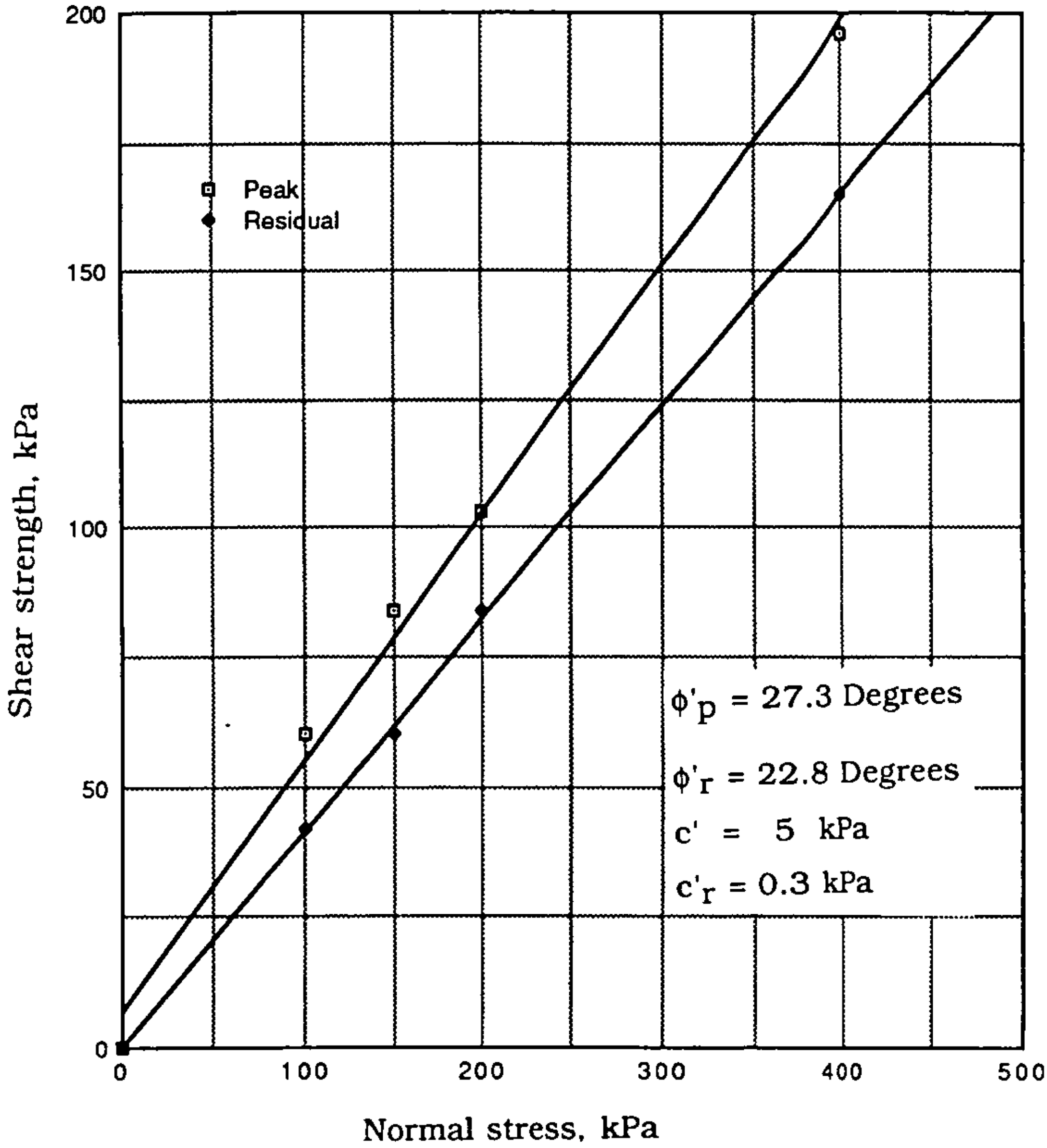


Fig. 7.3 Peak and residual shear strength values for Kaolin3 alone using the modified shearbox.

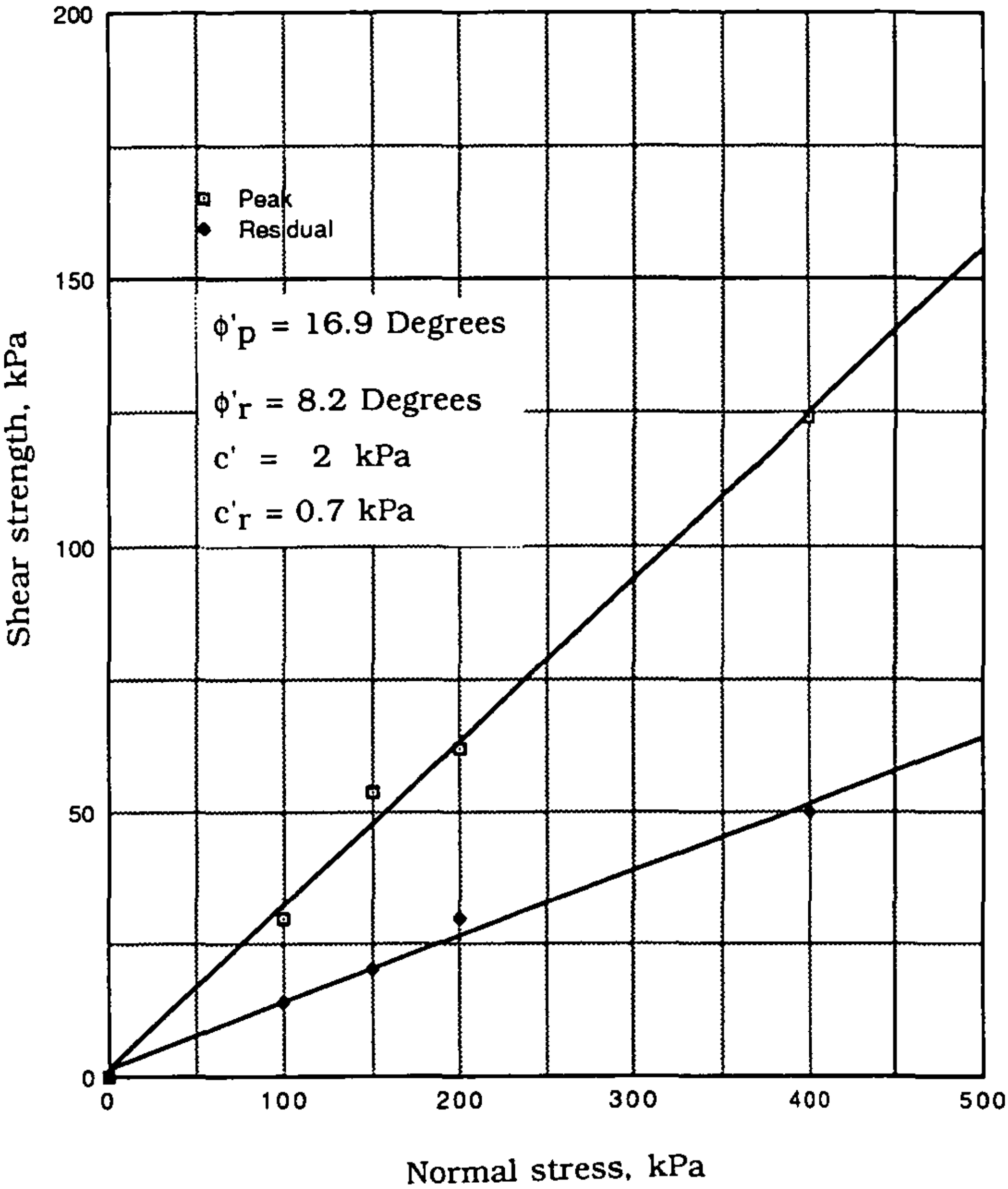


Fig. 7.4 Peak and residual shear strength values for London clay alone using the modified shearbox.

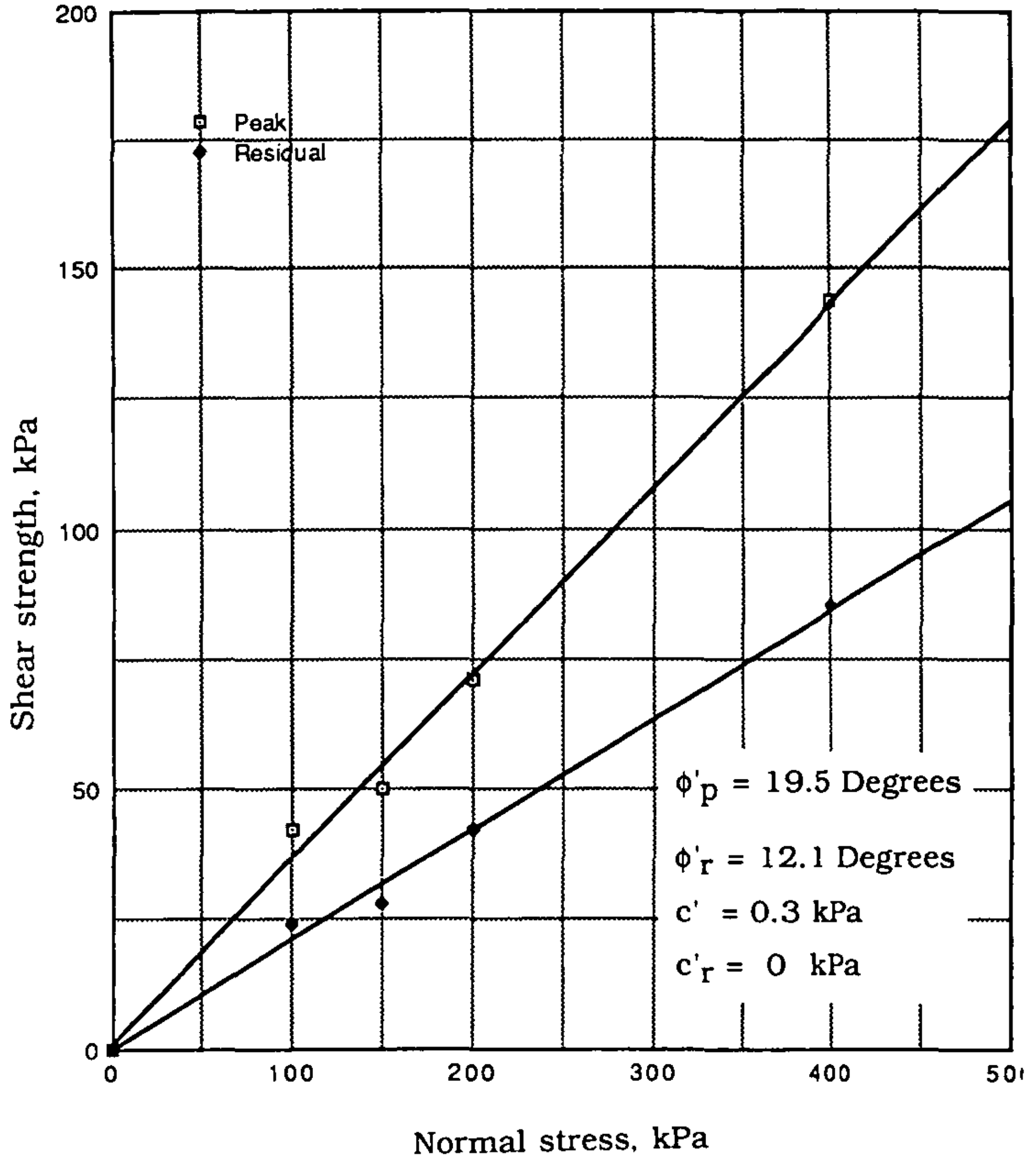


Fig. 7.5 Peak and residual shear strength values for Lias clay alone using the modified shearbox.

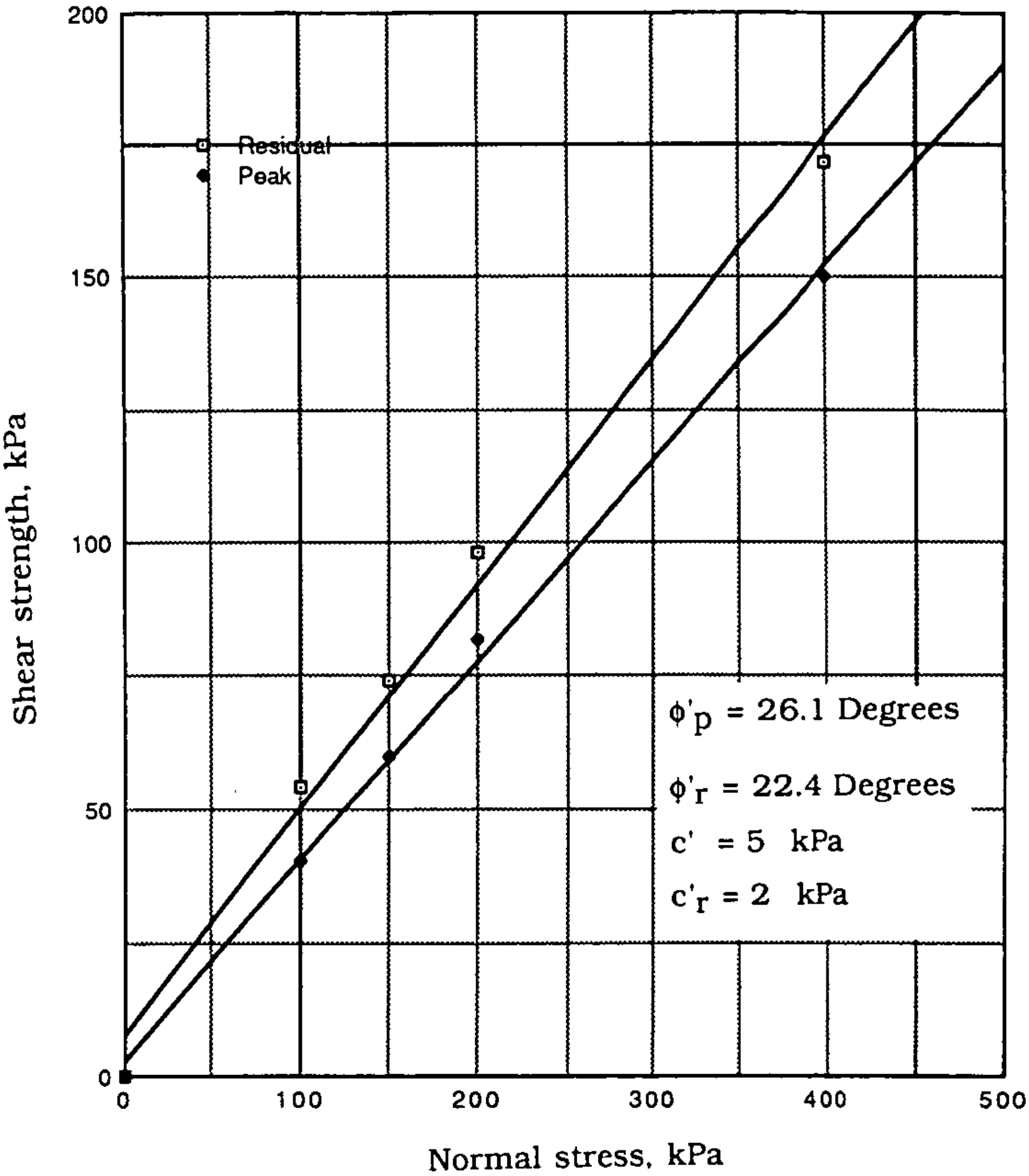
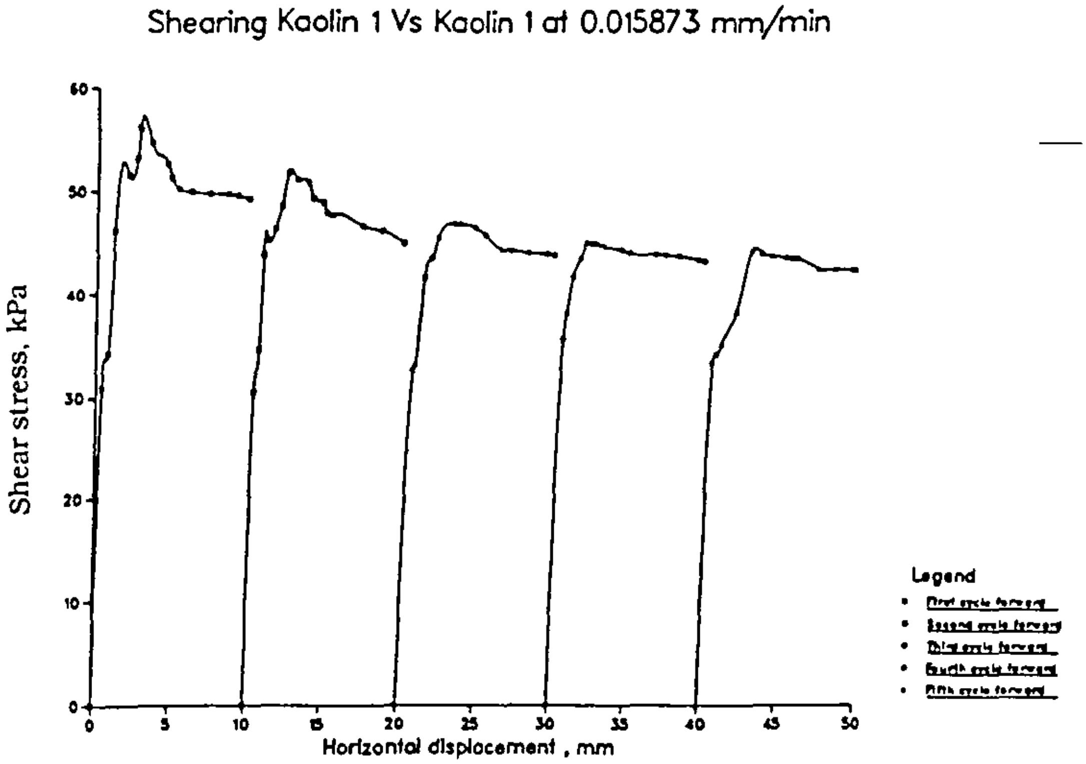


Fig. 7.6 Peak and residual shear strength values for Keuper Marl alone using the modified shearbox.



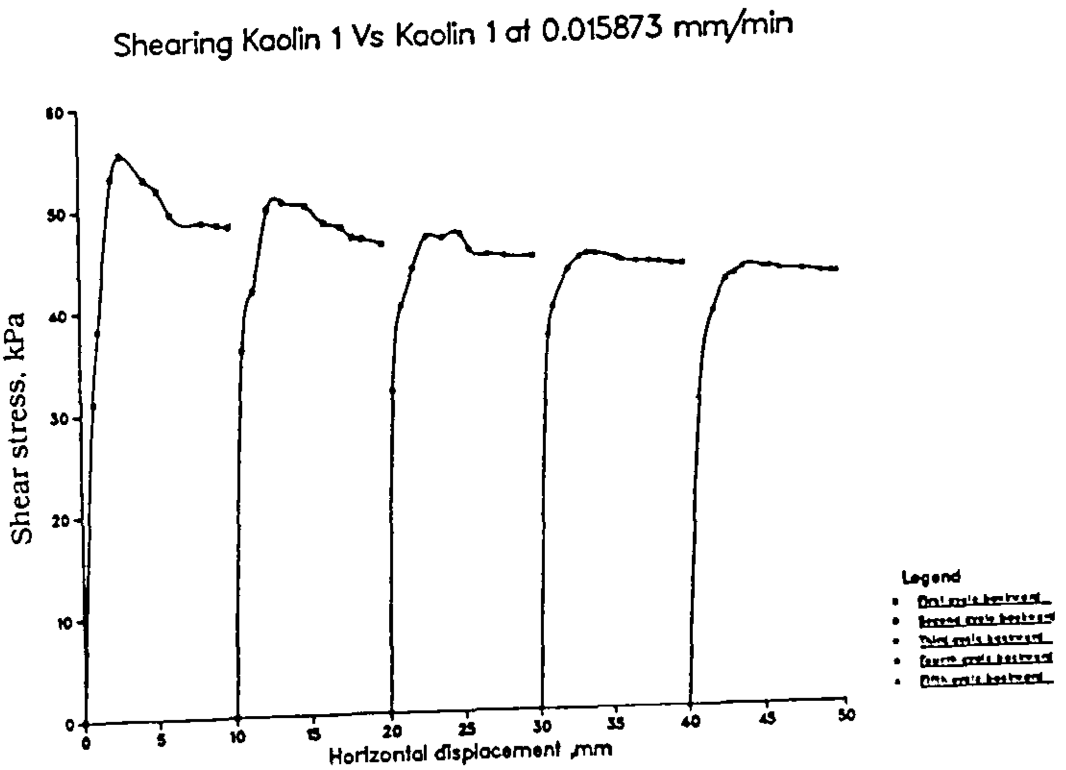


Fig. 7.7 Stress-displacement relationship for kaolin1- kaolin1 using modified shear box.

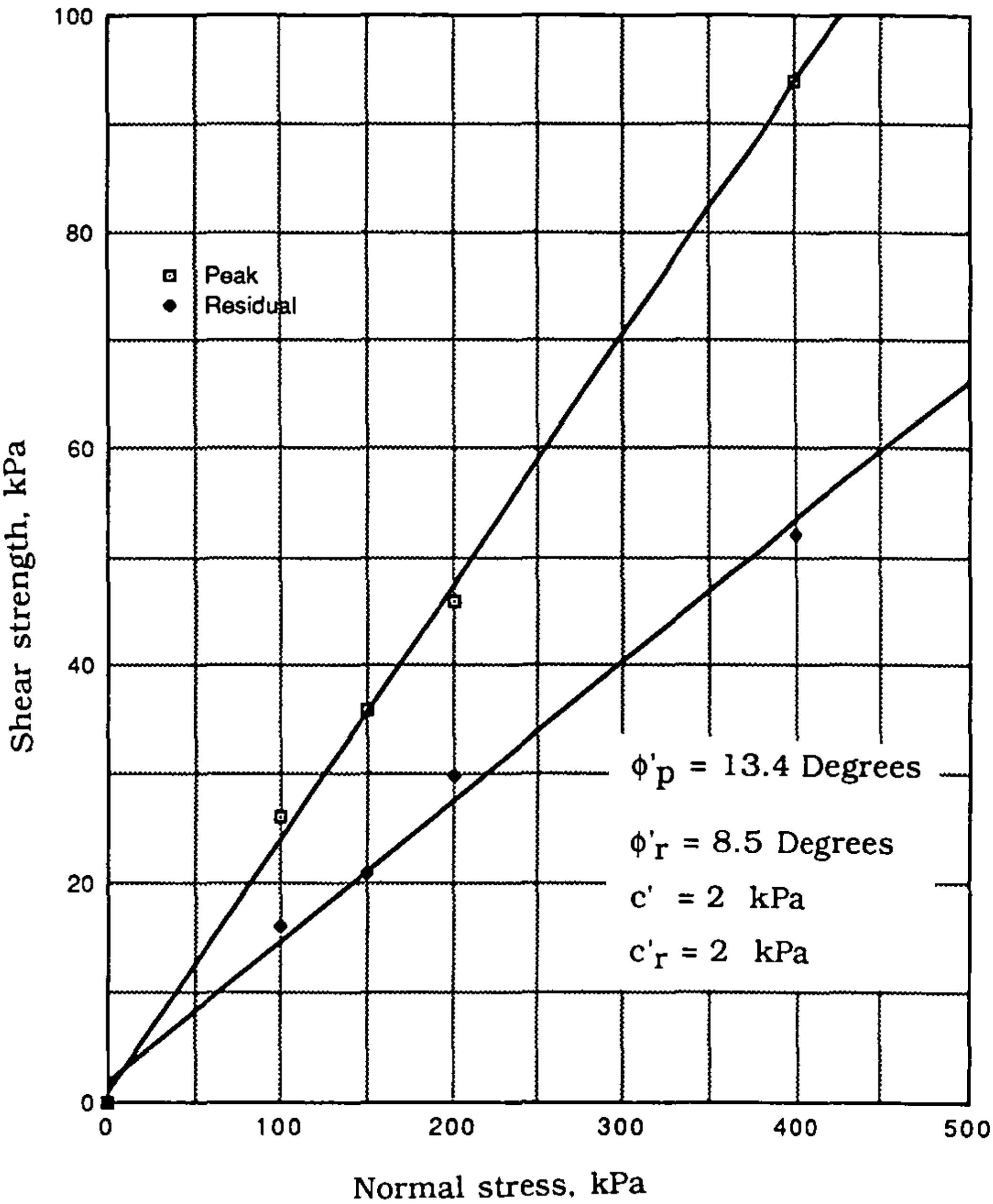


Fig. 7.8 Peak and residual shear strength values for Kaolin1 alone using the Bromhead ring shear

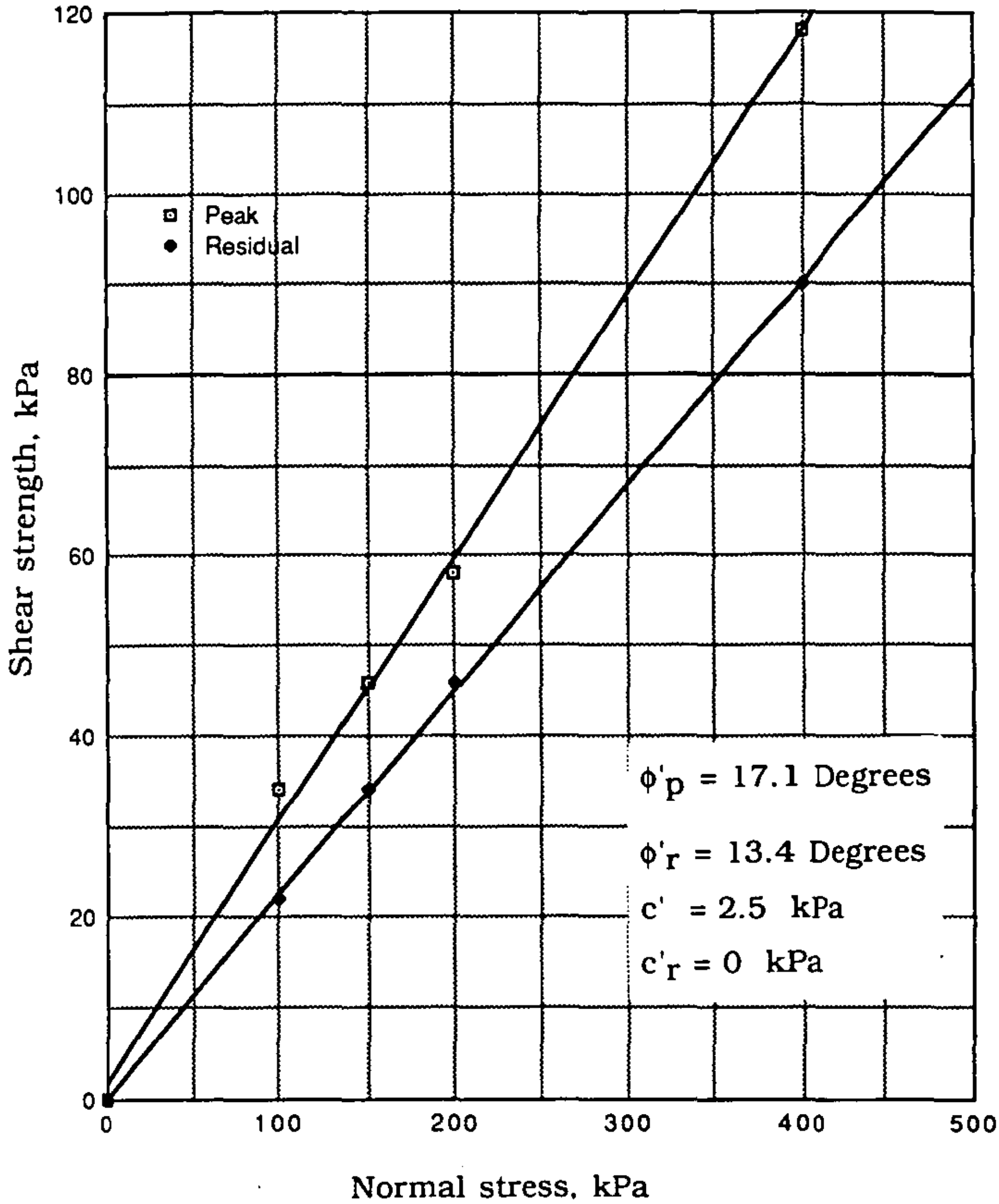


Fig. 7.9 Peak and residual shear strength values for Kaolin2 alone using the Bromhead ring shear

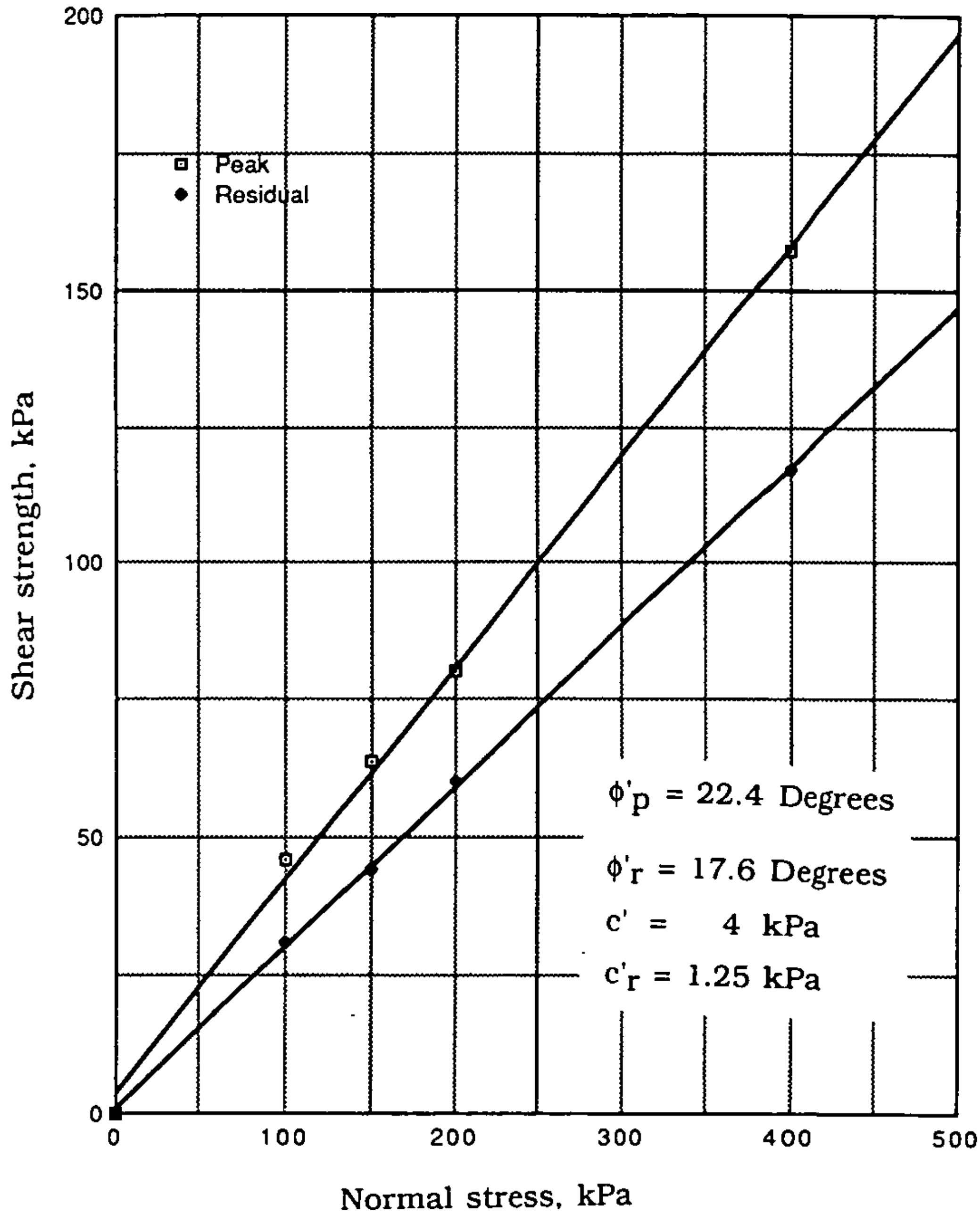


Fig. 7.10 Peak and residual shear strength values for Kaolin3 alone using the Bromhead ring shear

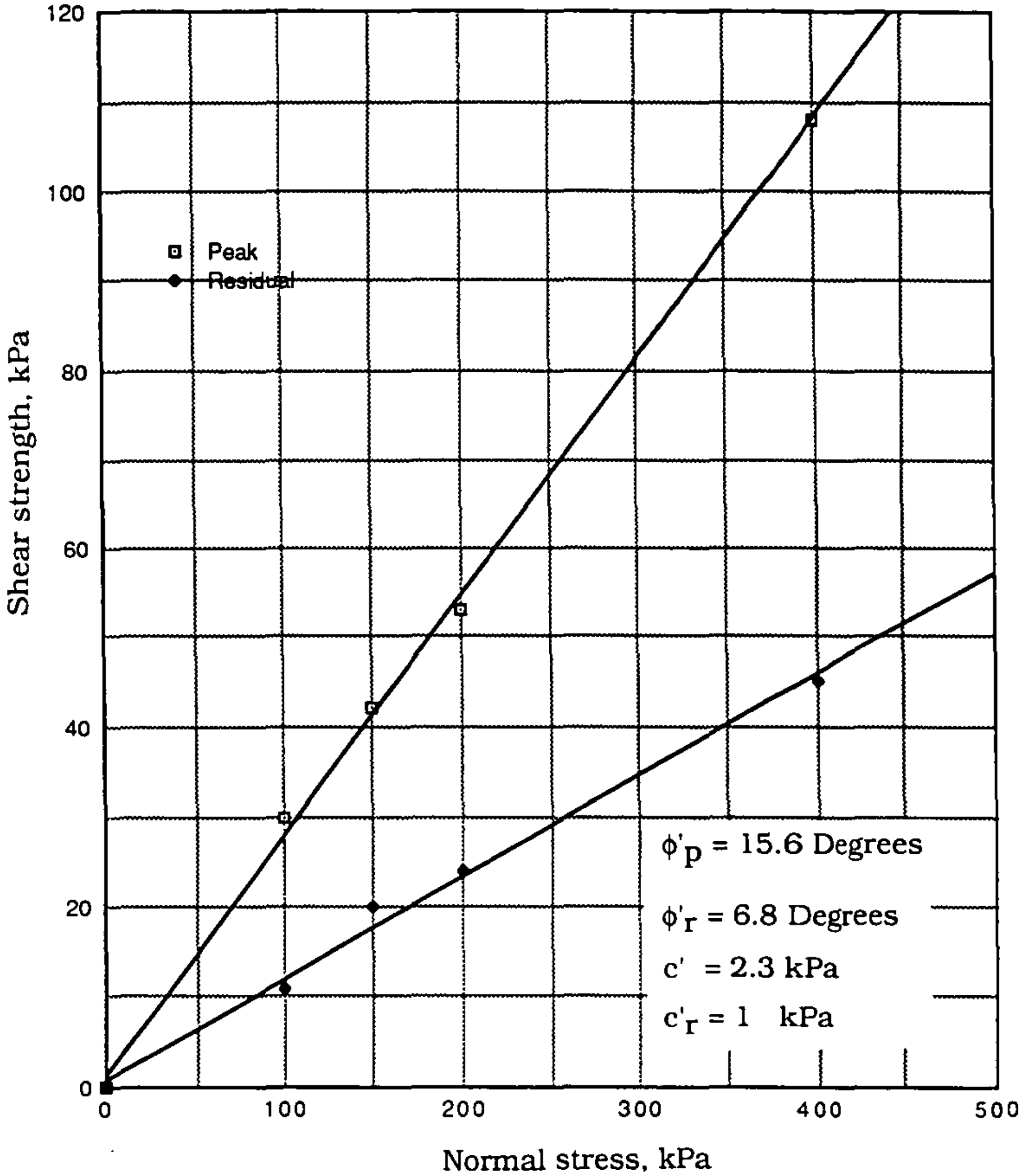


Fig. 7.11 Peak and residual shear strength values for London clay alone using the Bromhead ring shear

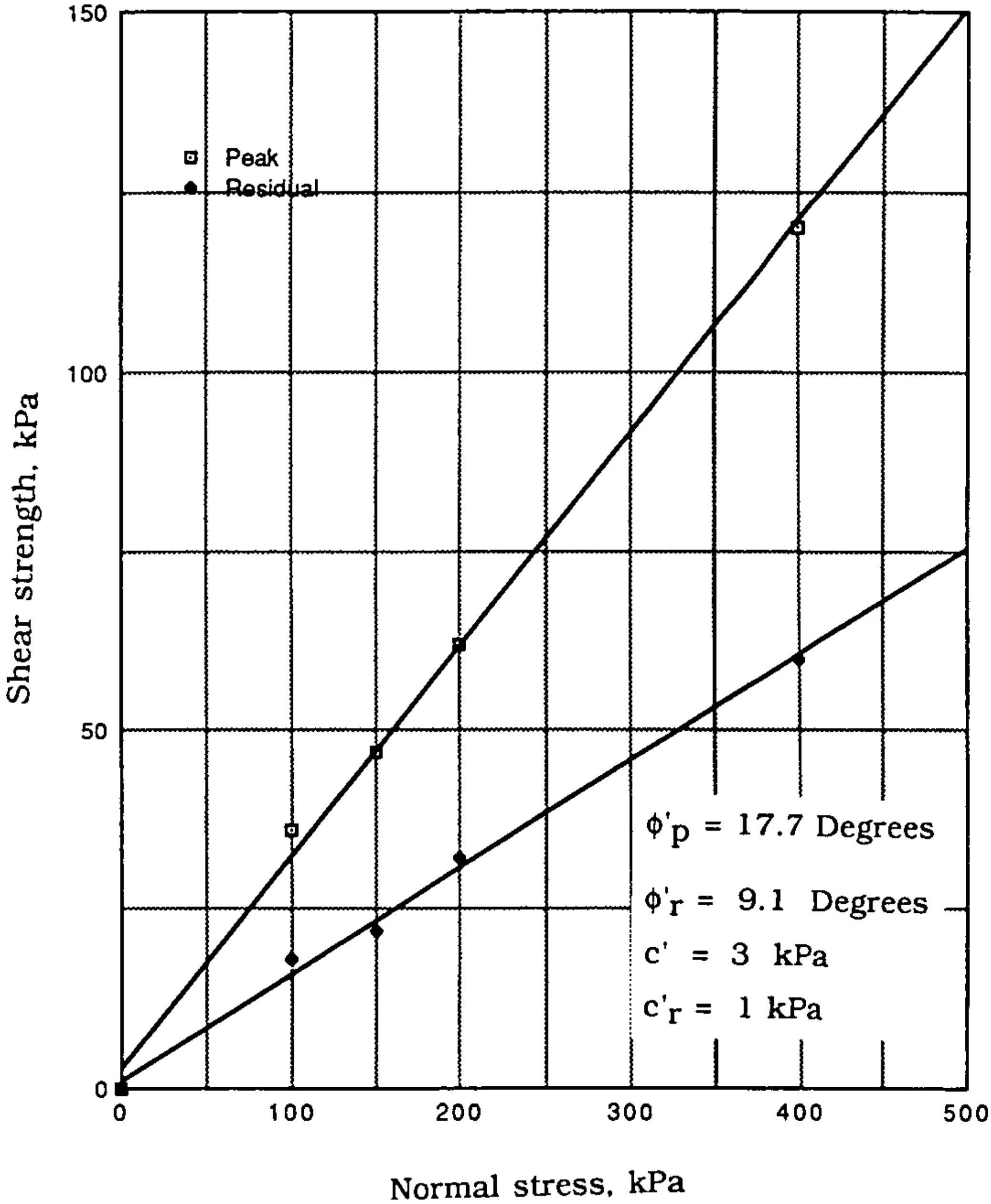


Fig. 7.12 Peak and residual shear strength values for Lias clay alone using the Bromhead ring shear

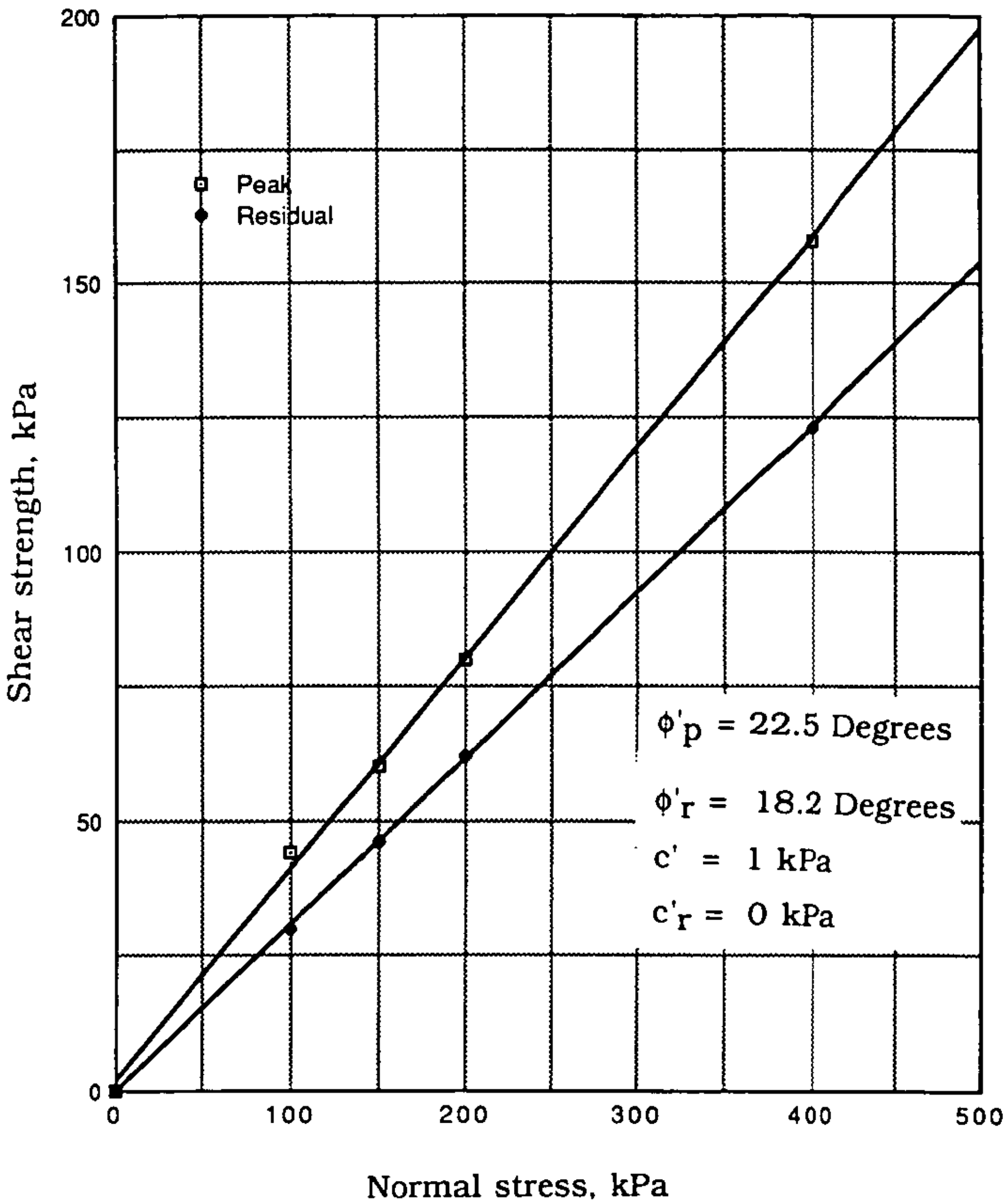


Fig. 7.13 Peak and residual shear strength values for Keuper Marl alone using the Bromhead ring shear

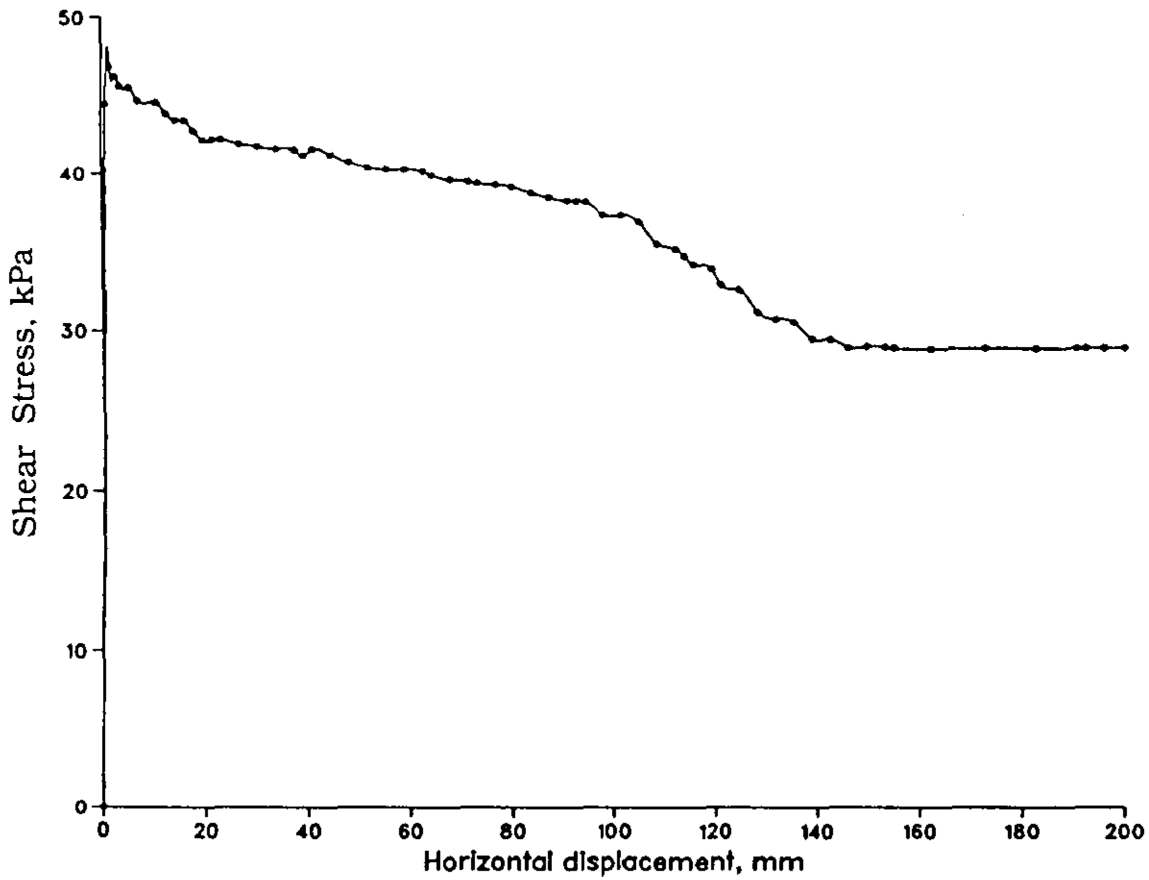


Fig. 7.14 Stress-displacement relationship for Kaolin1 (by using the Bromhead ring shear).

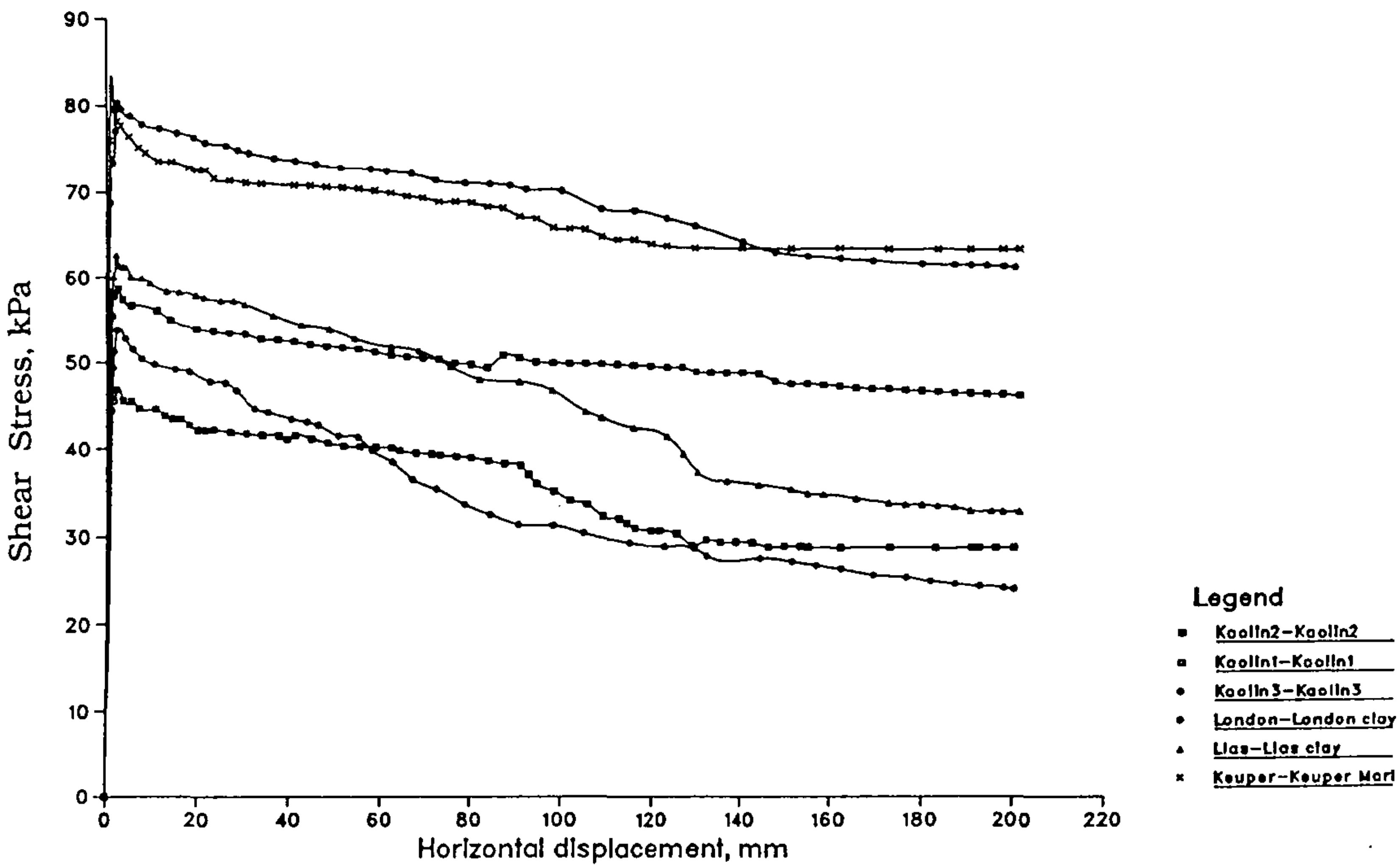


Fig. 7.15 Shearing Clay Vs Clay at 0.17808mm/min using Bromhead ring shear

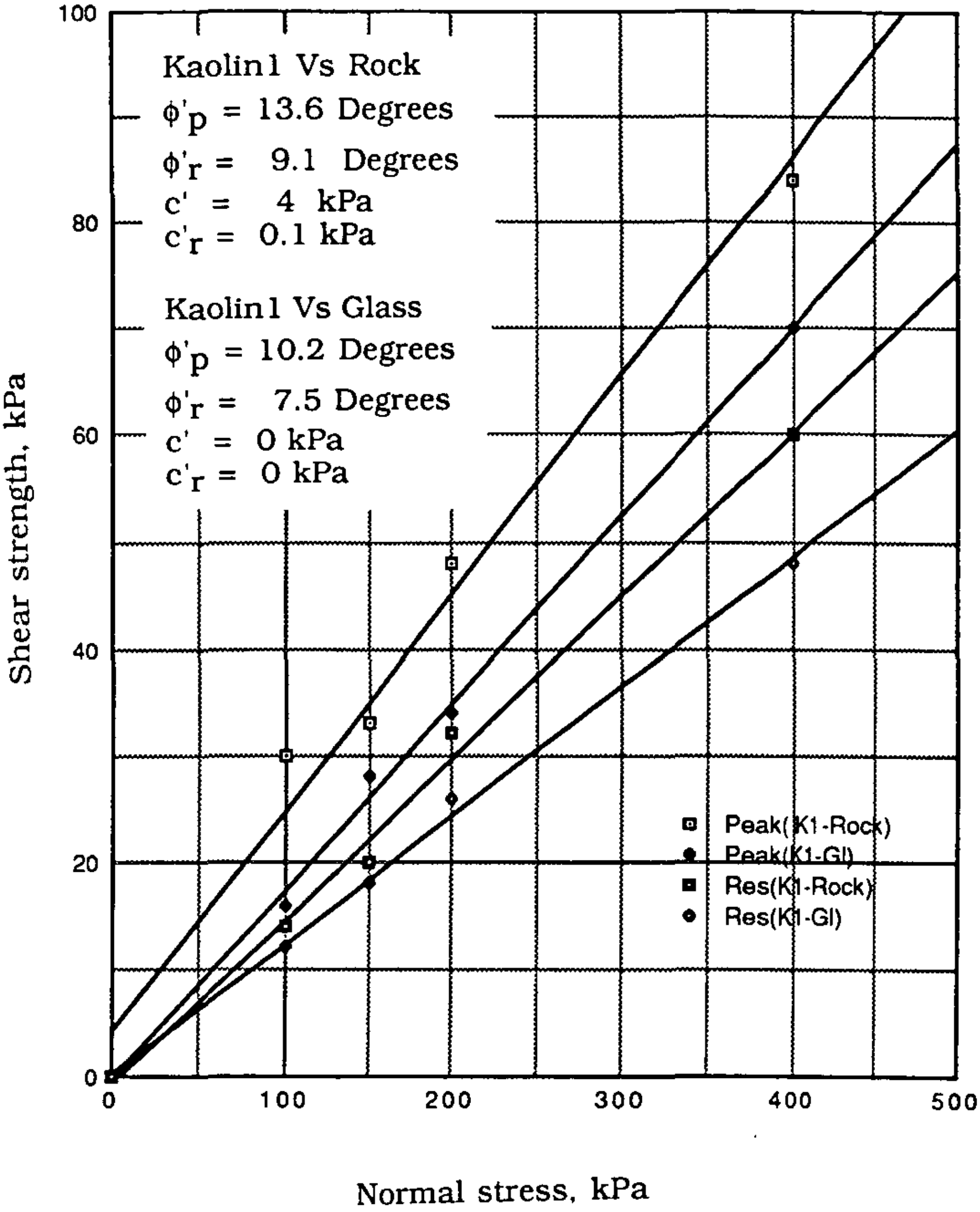


Fig. 7.16 Peak and residual shear strength values for Kaolin1 against interfaces using the modified shearbox

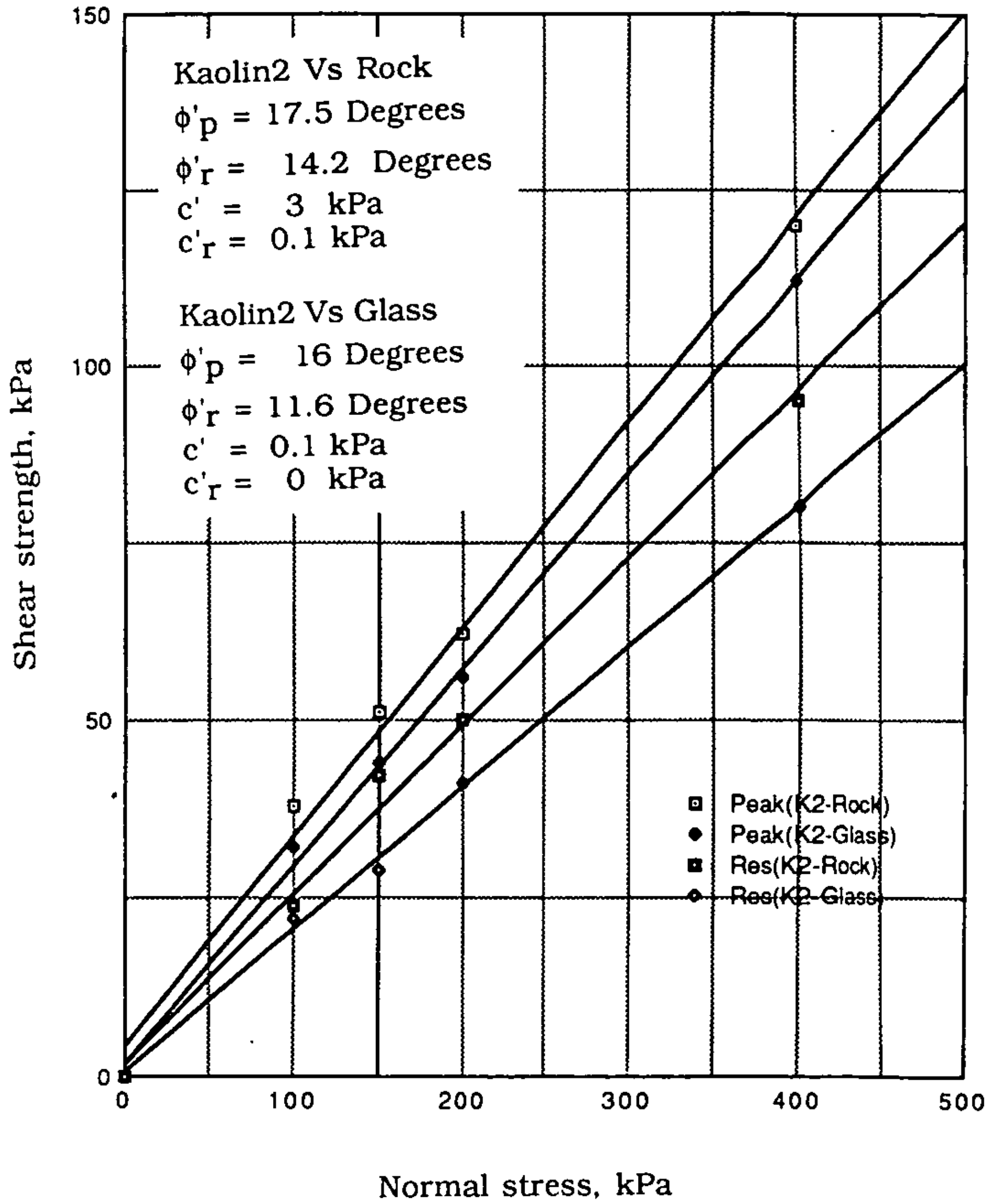


Fig. 7.17 Peak and residual shear strength values for Kaolin2 against interfaces using the modified shearbox

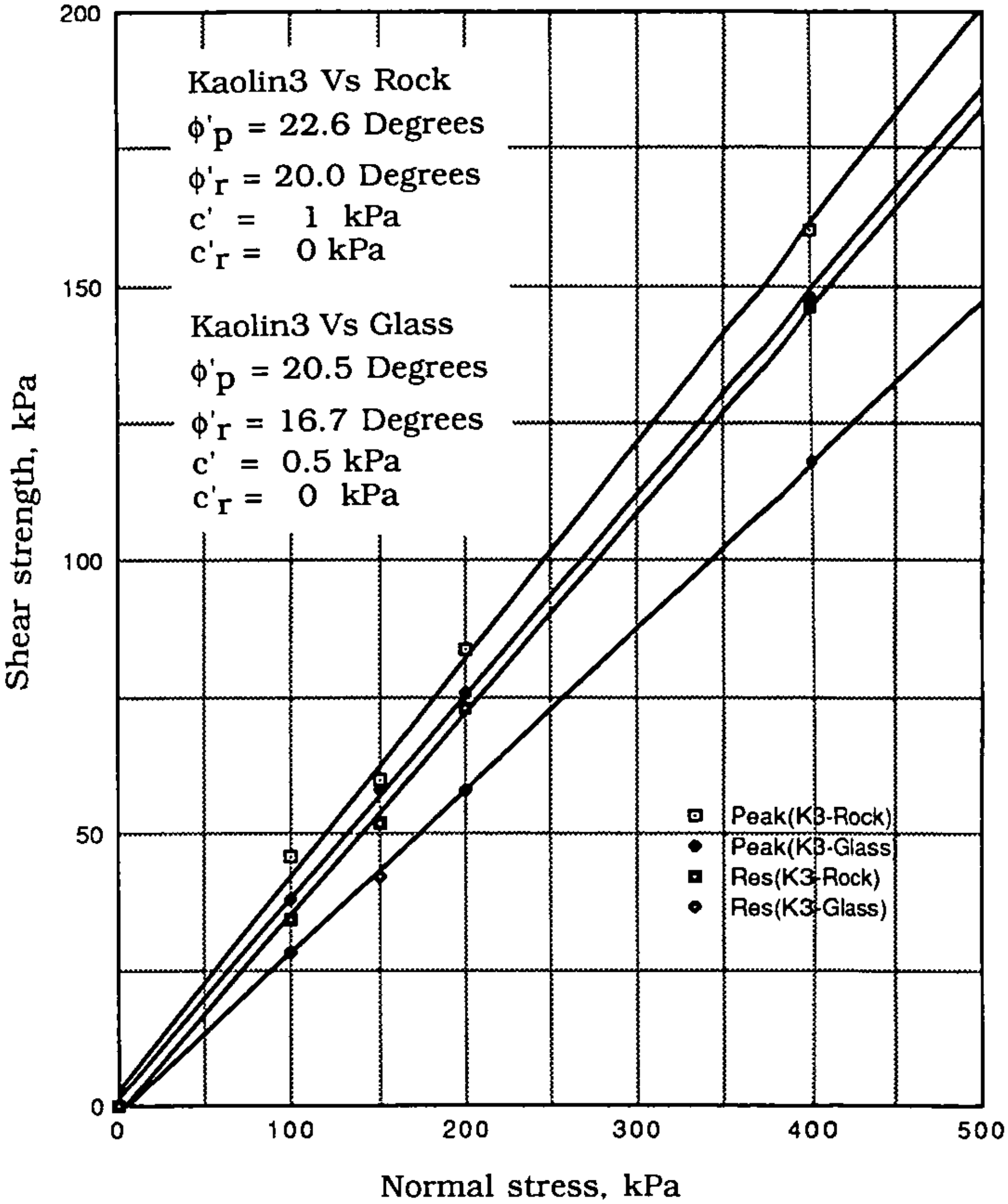


Fig. 7.18 Peak and residual shear strength values for Kaolin3 against interfaces using the modified shearbox

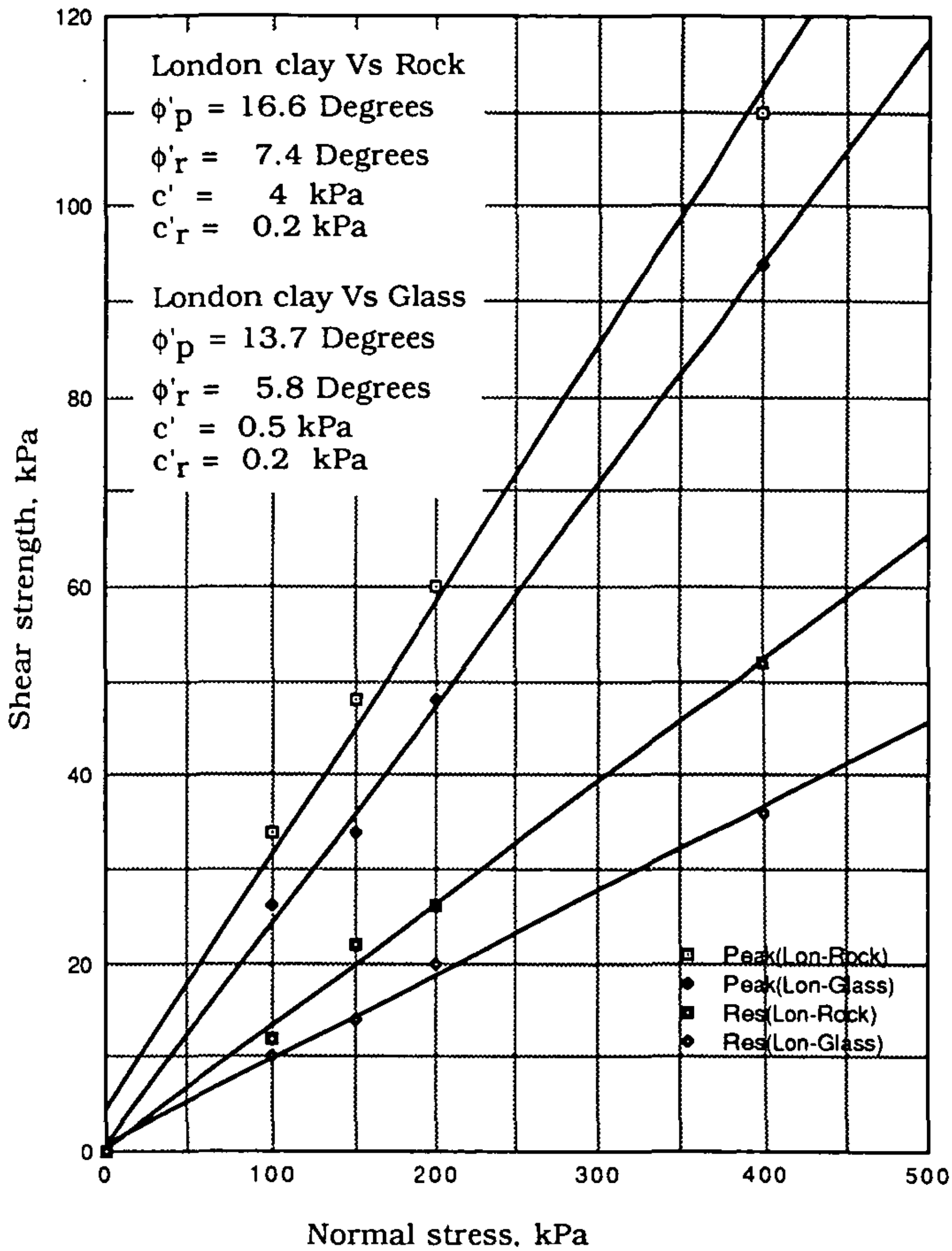


Fig. 7.19 Peak and residual shear strength values for London clay against interfaces using the modified shearbox

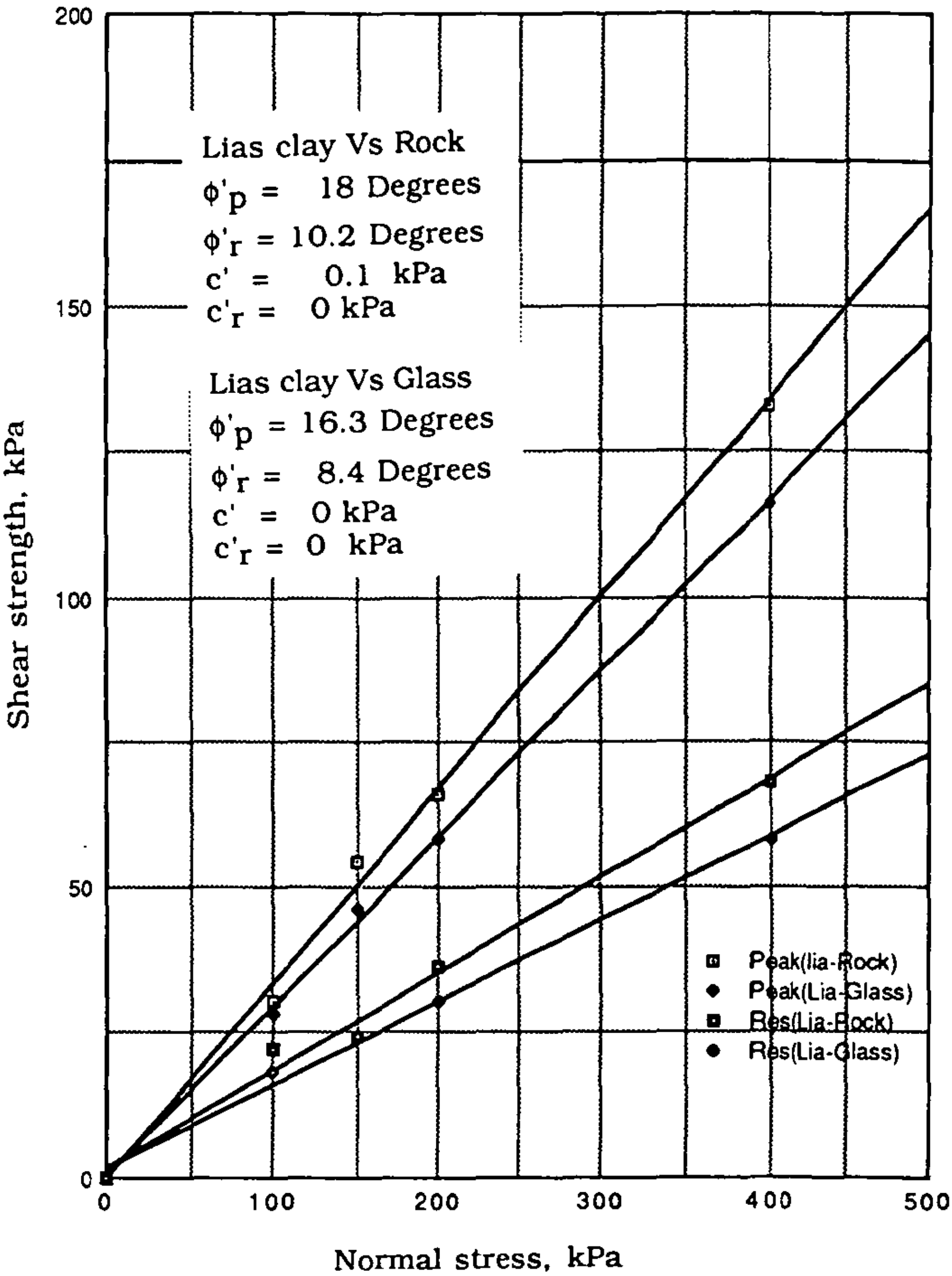


Fig. 7.20 Peak and residual shear strength values for Lias clay against interfaces using the modified shearbox

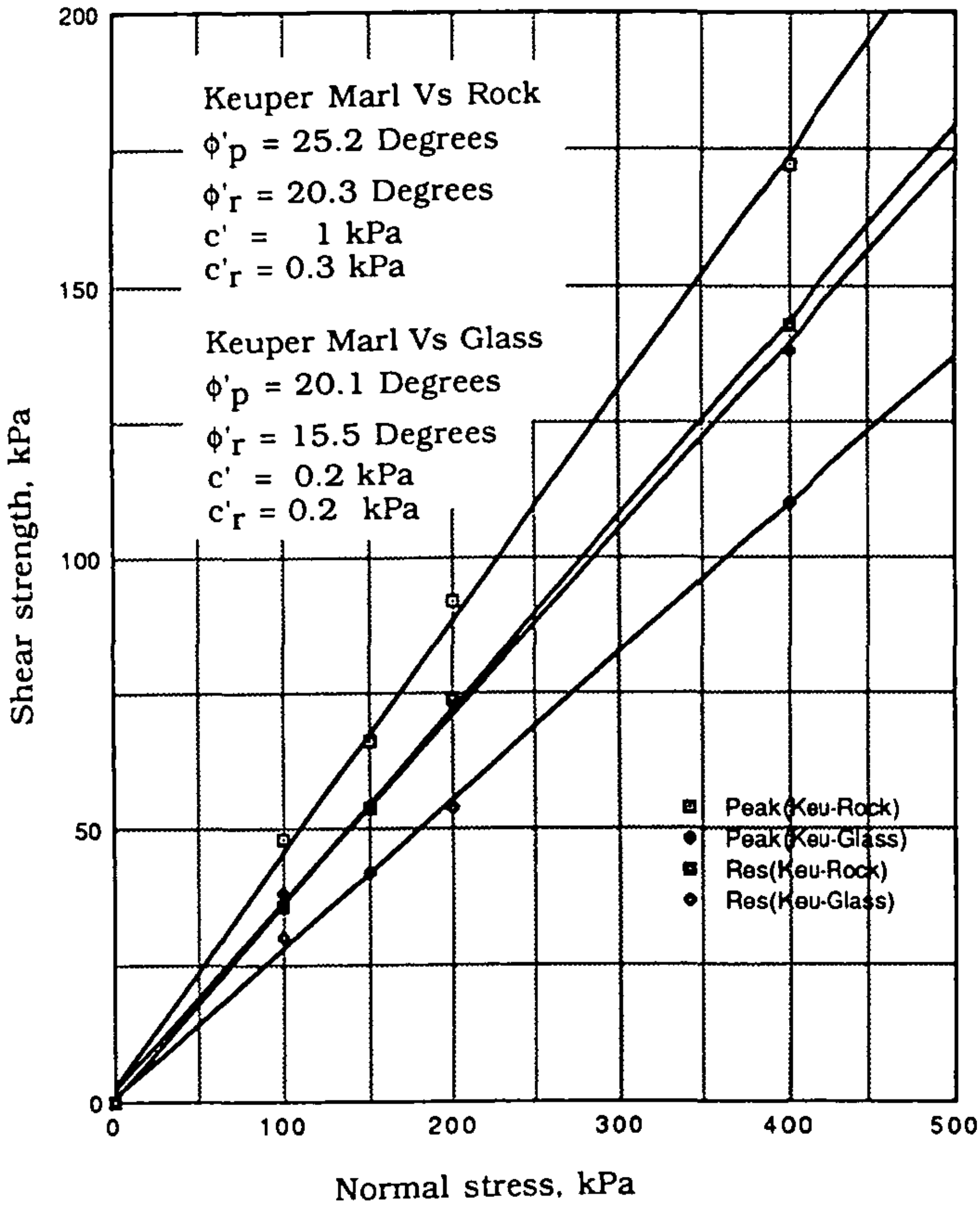
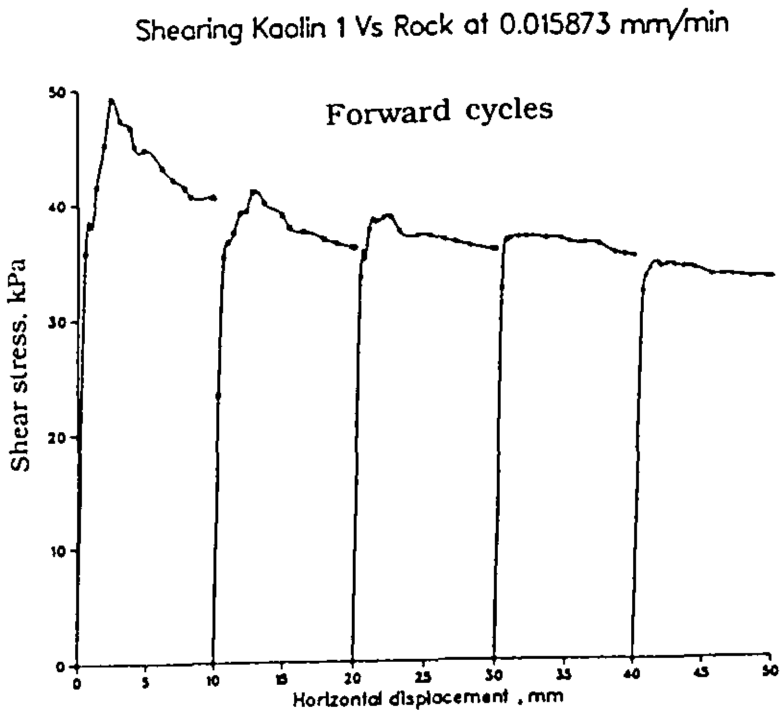


Fig. 7.21 Peak and residual shear strength values for Keuper Marl against interfaces using the modified shearbox



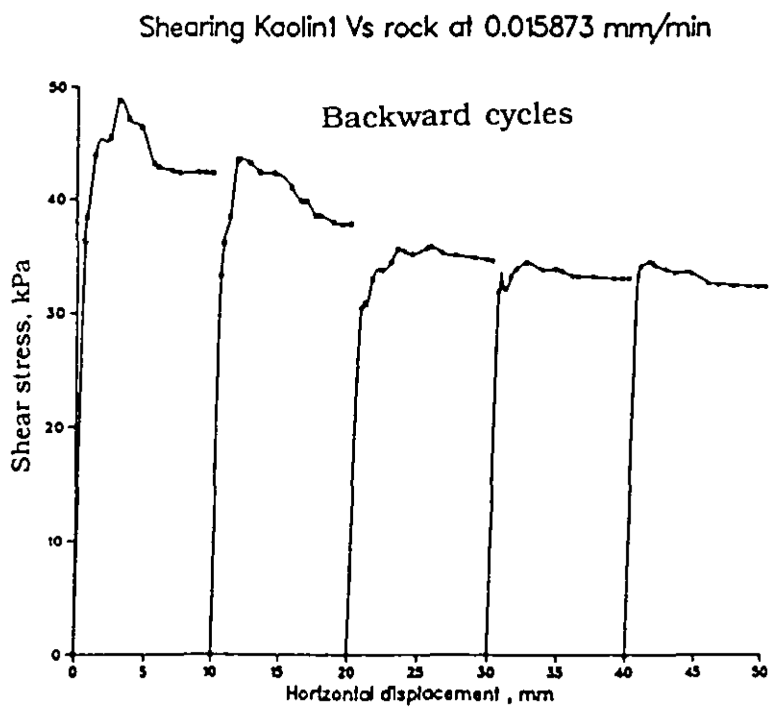
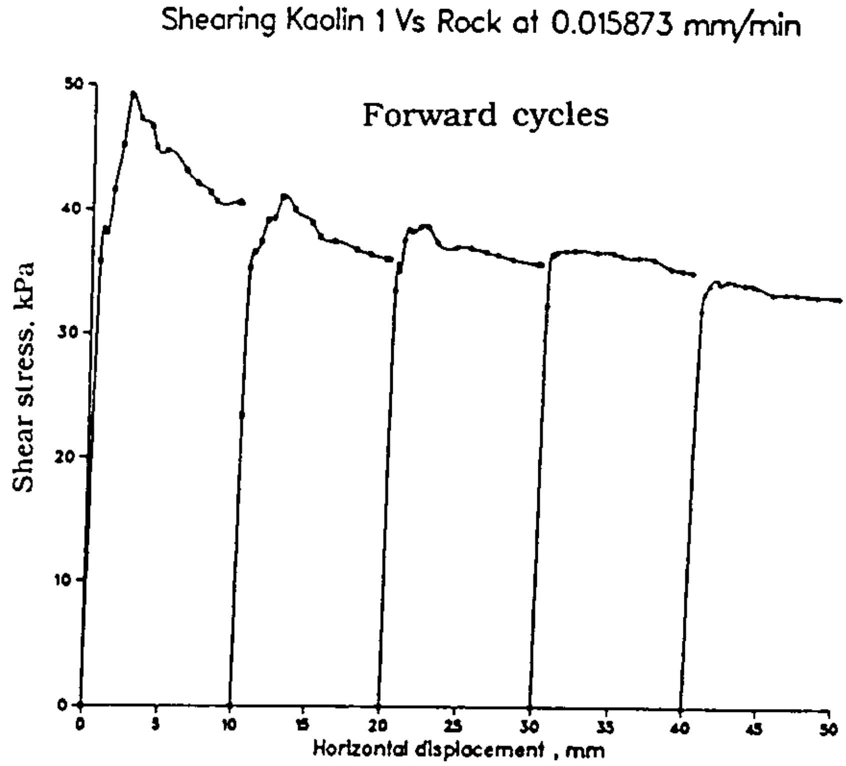


Fig. 7.22 Stress-displacement relationship for kaolin1- rock using modified shear box.



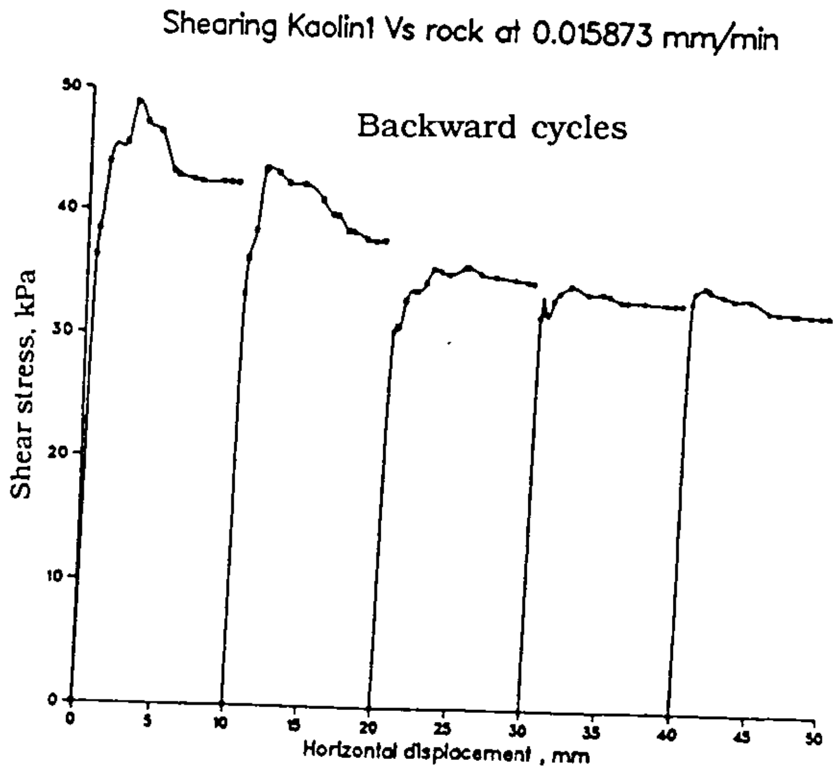
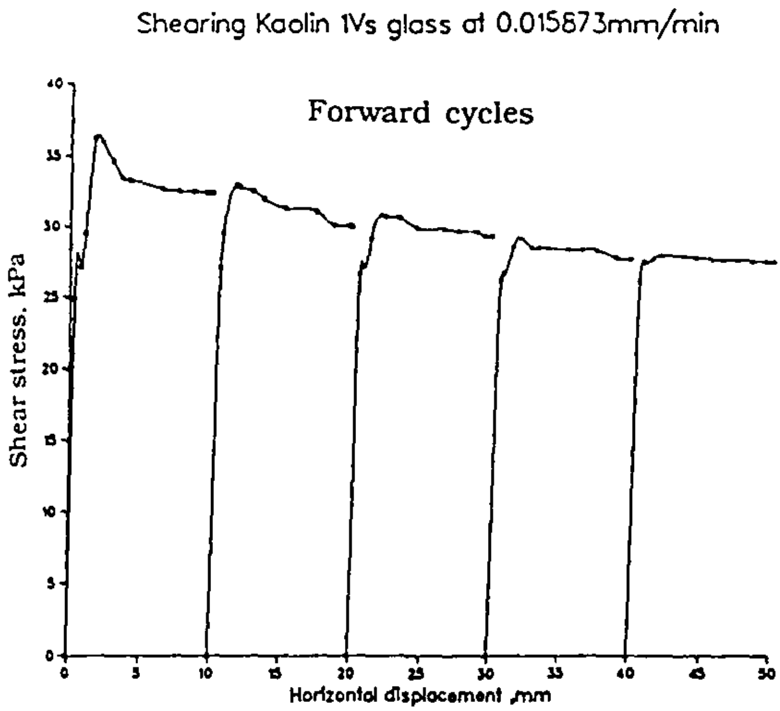


Fig. 7.22 Stress-displacement relationship for kaolin 1 - rock using modified shear box.



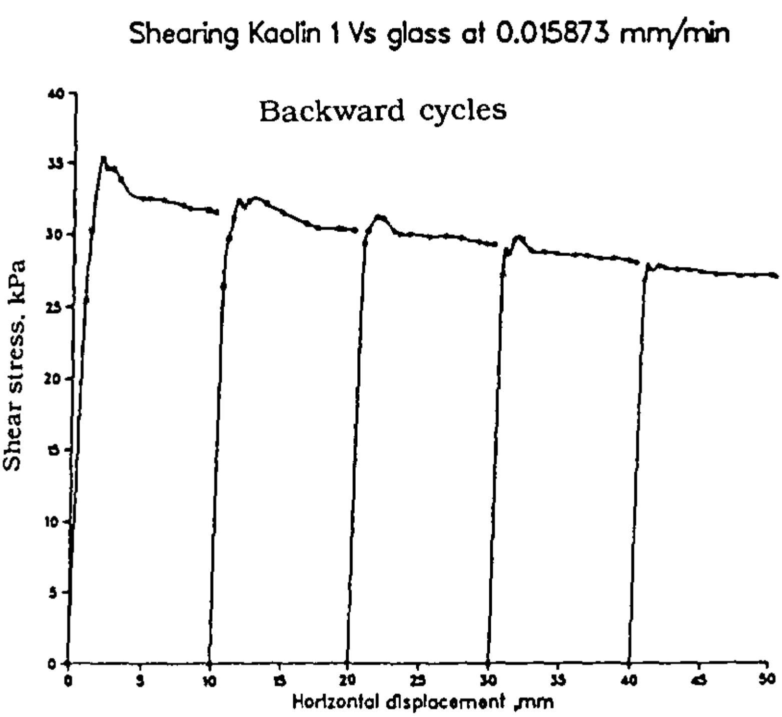
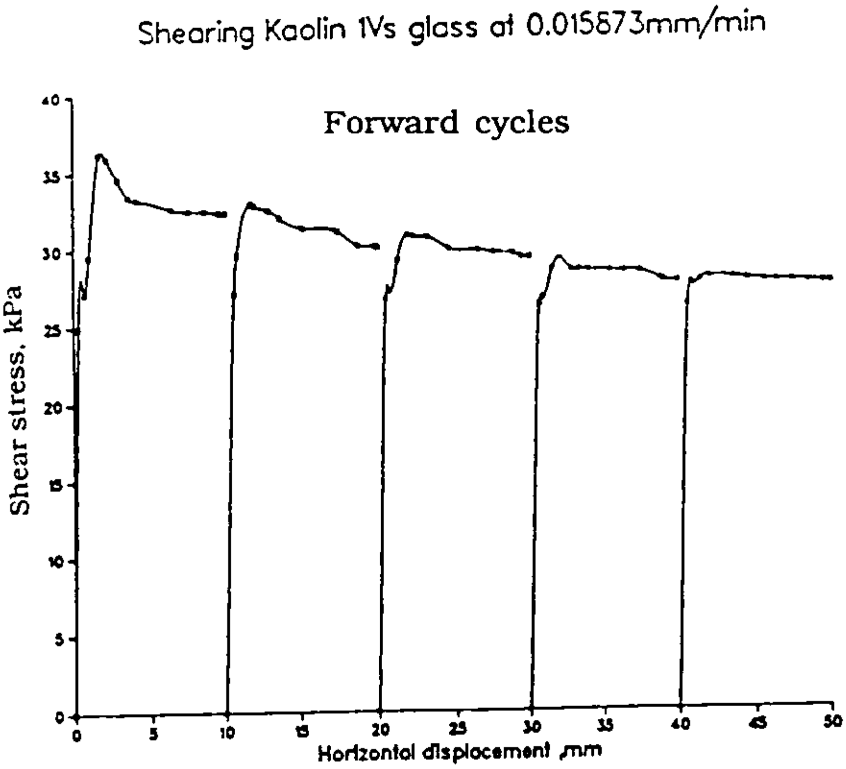


Fig. 7.23 Stress-displacement relationship for kaolin1 - glass using modified shear box.



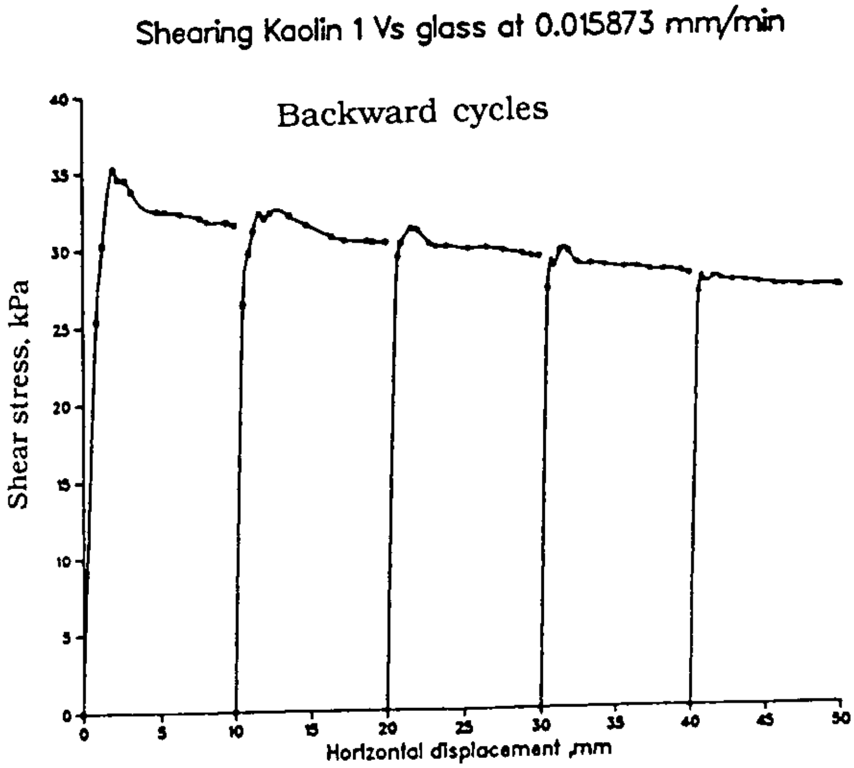


Fig. 7.23 Stress-displacement relationship for kaolin 1 - glass using modified shear box.

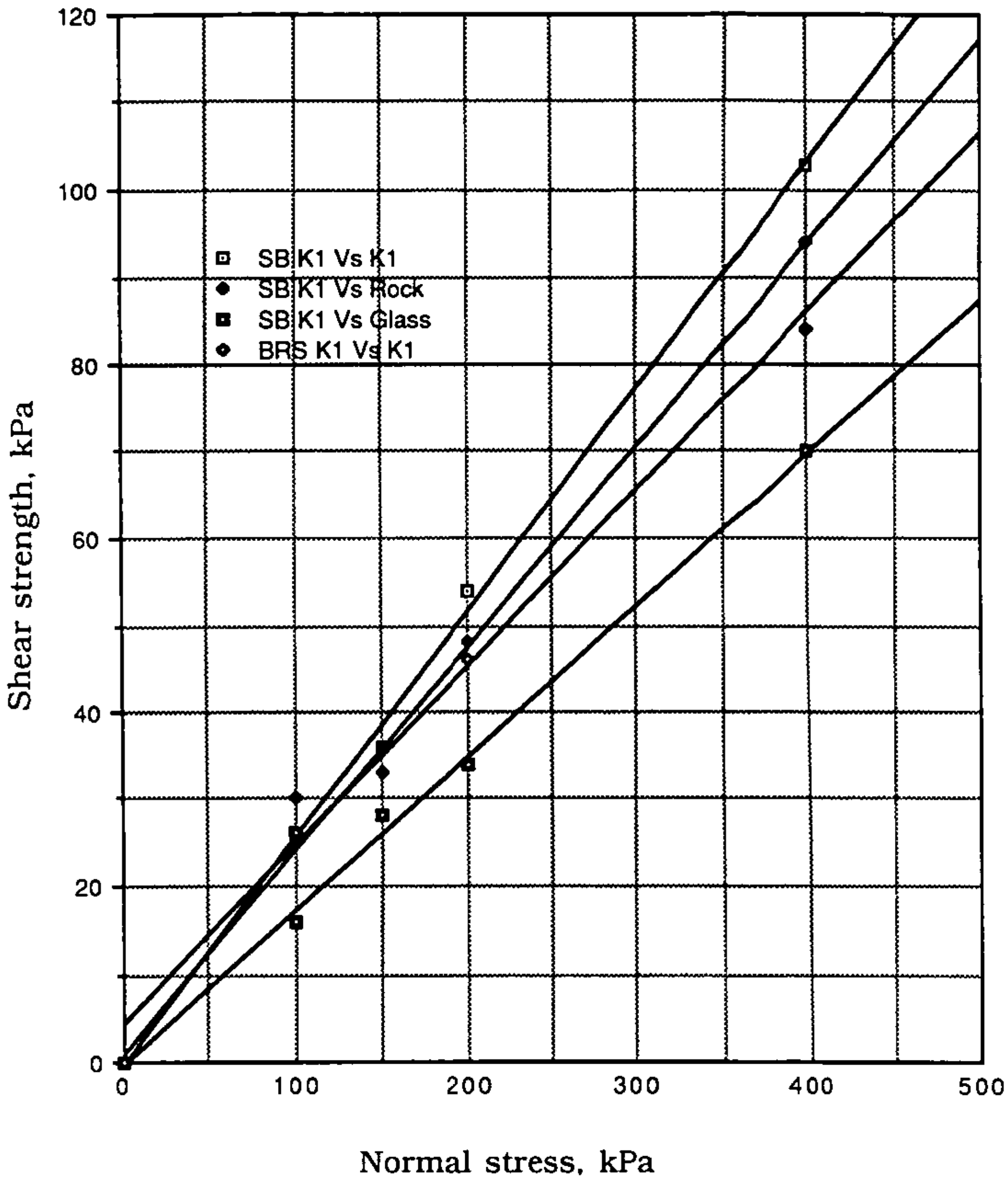


Fig. 7.24 Peak shear strength values for Kaolin1

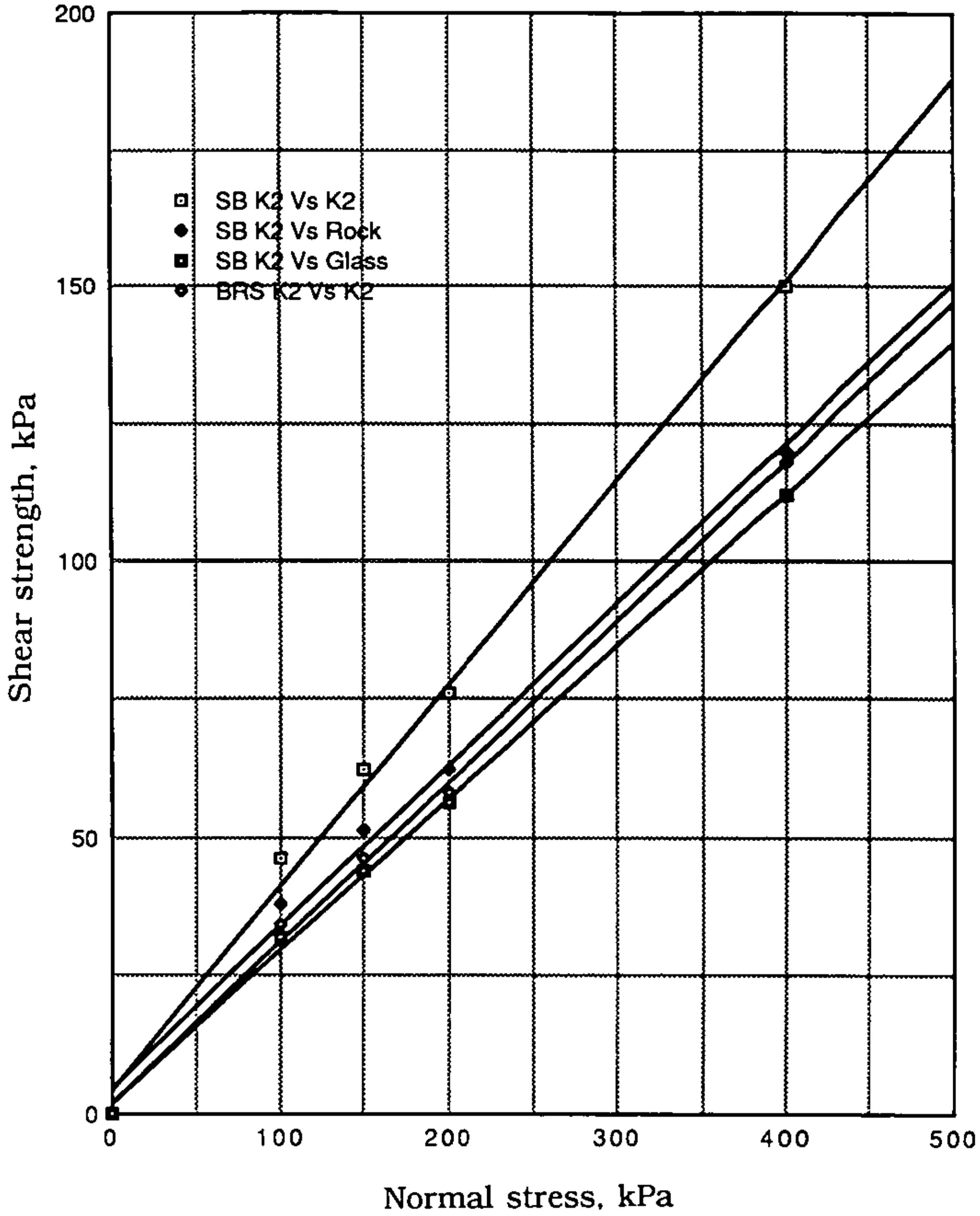


Fig. 7.25 Peak shear strength values for Kaolin2

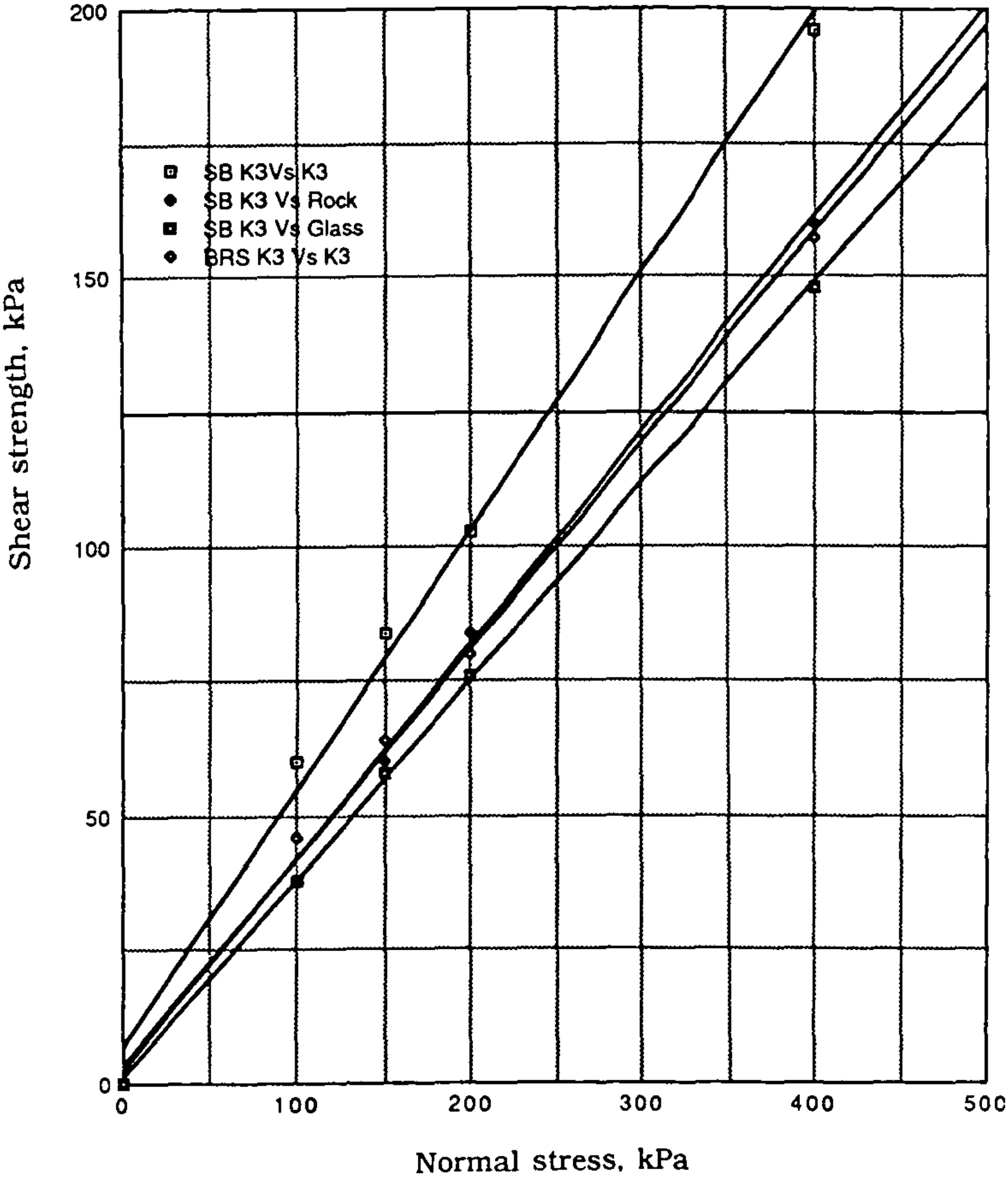


Fig. 7.26 Peak shear strength values for Kaolin3

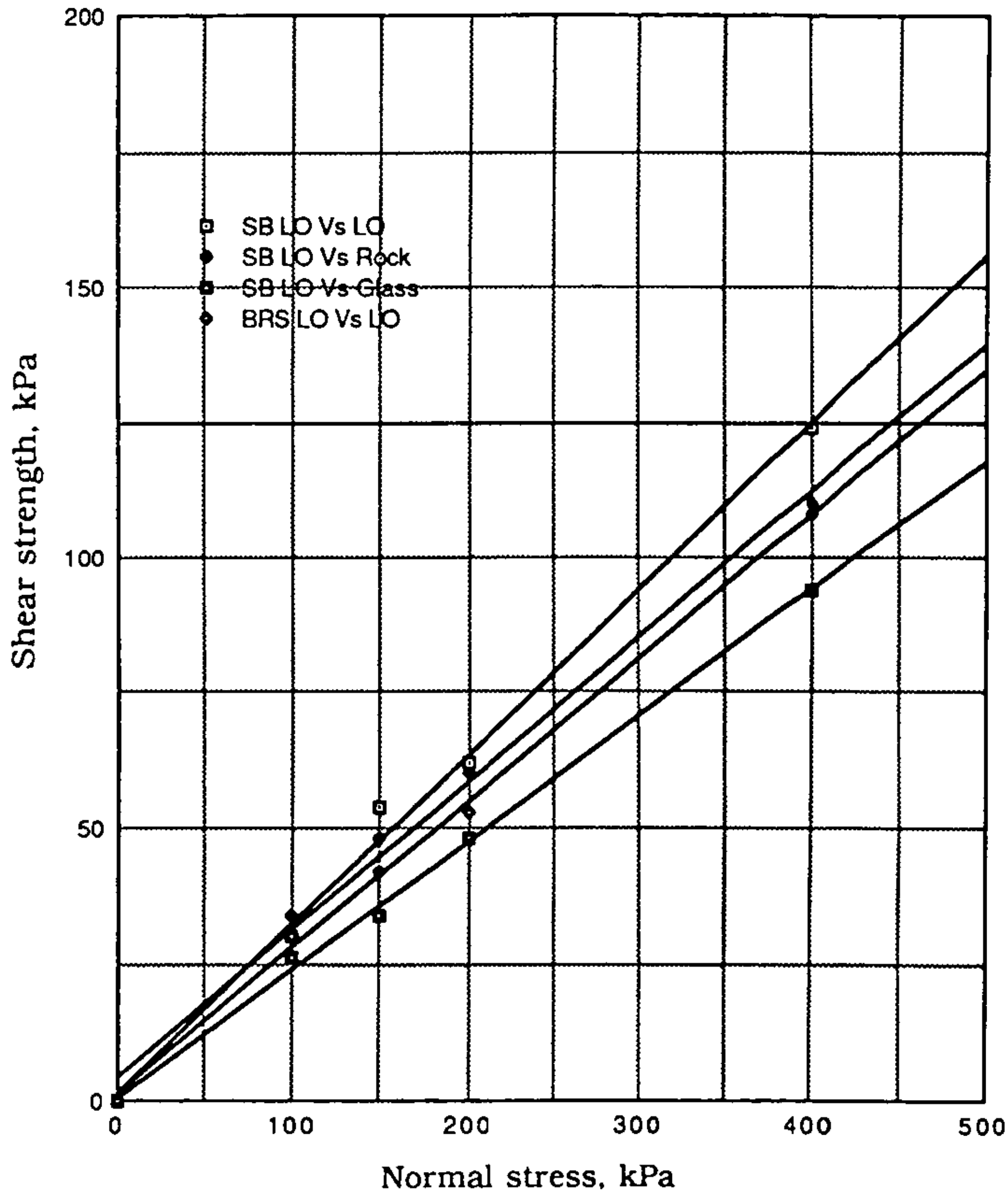


Fig. 7.27 Peak shear strength values for London clay

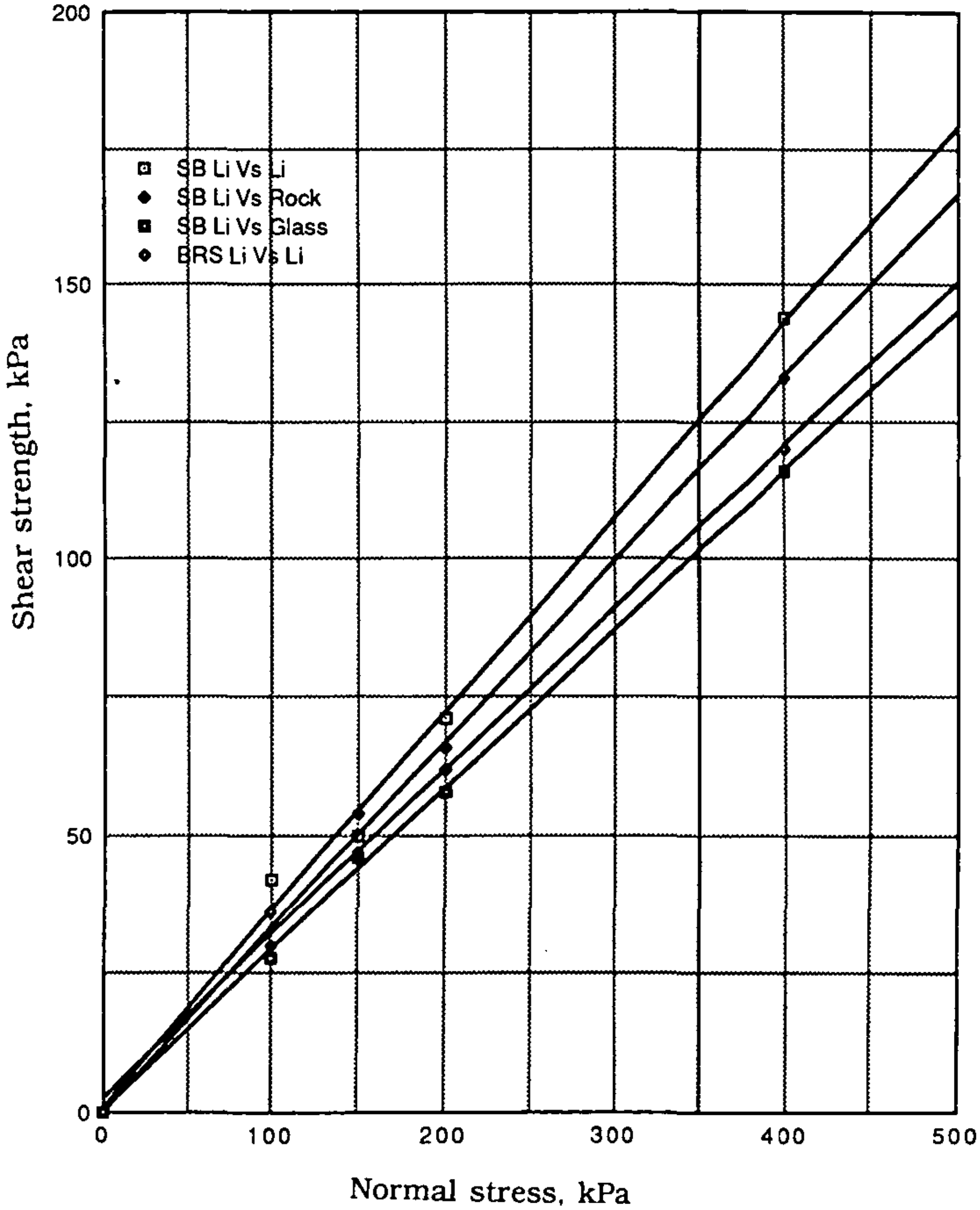


Fig. 7.28 Peak shear strength values for Lias clay

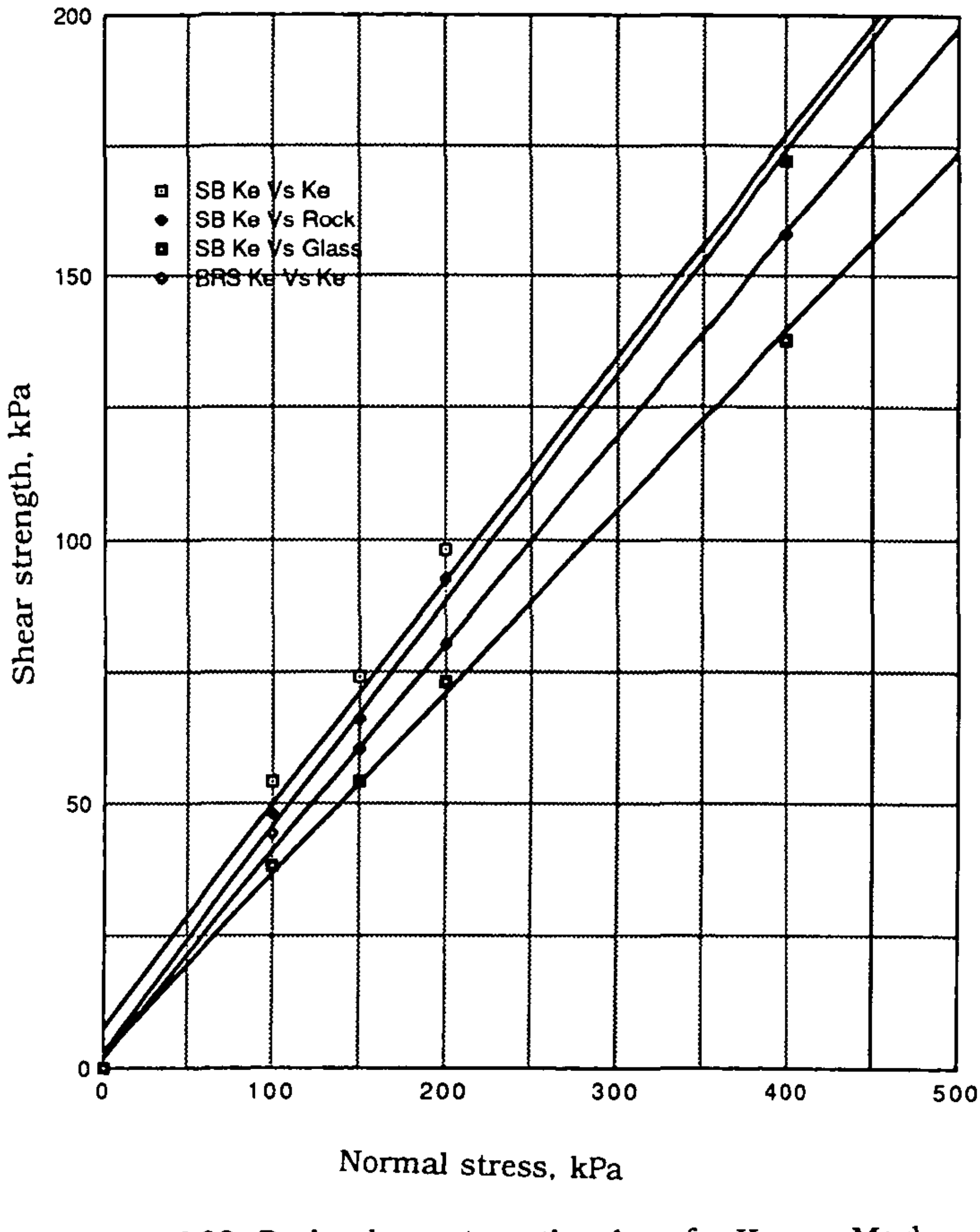


Fig. 7.29 Peak shear strength values for Keuper Marl

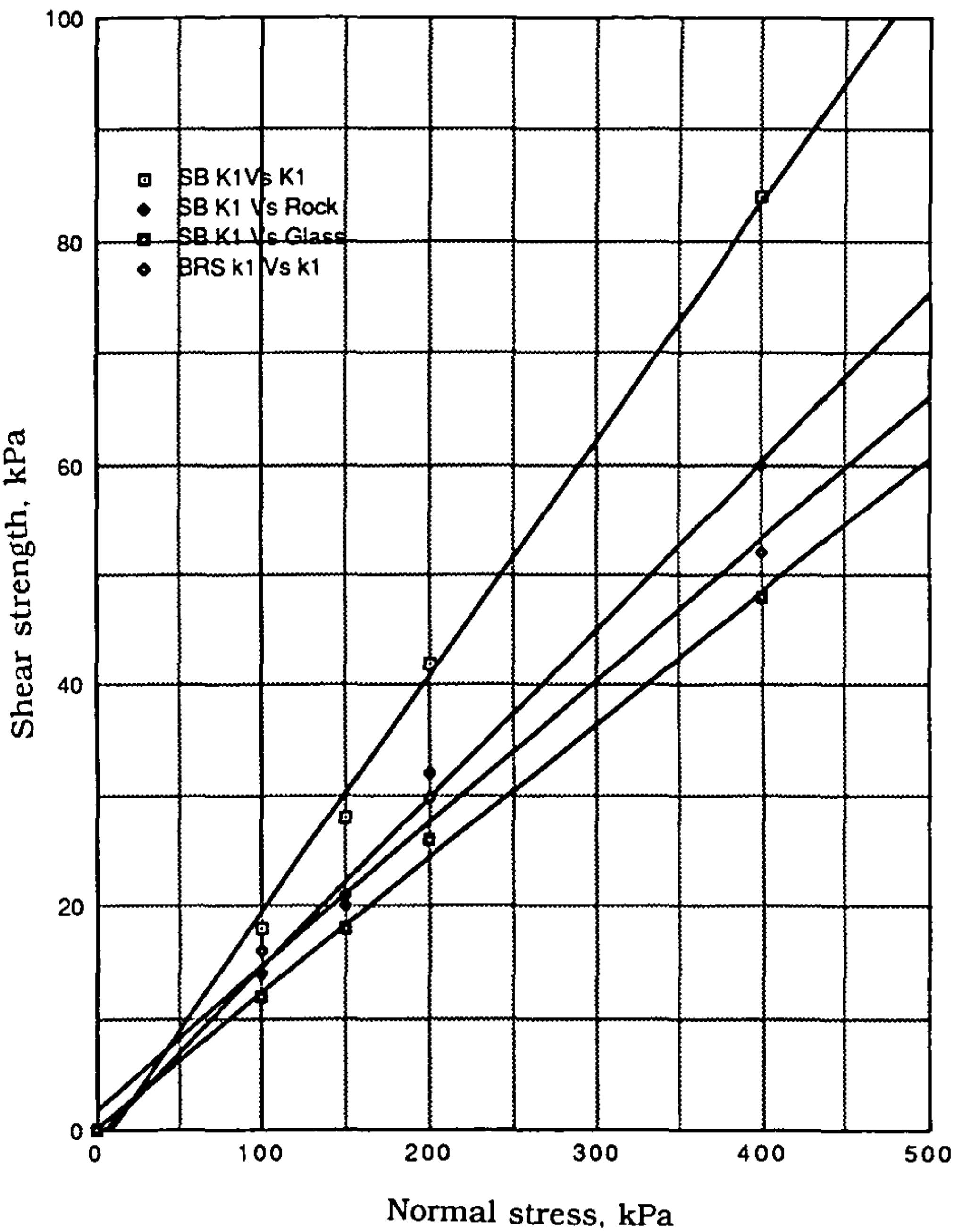


Fig. 7.30 Residual shear strength values for Kaolin1

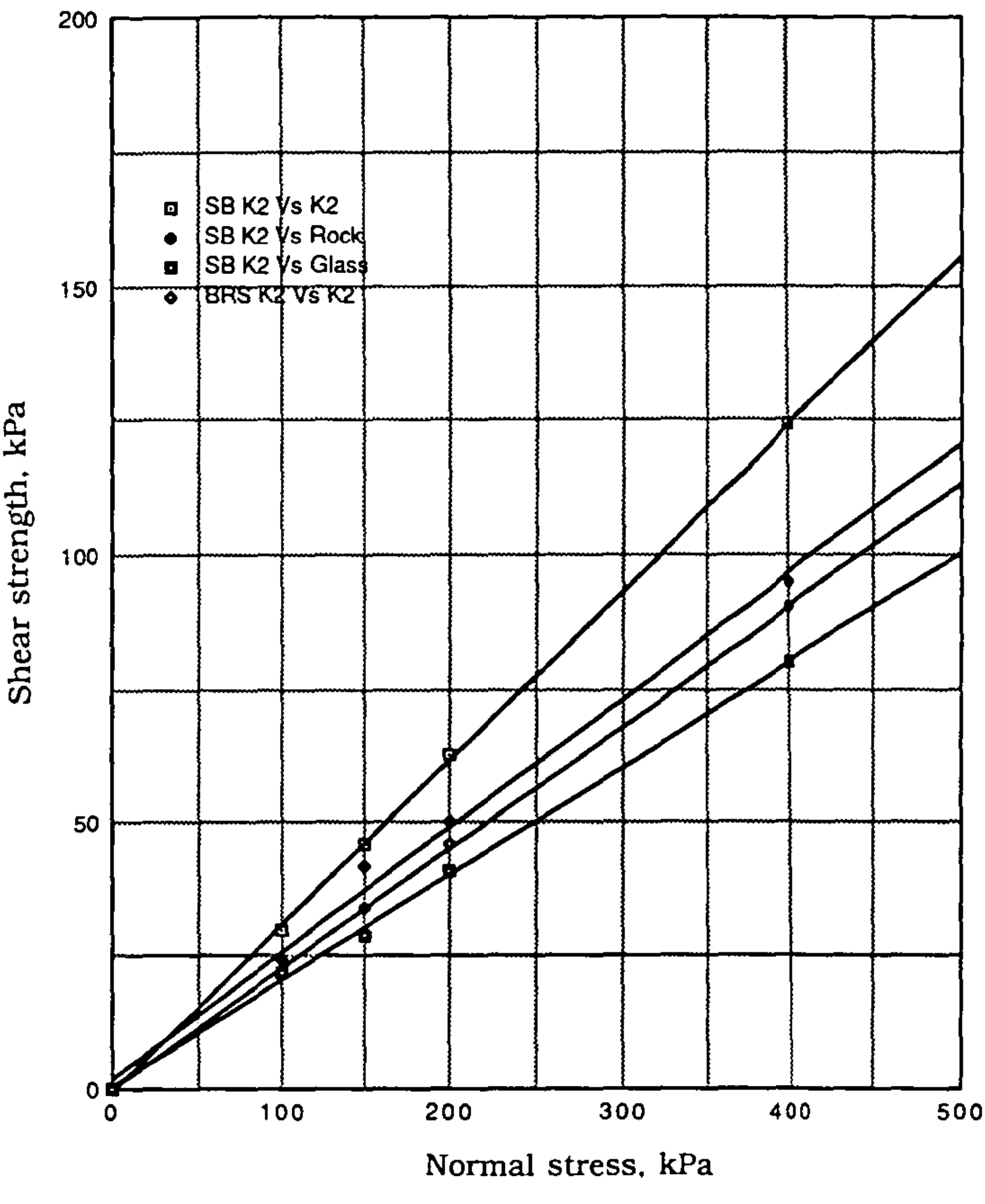


Fig. 7.31 Residual shear strength values for Kaolin2

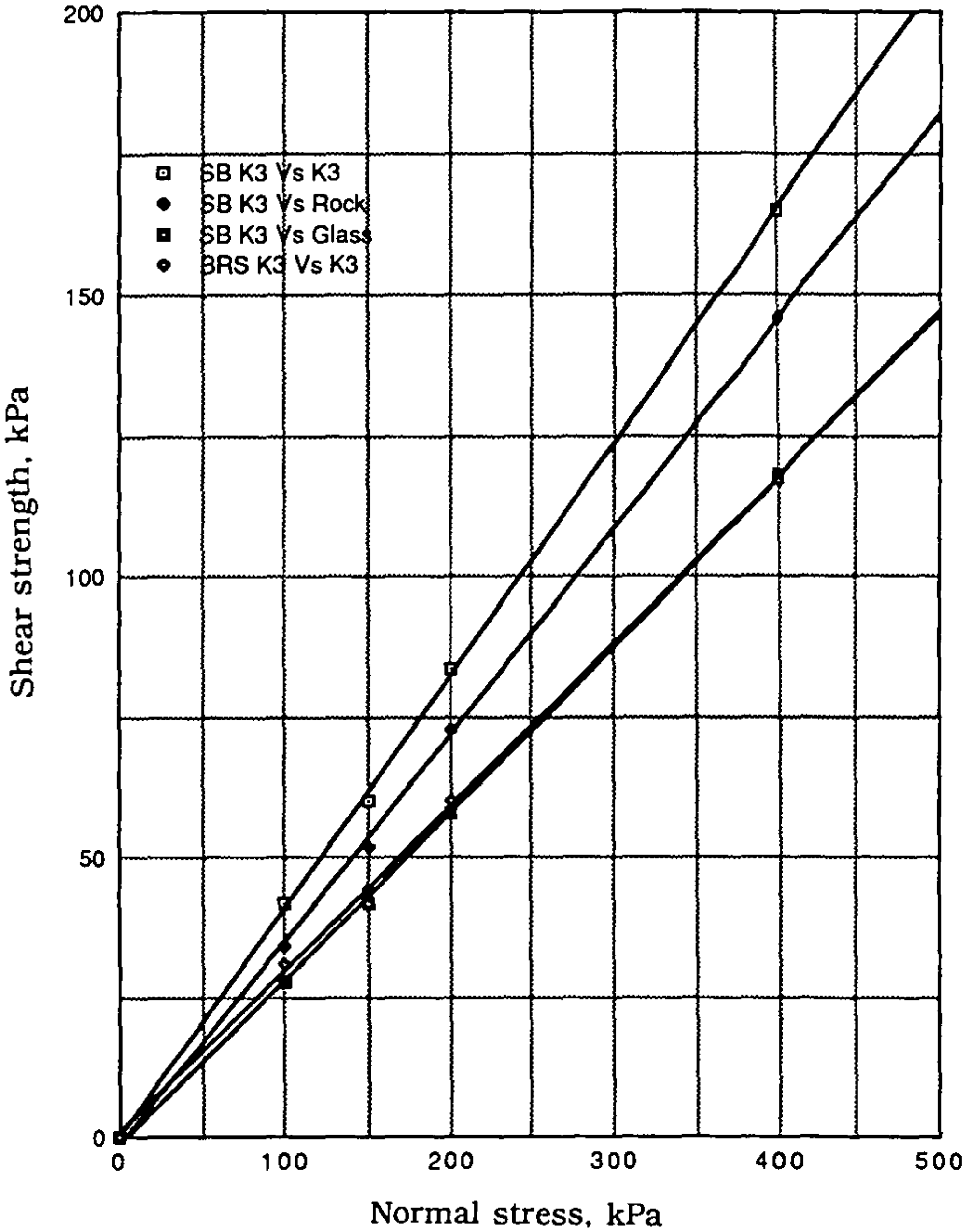


Fig. 7.32 Residual shear strength values for Kaolin3

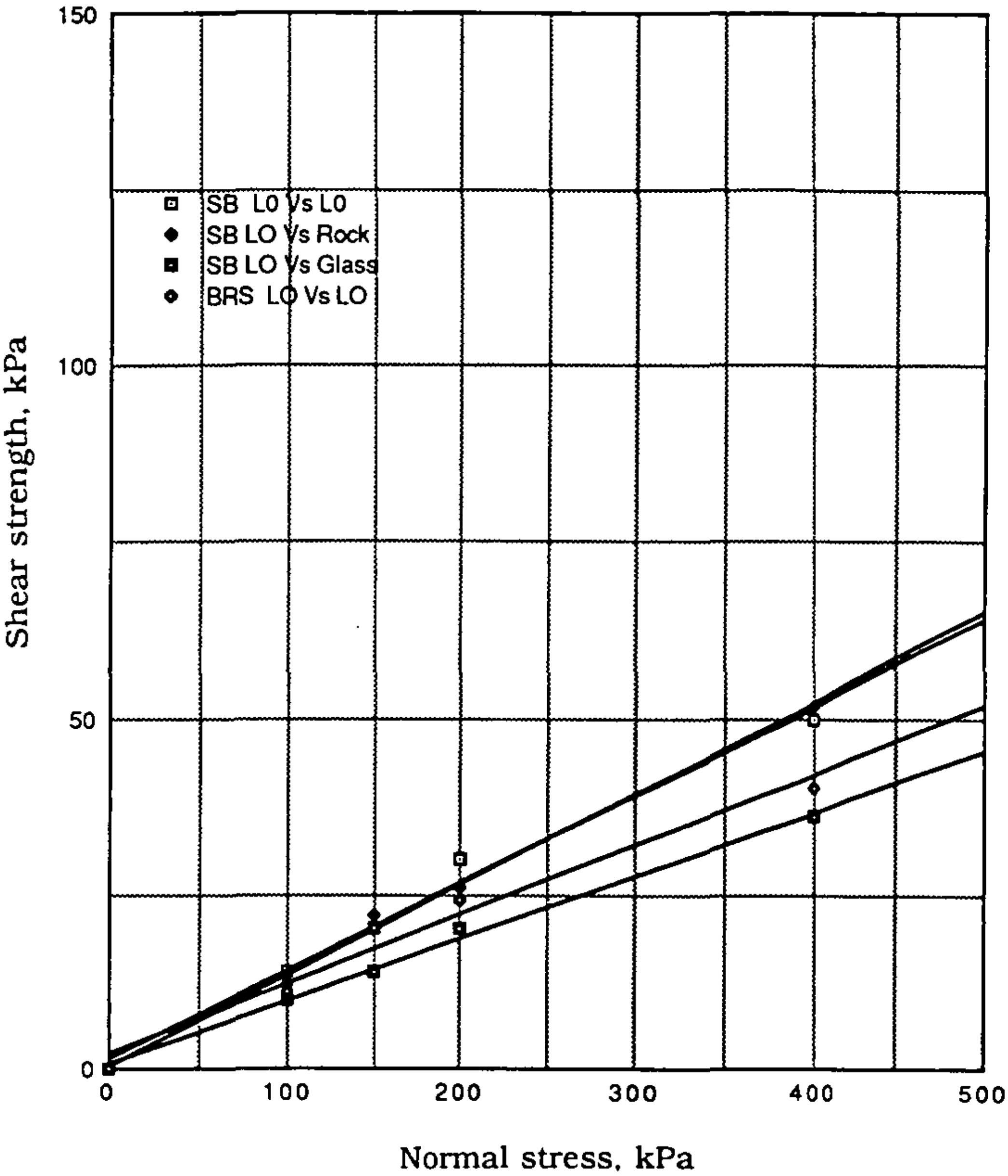


Fig. 7.33 Residual shear strength values for London clay

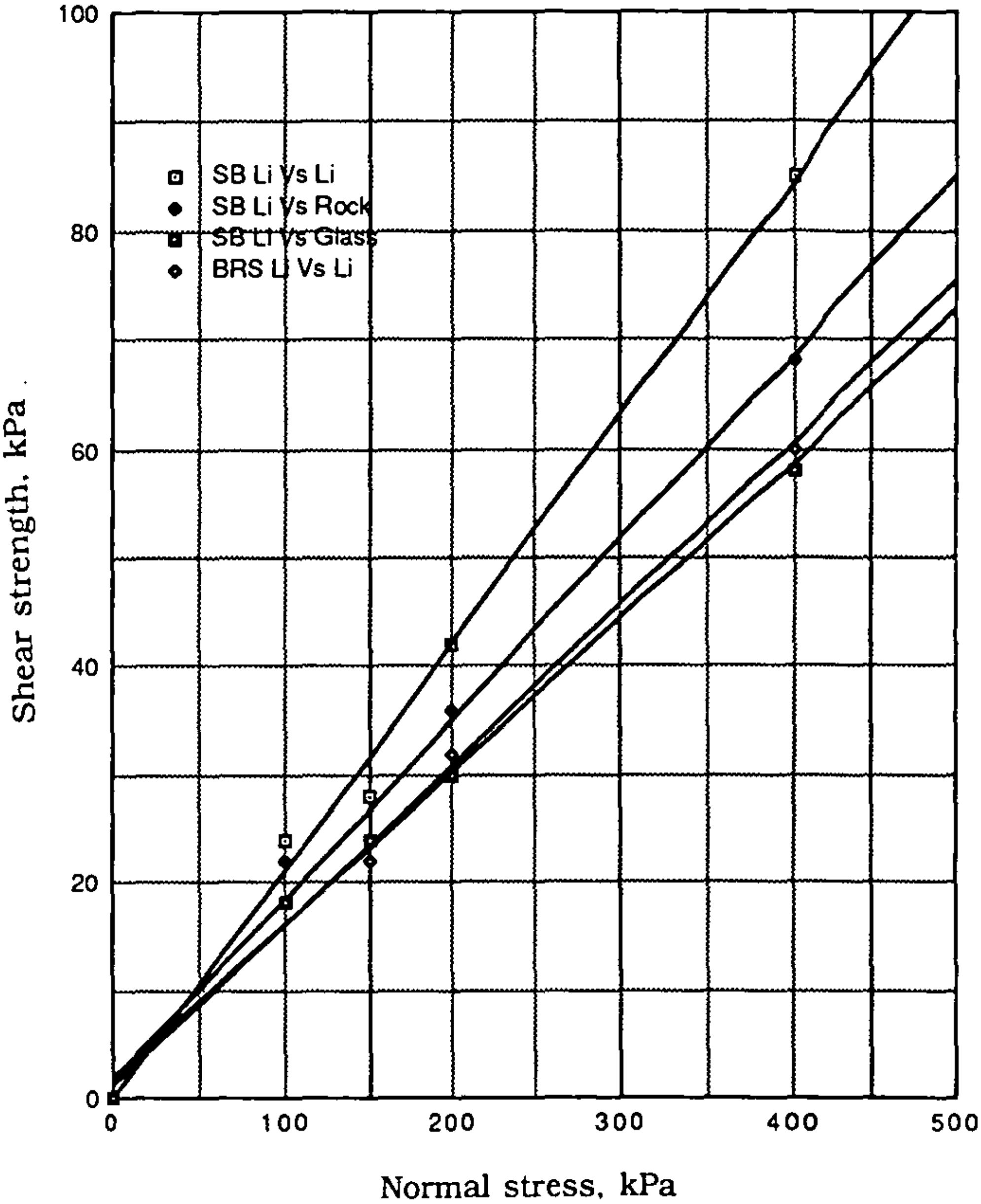


Fig. 7.34 Residual shear strength values for Lias clay

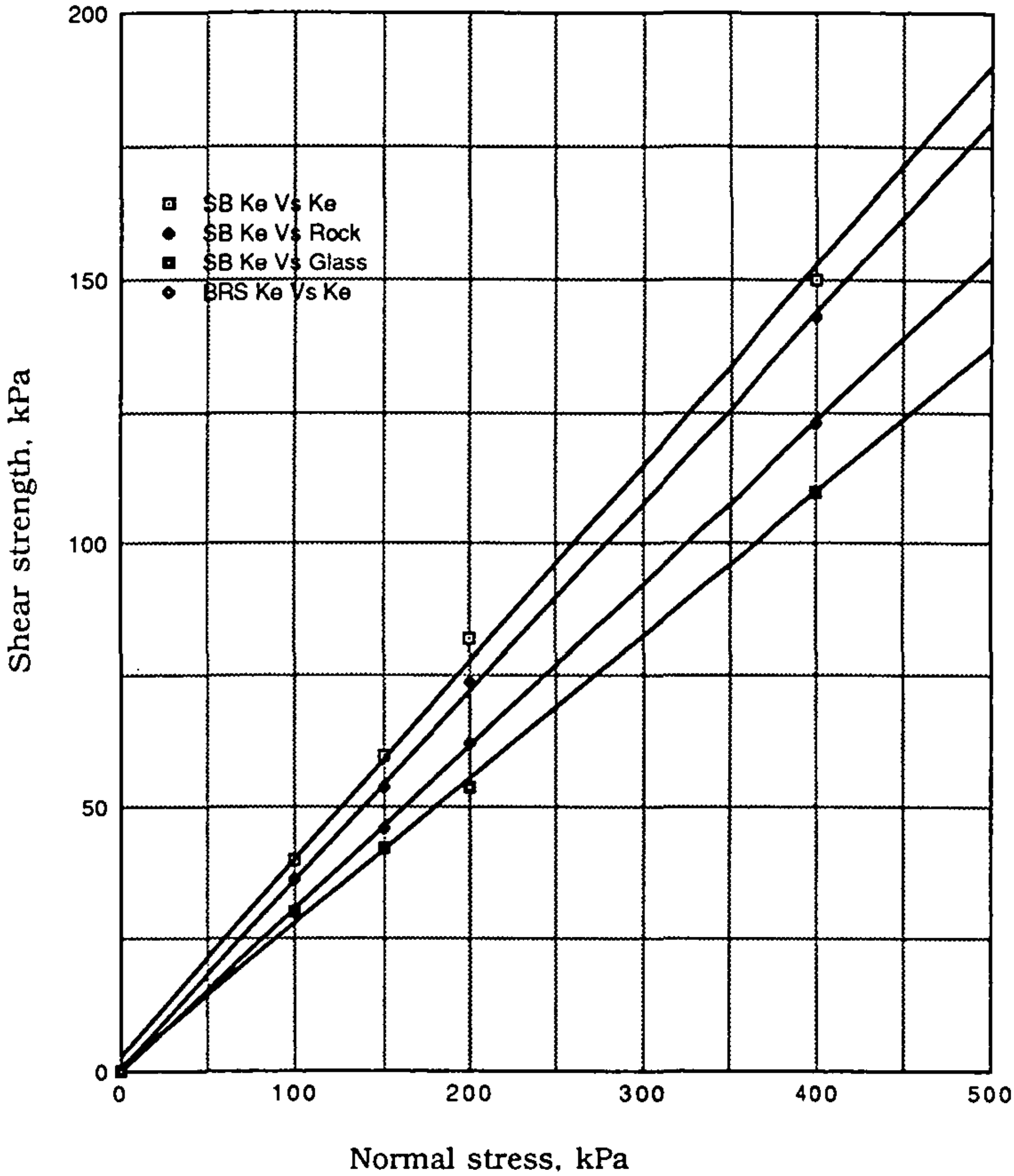


Fig. 7.35 Residual shear strength values for Keuper Marl

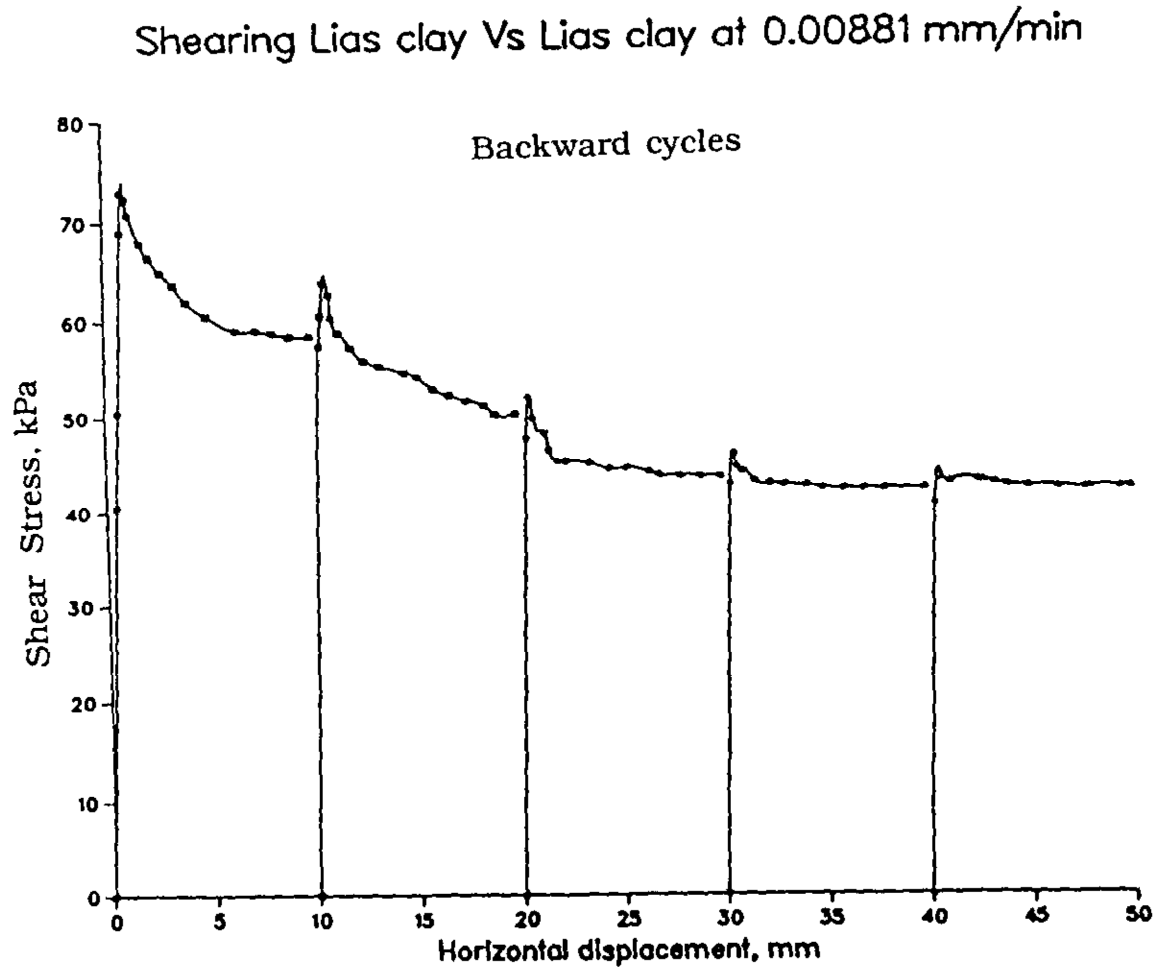


Fig. 7.36 Development of residual strength with the normal stress off during forward cycles for Lias clay using modified shear box.

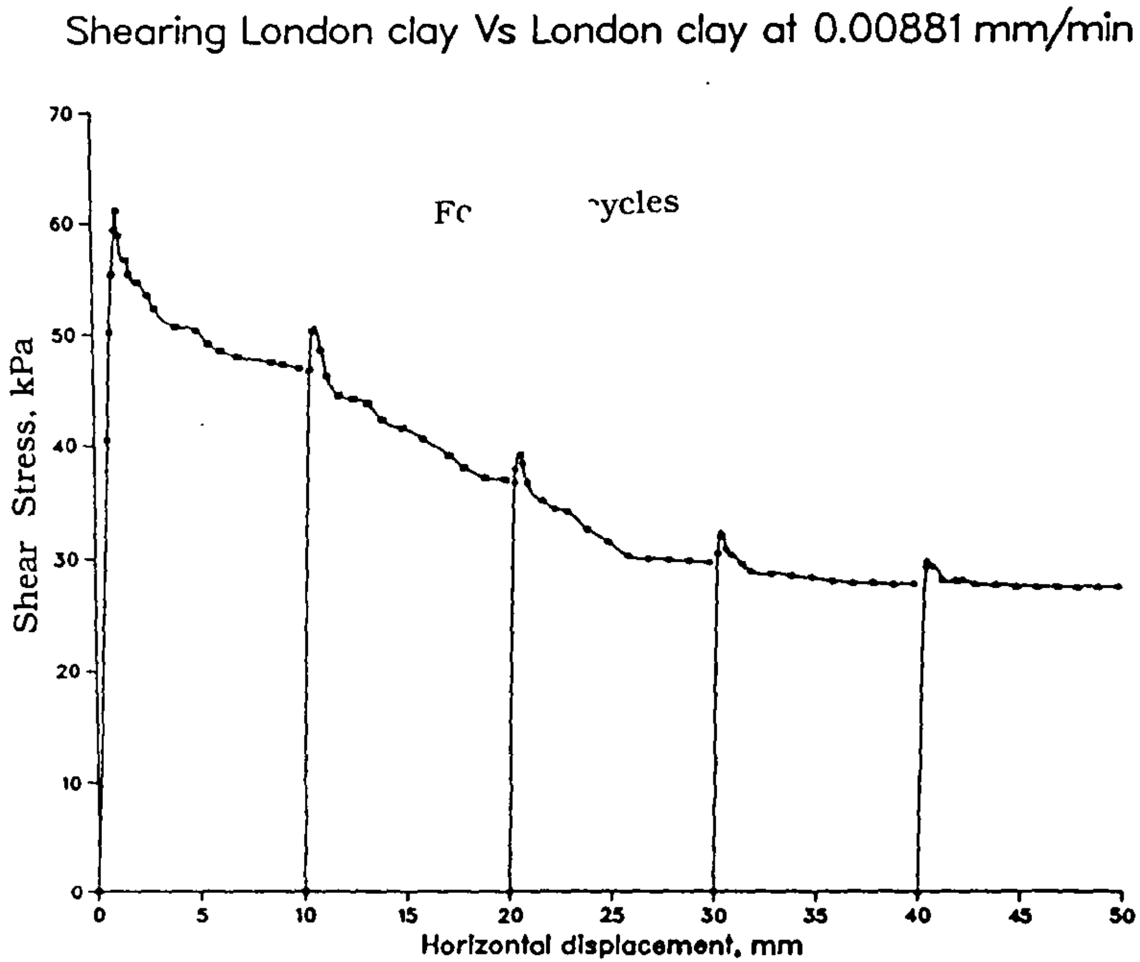
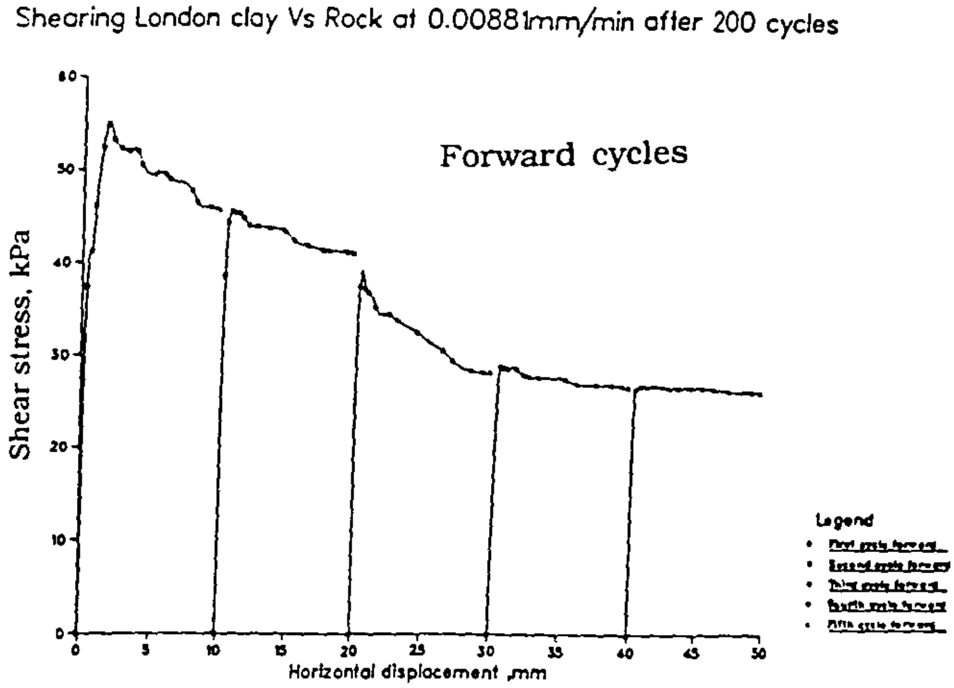


Fig. 7.37 Development of residual strength with the normal stress off during forward cycles for london clay using modified shear box.



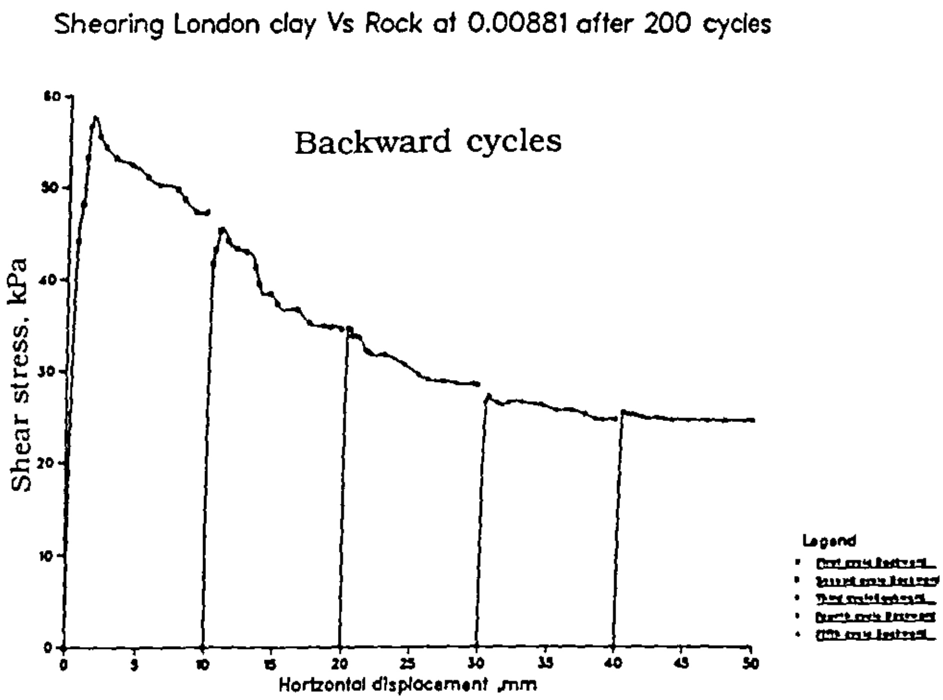
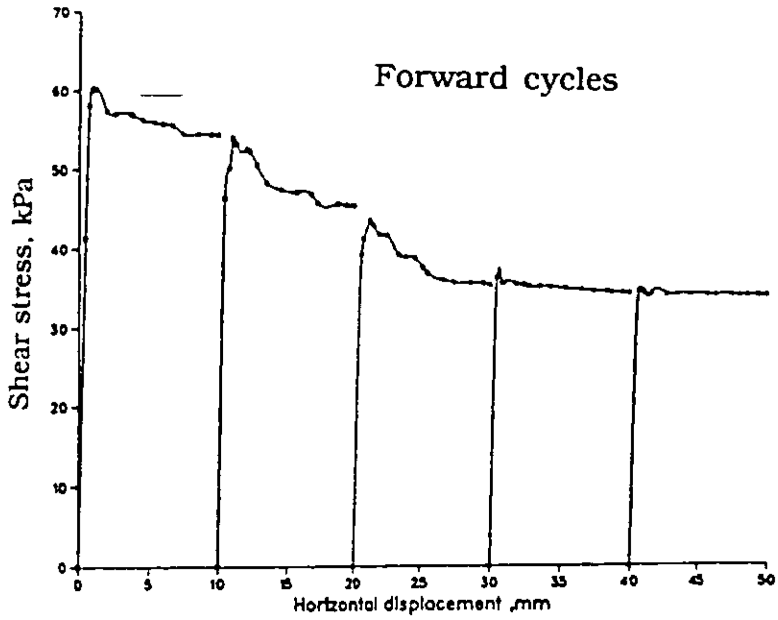


Fig. 7.38 Stress-displacement relationship for London clay-Rock after 200 cycles

Shearing Lias clay Vs Rock at 0.00881 mm/min after 200 cycles



Shearing Lias clay Vs Rock at 0.00881 mm/min after 200 cycles

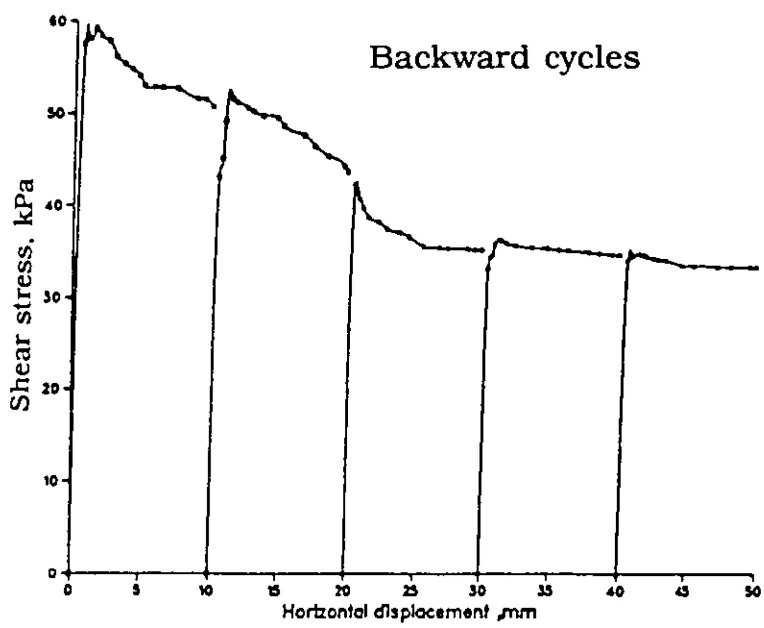
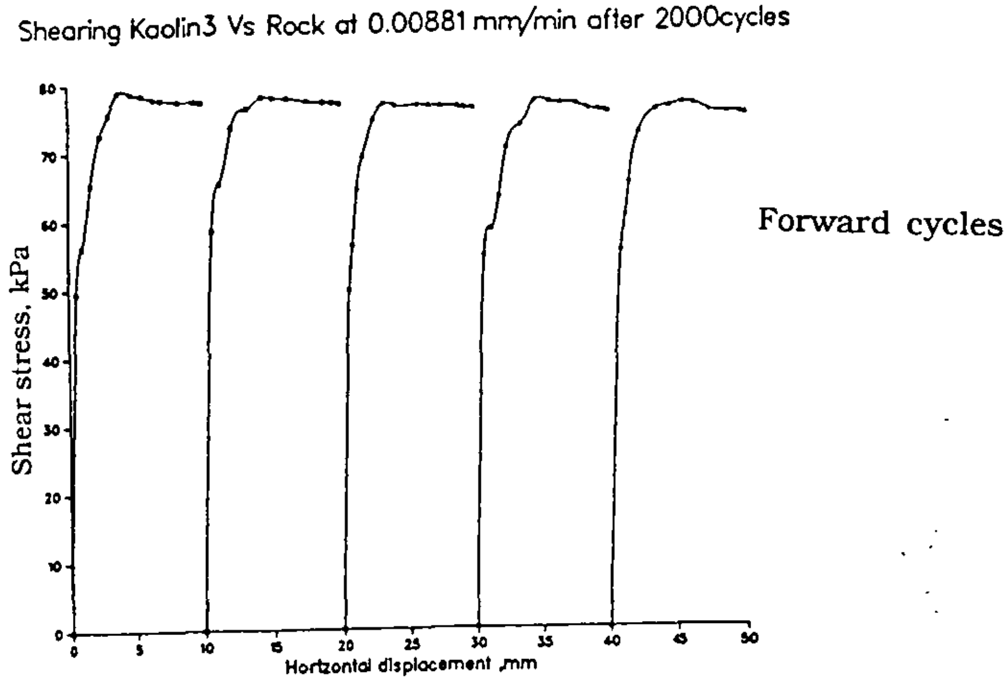


Fig. 7.39 Stress-displacement relationship for Lias clay-Rock after 200 cycles



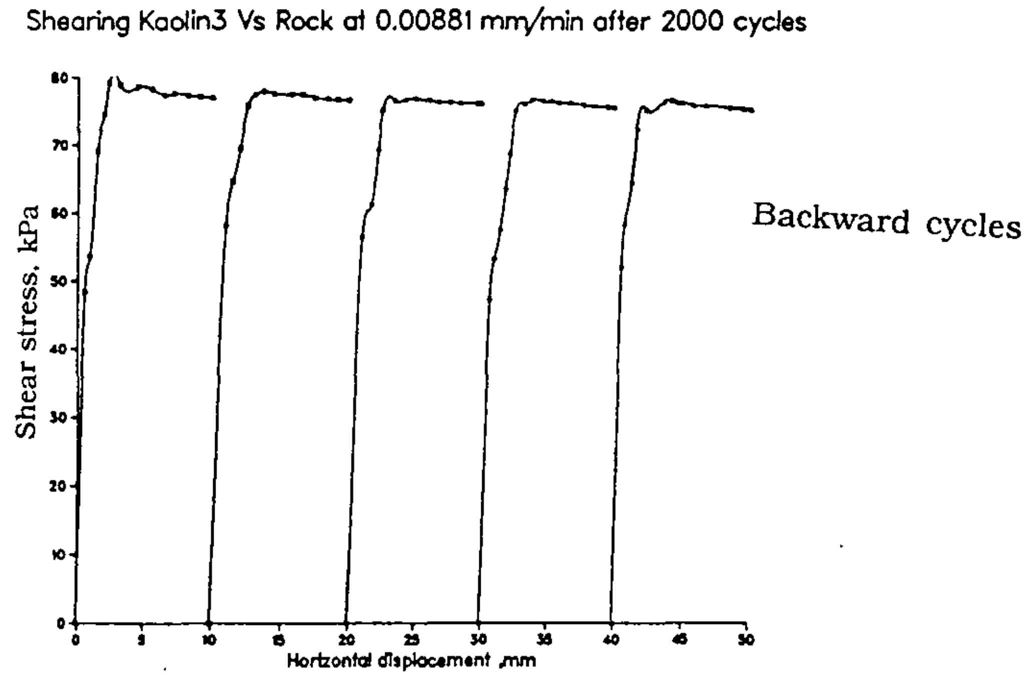


Fig. 7.40 Stress-displacement relationship for Kaolin1-Rock after 2000 cycles

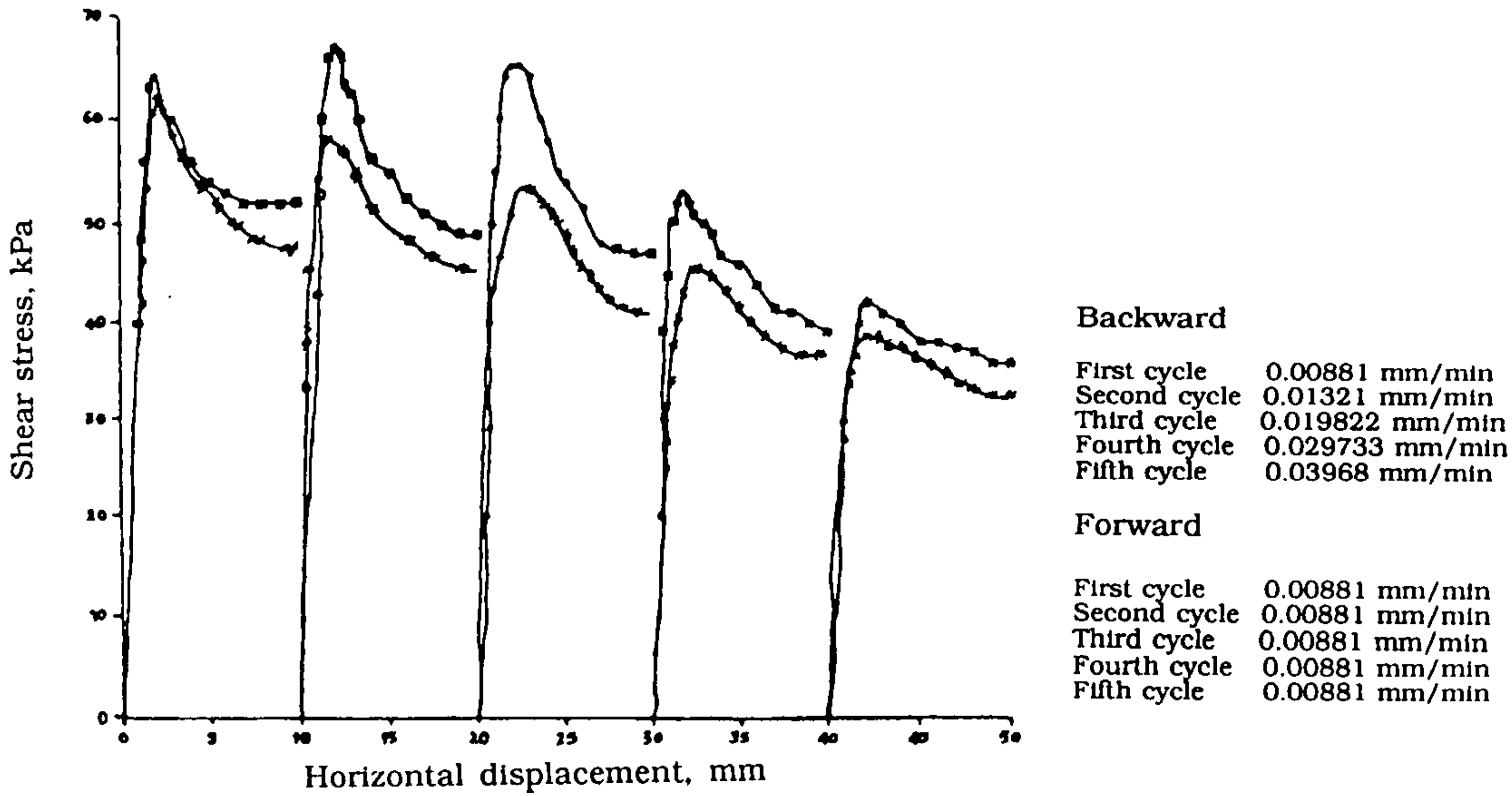


Fig. 7.41 Development of residual strength with increasing displacement rate for London clay using modified shear box.

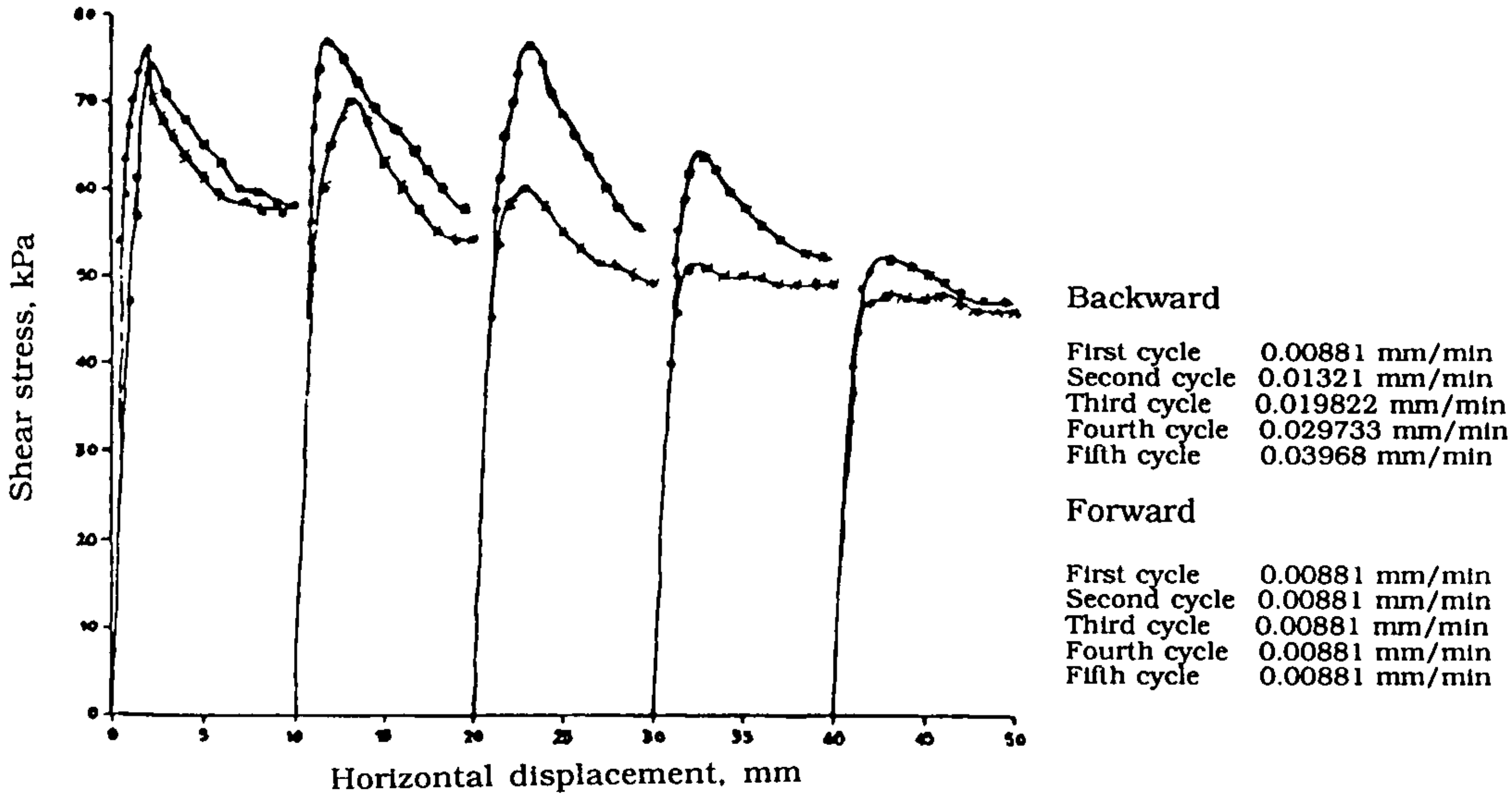


Fig. 7.42 Development of residual strength with increasing displacement rate for Lias clay using modified shear box.

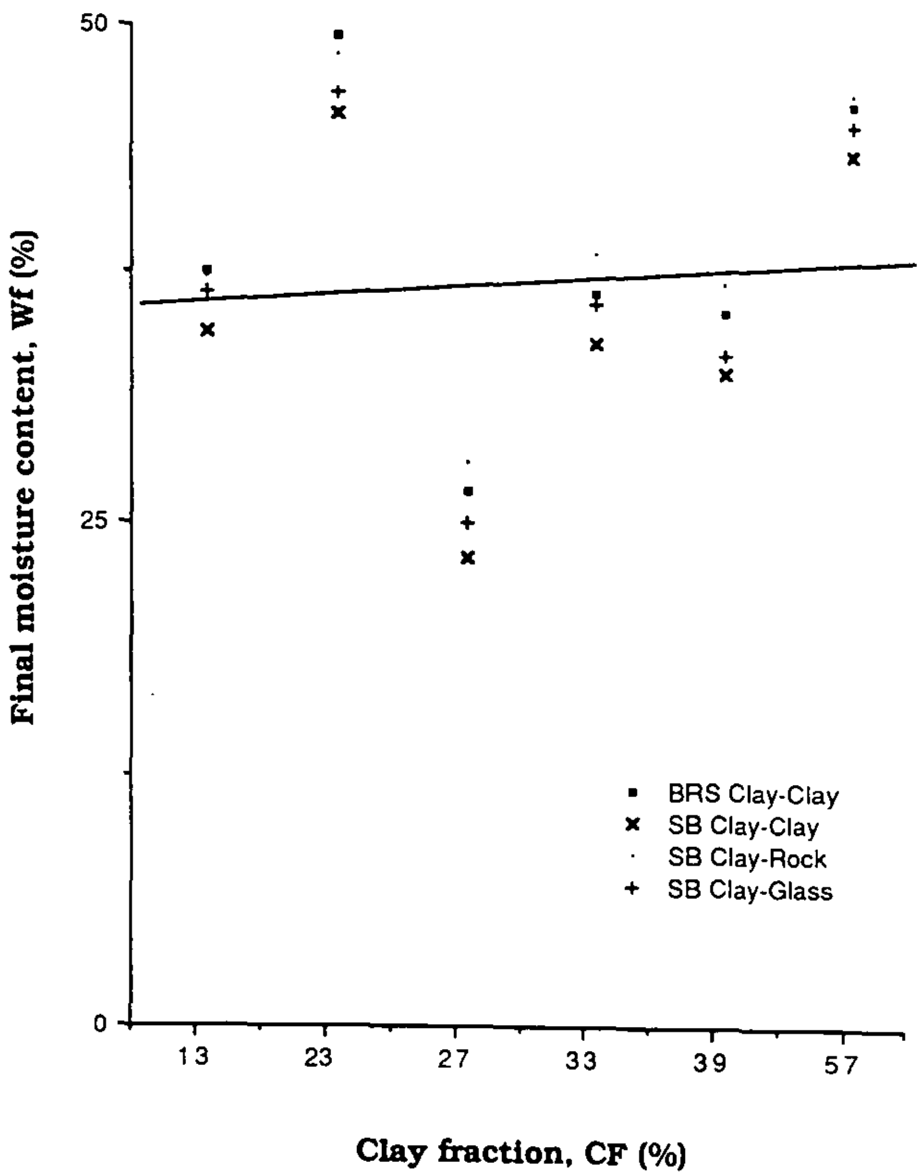


Fig 7.43 Summary of the final moisture content for all clay sheared alone and against interfaces for both Bromhead ring shear and the modified shear box

Fig. 7.44 Formation of shear zone in Lias clay

CHAPTER EIGHT

DISCUSSION OF RESULTS

8.1 Introduction

All the soils' behaviour is discussed in terms of effective stress. In an attempt to obtain a more complete understanding of the strength changes that can occur in practice, samples were subjected to high rate of shear and vibrationary loading and the results have been compared to those of samples subjected to slow rates of shearing.

The results of tests performed thus give more understanding to the problems of structures which are subjected to large relative displacements, and the effect of other phenomena such as the strength of shear zones on the sides of driven piles (Martins and Potts, 1985). Tomlinson, in his significant contribution to the understanding of the behaviour of piles in clay over the years, agreed that it was important to focus on the behaviour of a thin layer of soil adjacent to the pile. An attempt has also been made to obtain a more complete understanding of the difference which exists between the modified shearbox and the Bromhead ring shear. The results of all of these investigations are discussed below.

8.2 Discussion on the Results of Interface and Bromhead ring shear Tests

The purpose of this section is to report the tests to investigate the shear strength of interfaces on the one hand, and to compare the results between the modified shearbox and Bromhead ring shear tests on the other hand. The stress-displacement curves for both the interface tests (Figures 7.22 and 7.23) and soil sheared alone (Figure 7.7) are similar except that the drop in strength for soil sheared against either rock or glass occurs quickly after the peak strength is reached. This is explained by the plane surface facilitating the reorientation of clay particles and the destruction of the bond between particles during shearing being aligned in the shear zone quickly.

Lupini et al (1981) presented an extensive study of the residual strength of cohesive soils as measured in the ring shear apparatus. They found that residual strength measured at slow drained displacement rates resulted from three types of shearing mechanism. In the first mechanism large strain involves rotation of the rotund particles, as in granular soils, and particle orientation has a negligible effect. This mode of deformation was termed turbulent shear. If a high proportion of clay particles is present, a continuous orientated shear surface can form between any rotund particles. This mode of deformation was termed sliding shear. At intermediate proportions of clay particles, orientated shear surfaces can partly form, but are continuously disrupted by the rotund particles. This mode of shear was termed transitional shear.

Turbulent residual shear has thus been defined as the state of residual shear at constant volume for which no particle orientation occurs. In this case soils that shear at residual conditions exhibit typically high residual strengths with ϕ'_r in excess of 25 Degrees. The results reported herein indicate that all the residual shear strengths were under 25 Degrees, which in turn indicates that the samples exhibit either sliding shear mode or transitional shear mode. It can thus be stated that particle orientation is involved in all of the shear mechanisms and this will lead to a residual state being reached at large displacements. The sliding shear mode is characterised by a shear surface that is formed by strongly oriented clay particles and usually has a low residual friction angle (typically in the range from 5 to 12 Degrees).

The highest residual strength angle, ϕ'_r, for Kaolin3 was typically 22.8 degrees, when sheared in the modified sheabox. An explanation of this high value could be attributed to the mineralogy of Kaolin3, which is entirely dominated by Kaolinites. This was shown by Lupini et al (1981) who tested soils of different mineralogies, and found that Montmorillonite soils had the lowest residual friction angle, and Illite or Kaolinite soils the highest. With regard to this the results indicated that all the three Algerian clays contained predominantly Kaolinite, and the residual friction angles were 11.8, 17.6 and 22.8 degrees for Kaolin1, Kaolin2 and Kaolin3 respectively. Despite the first clay having a slightly lower value in comparison with the other two clays, such a relationship is not always true. The Lias clay with Illite constituting the dominant mineral, gave ϕ'_r = 12.1 degrees, from which it can be seen in fact that there is only a relatively small difference, between this value and the value of Kaolin1. In this research, Kaolinitic soils gave results ranging between 11.8 and 22.8 degrees. Despite Keuper Marl not being dominated by either Illite or by Kaolinte, it gave a high residual strength angle of 22.4 degrees. As far as the clay fraction is concerned, Keuper Marl is mainly dominated by silt particles which are not platelets. Chattopadhyay (1972), as reported by Mitchell (1976), Wesley (1977) and Vaughan et al (1978) related residual strength to particle shape. They found that low residual friction angles were associated with platy particles, and that subangular and needle-shaped particles gave high residual friction angles. Regarding these findings, and that because silt contains many rounded particles, the mechanism of failure involved particle rolling and translation, rather than direct sliding, this being prevented by interlocking of the particles. It is therefore, possible that during shear, the continuous oriented planes are interrupted by the silt particles, such that the silt particles gave high residual friction angles. In contrast, London clay has the lowest residual strength angle of ϕ'_r = 8.2 degrees, for which a possible explanation could be related to the high clay fraction which is 39%. The low residual friction angle was associated therefore, with good orientated bands of high clay fraction, preferentially orientated. This produced a low residual strength during shear. As mentioned earlier, concerning the low friction angles (typically in the range from 5 to 12 degrees) it seems that only Kaolin1 and London clay values lie in this range.

The drop in strength post-peak was found to occur quicker with the glass interface than with the rock interface. The relatively quick drop in strength with the glass interface is explained by the smoothness of the surface which facilitates the rapid reorientation of clay particles parallel to the plane and hence to each other. Evidence that the formation of orientation domains begins at relatively small strains was achieved by Goldstein et al (1961). There is also such evidence for the presence of continuous bands of almost perfectly orientated particles in clays subjected to large strains, both in the laboratory (Astbury, 1960) and in the field Skempton (1964). It is clear from this study that the glass acts solely as an interface for the reorientation of clay particles and that the smoother the surface, the more rapid the reduction in strength and the lower the measured residual angle. Another purpose for using the glass interface was to find a relationship between the results from the modified shearbox and the Bromhead ring shear, with the aim of producing comparable values so that the commonly available standard shearbox can be used instead of the much rarer ring shear for residual strength testing.

Kanji (1974a, 1974b) and Kanji and Wolle (1977) tested soils against hard polished rock. They found that the peak shear strength τ_{max} was lower and occurred at small displacement, and also that there was a rapid drop in strength after the peak strength had passed. They explained this drop by stating that the hard polished surfaces encourage the development of residual strength at small shear displacement. In this study, it was found that the clay sheared against glass gave the lowest values of peak and residual strength, for all six clays, compared with rock. The difference between the strengths for both sandstone rock and glass interface tests are given below in Table 8.1

Clay	$\Delta\phi'_r$ (Degrees)	$\Delta\phi'_p$ (Degrees)
Kaolin1	1.6	3.4
Kaolin2	2.6	1.5
Kaolin3	3.3	2.1
London clay	1.6	2.9
Lias clay	1.8	1.7
Keuper Marl	4.8	5.1

Table 8.1 The difference between the strengths of Sanstone rock and glass interface tests.

The tests have thus yielded the following ranges

1.6 Degrees $\leq \phi'_r$rock - ϕ'_r glass $\leq$ 4.8 Degrees

1.5 Degrees $\leq \phi'_p$rock - ϕ'_p glass $\leq$ 5.1 Degrees

Since the development of shears in clay is accompanied by particle orientation, the difference between the two interfaces could therefore be attributed to the fact that the smooth area of glass permits the clay particles to be more strongly orientated in the direction of movement than the rock interface. It is worth noting from these differences that the smooth surface, against which the particles have attained their maximum degree of orientation, must possess the minimum possible resistance to shear, which is defined as the residual strength of the clay. From this examination it is reasonable to suppose that the interface leads to the ready destruction of the cohesion and that there is a strong orientation of clay particles parallel to the surface of shear.

The lack of consistency between the various tests in different apparatuses leaves the engineer with a dilemma in deciding which, if any, is the correct result. Thus in discussion of a new piece of testing equipment two questions must be asked : Do the results represent a correct measurement of the relevent soil property ? and, if so, what is their significance ?
From the results of tests on the six clay soils the Bromhead ring shear tests were found to give much lower values for both peak and residual strengths that those obtained from the modified shearbox tests. The difference in strength for each clay is tabulated in Table 8.2 .This yields the following ranges of strength difference

1.3 Degrees $\leq \Delta\phi'_p \leq$ 4.9 Degrees

1.4 Degrees $\leq \Delta\phi'_r \leq$ 5.2 Degrees greater for the modified shearbox than for the Bromhead ring shear because the gap between the confining rings is small enough to prevent the loss of soil by squeezing. The quantity of the sample tested in the Bromhead ring shear is small, thus allowing it to be drained quickly, and the shear zone is well defined allowing for complete reorientation of the clay particles. Similar findings were mentioned in the literature by Hutchinson et al (1973) who presented results of an investigation of a pre-existing landslide in preglacially disturbed Etruria Marl. They found that the direct shearbox tended to overestimate the residual strength mobilized in the field, whereas the ring shear tended to underestimate it.

The four methods adopted for shearing to obtain peak and residual strength values are summarised in Figures 8.1 and 8.2. It is seen from these two figures that all the results follow the same pattern towards the residual shear strength. The values of the Bromhead ring shear apparatus gave lower peak and residual shearing angles for all the tests used than did the modified reversal Shearbox tests. This difference could be due to the changes in structure and interference between particles within the shear zone, giving slightly higher strength values for the modified shearbox. In contrast, the lower values obtained by the Bromhead ring shear are due to the well-orientated and continuous shear surface behaviour. Furthermore, clays tested against a smooth interface (rock or glass) show lower strength values. This reduction in strength could be explained largely by the orientation of particles along the shear zone, due to the smoothness of the plane surface of the interfaces. The strength values obtained by the Bromhead ring shear were found to lie in between the strength values of clays tested against the smooth plane surface (rock or glass) , with the lowest values obtained with the clay sheared against glass.

This correlation shows definitely the great role played by the reorientation of the particles during shear.

The absolute residual strength values as a percentage of the residual Bromhead ring shear values are given below in Table 8.3

Clay	Clay-Clay %	Clay-Rock %	Clay-Glass %
Kaolin1	139	107	88
Kaolin2	134	106	87
Kaolin3	130	114	95
London clay	121	102	85
Lias clay	133	112	92
Keuper Marl	123	112	85

Table 8.3 Residual strengths measured in the modified shearbox as a percentage of Bromhead ring shear values.

It is clear from Table 8.3 that the range for clay-clay is higher than the two residual interface tests , which is between 121%-139%, whereas for rock and glass the results lie between 106%-114% and 85%-95% respectively.

8.3 Discussion on the Brittleness Index, I_B

The brittleness index I_B first was defined by Bishop(1967) as :

$$I_B = (\tau_p - \tau_r)/ \tau_p \qquad (7.1)$$

where

τ_p Denotes the shear stress at failure (peak)

τ_r Denotes the residual shear stress

If a clay is brittle, the post-peak decrease in strength will be pronounced, the ratio of the peak strength to the residual strength indicating the degree of Brittleness of the clay. The Brittleness index depends primarily on three factors :

a) The dilatancy accompanying failure,

b) The reorientation of clay particles adjacent to the slip surface,

c) Cementation bonds between particles and particle groups.

As the tests were carried out under normally consolidated conditions, the cementation bonds will have been largely destroyed by remoulding and dilatancy will be absent. Therefore the Brittleness of remoulded clay must be attributed wholly to the reorientation of the platey clay particles.

The Brittleness Indices for the main programme of tests are tabulated in Table 8.4 as follows :

Clay	Clay Fraction	Modified shearbox			B.R.S
		IBc-c	IBc-r	IBc-g	IBc-c
Kaolin1	57	0.22	0.33	0.23	0.35
Kaolin2	23	0.17	0.19	0.26	0.20
Kaolin3	13	0.18	0.13	0.23	0.25
London clay	39	0.51	0.56	0.58	0.54
Lias clay	33	0.40	0.45	0.49	0.48
Keuper Marl	27	0.16	0.19	0.26	0.22

Table 8.4 The Brittleness Indices for the main programme of tests.

In general, the highest Brittleness Index was achieved when shearing clay against glass in the modified shearbox, although this is not the case for Kaolin1 and Kaolin3 since the peak strength as well as the residual strength was found to be lowest with the glass interface tests.

One possible reason to justify that the Brittleness Index depends mainly on the reorientation of the platey clay particles is that low values have been found for the Keuper Marl sample. It may be that the silt-sized particles, which consist mainly of conglomerated clay-sized particles, are broken up in the shear strength test (especially as in this case the test was carried out at fairly high effective normal stresses of 100-400 kPa). This would result in the silt-sized particles affecting to some extent to the reorientation of particles during shear. Borowicka (1965) reported reversal shear box tests on different clay soils produced artificially by mixing in the laboratory. He found that Brittleness increased and residual shearing angle decreased with increasing clay fraction.

It seems that correlations between residual strength and soil index parameters cannot be general. They probably depend on the mineralogy of clay particles as mentioned earlier and on the clay size fraction. A correlation between clay size fraction and clay minerals particles are commenly less than 2 micron in size. However, such a correlation need not be general because it is also possible to find non-platy mineral particles in the clay size range. Furthermore, a correlation, if any, between clay size fraction and particle platyness is only indirect.

8.4 Discussion on the Vibrationary Loading effects

The influence of fast rates of displacement on the strength of shear surfaces in cohesive soils must be considered in the study of seismic slope stability. Pre-existing shear surfaces at or close to residual strength are frequently present in slopes of clay and weak mudstone, due to previous slope movement or to tectonic disturbance. Thus, a knowledge of the strength of such surfaces under rapid loading is necessary if stability during and after an earthquake is to be examined.

Lemos et al (1985) showed that if a shear surface or zone is formed at residual strength by slow drained shearing, and then subjected to more rapid displacement rates, the following features are typically observed.

1) There is an initial threshold strength on the shear surface, mobilised without further displacement, which is a function of the rate of fast loading, and which is considerably in excess of the slow residual strength. This is in general agreement with the commonly observed rate effect on the peak strength of clays.

2) There is a further increase of strength with fast displacement on the shear surface.

3) The strength is then likely to drop with further fast displacement. It usually remains higher than the slow residual value, but may drop to a lower value.

4) If after fast displacement of a soil in which sliding or transitional shear occurs, the shear surfaces are tested slowly, then an initial peak strength greater than the slow residual strength is measured, indicating that fast shear has caused disordering of the shear surface.

In this study, tests were carried out using rapid drained shearing following which the samples were subjected to slow displacement rates, using the modified shearbox for clay sheared against plane sandstone. The tests were carried out into two ways : vibrationary loading for 200 cycles with 10mm length of travel, and vibrationary loading for 2000 cycles with 1mm length of travel.

The aim of these tests was to define as well as possible the effect of vibrations on the peak and residual strength of the soils. It should be noted that in nature, residual shear strength conditions are reached as a result of large uni-directional deformations, whereas in the shearbox large deformations can only be achieved by cumulative small deformations in opposite directions. However, under certain man-made conditions (eg beneath large machinery and during construction operations) vibrationary loading can occur. The values of the peak and residual shear strength for vibrationary loading for 200 cycles of vibrations with 10mm length of travel were found to be lower than the values obtained from the tests without vibration. It is considered that the length of travel caused considerable deformations to the structure of the sample during the cyclic loading. In contrast, for the vibrationary loading for 2000 cycles with 1mm length of travel, only the peak strength was found to be lower than the corresponding value without vibration, the residual strengths being approximately the same. Samples subjected to 1mm of cyclic loading caused some small amount of strain but did not produce as much deformation as the first series of tests did. Despite the fact that the number of cyclic vibrations for the second series of tests were 10 times more than the tests of the first series, it does appear that the large length of travel had a more severe effect on the strength of the sample than the small length of travel with cyclic loading.

The significant difference between the results of the two types of test could be explained by the fact that the clay particles during the 1mm travel may not be fully orientated due to the lack of large movements, whereas for the 10mm travel the vibration causes more effect to the particles in the minor shear zones. These could be orientated after slow shear displacement in which the degree of particle orientation is high.

8.5 Discussion on the effect of Normal stress and Rate of shear

The effect of the normal stress and rate of shear were investigated for both London clay and Lias clay. The purpose of these further tests was to investigate the effects of the normal stress on the residual shear strength determined using the shearbox, which has been criticised in the literature because of the problem of disturbing the shear zone during the reverse travel of the box. These tests were conducted in an attempt to minimise the effect of disturbance and, hence, its effect on the residual strength.

From the results presented in chapter eight, the amount of reduction in residual strength for London clay and Lias clay is 0.3 degrees and 0.27 degrees respectively. For the two samples tested the reduction in residual strength can be wholly explained by the reduction in the disturbance during the reversal travel of the box. It is likely that the shear zone was better defined using this technique in comparison with the standard method used previously.

The rate of shear plays a great role in the explanation of slope movement and the mechanism which occurs during failure or instability problems. Rate effects are here investigated for varying displacement rates every backward cycle, the rate increasing with each cycle, while using a slow constant rate of shear for every forward cycle until residual conditions are established.

In general there seems to be a clear trend towards an increase of shear strength with increase of displacement rates for the three first backward cycles. These results are contrary to the three first forward cycles where the strength decreases every forward cycle. It is consistent, however, with observations made by Petley(1966) and Garga(1970). Another factor, which complicates the picture and it is very difficult to avoid it, is the slight but continuous loss of material through the gap between the two halves of the shearbox. This process has been found to be relatively independent of displacement, but if fast enough rates are used, it is possible that the rate of loss of material may to some extent influence the pore pressure behaviour(Lupini, 1981).

The study of rate of shear was also performed to investigate the amount of disturbance that fast rates would induce on an existing shear surface at residual conditions. It was revealed that after the first three cycles the drop in strength could be attributed to a significant change in structure. Fast rates produce some disruption in the orientation of the clay platelets on the shear surface, possibly due to disturbance induced by the increase in the angle of friction between clay platelets. The increase of rate of shear is thought to lead to the generation of new slip surfaces along the shear zone, because the clay platelets are thought to be unable to adjust into as perfect parallel alignment at the fast rates as at slow rates. Thus the drop in strength after three cycles is probably due to the disappearence of the disorder induced in the initial cycles, and the alignment of the shear becomes well defined.

There is an increase in the residual shear strength for both London clay and Lias clay compared with the values sheared without an increase in displacement rate. The difference is 0.85 degrees and 1.4 degrees for Lias clay and London clay respectively. The conclusion is that the fast rate of shear will disturb the shear plane and this disturbance increases the strength of the sample. However, at the same time there is a destruction of the cohesion and after some displacement the bonds between particles break which introduces the drop in strength.

The picture that arises from the literature review and from tests reported in this section suggests that the two clays tested present a sliding type of shear because they show a slight increase in residual strength with shear rate. Lupini (1981) concluded that soils which present a sliding type of residual shear show, in general a slight increase in residual strength with shear rate, whereas soils which shear in a turbulent mode show a tendency towards a decrease of residual strength with shear rate.

8.6 Discussion on the Moisture Content

The process of straining along a shear surface results in the formation of several domains of oriented particles. The main domain containing strongly oriented particles lies between other domains in which the particles are moderately oriented. Outside this zone there is negligible particle orientation (Chowdhury, 1971). Precise determination of the water content in the actual field slip zone is difficult to obtain due to the small extent of the zone, which means that very thin specimens taken from the failure plane may contain a proportion of unsheared soil. For this reason, more sensible results are likely from tests on samples prepared in the laboratory. The values of the final moisture contents for interface tests, together with the values of the final moisture contents for both modified shearbox and Bromhead ring shear tests on the clay alone have been made. The final moisture content of the shear zone was determined after each test by taking the average values of five water content determinations. These values (Figure 7.43) show that on the shear zone, samples sheared against rock have a higher final moisture content than samples sheared against glass, which in turn have higher values than for clay sheared alone in the modified shearbox. The samples tested in the Bromhead ring shear gave the highest values of moisture content, whereas the modified shearbox gave the lowest values, for Algerian clays, but not for the British clays. It is not clear from these results why this occurs, one possible explanation of this phenomenon being the enviromental conditions of the composition of the internal structure.

An X-ray diffraction laboratory test was carried out to determine the mineralogy of each of the clays used. The Algerian clays were found to be dominated by the Kaolinite group, whereas the British clays were found to be dominated by Smectite, Illite and Chlorite for London clay, Lias clay and Keuper Marl respectively. It could be the mineralogical composition of the clays that accounts for this difference. It was noted that the final water content at the residual state was not easier to measure, this is probably due to the fact that some differences which were attributed to the variation in the degree of weathering of different samples, also the problem of the water bath during the shearing effects the measurement of the final water content.

8.7 The relationship between drained friction angles, Atterberg limits and clay fraction.

The purpose of this note is to call attention to a practical correlation which seems to exist between residual shear strength, Atterberg limits and clay fraction and which has been recognized for at least 15 years. In this study, a series of modified shearbox tests has been conducted using selected clays with plasticity indices and clay fractions varying over a wide range. The soils were throughly remoulded and the water content prior to consolidation was near to the liquid limit. Figure 8.5 shows the residual friction angles against plasticity index for both clay sheared against clay and clay sheared against interfaces in comparison with other values which are taken from literature. It is interesting to note that the values obtained from this study have the same shape as the other results, with the minimum residual friction angles attained being the lower values for the interface tests.

The clay fraction factor has been considered in the literature by many researchers. Skempton(1964) has claimed that there is a decrease in ϕ'_r with increasing clay fraction due to the clay fraction helping the reorientation of clay particles into the shear zone to be defined quickly. Furthermore two curves, one defined by Skempton(1964) and another defined by Lupini(1981), are used for comparison with this study. It is worth noticing that the clay sheared against clay test data lie between the upper and lower bounds, whereas for clay sheared against interfaces, the data lie on the lower bounds, even much lower for the case of clay sheared against glass, (see Figure 8.6). On the other hand, all the values either for clay sheared against clay or clay sheared against interfaces were found to fall below the ranges given by Skempton(1964, see Figure 87).

In Figure 8.8 the residual friction angle has been plotted against the liquid limit which is in fact a measure of the ability of the soil composition to hold water. As the particle size decreases and therefore the particle surface area per unit weight increases, the liquid limit is expected to increase. Thus a correlation between liquid limit and residual friction angle is expected, in which there is a drop in residual friction angle with increasing liquid limit.

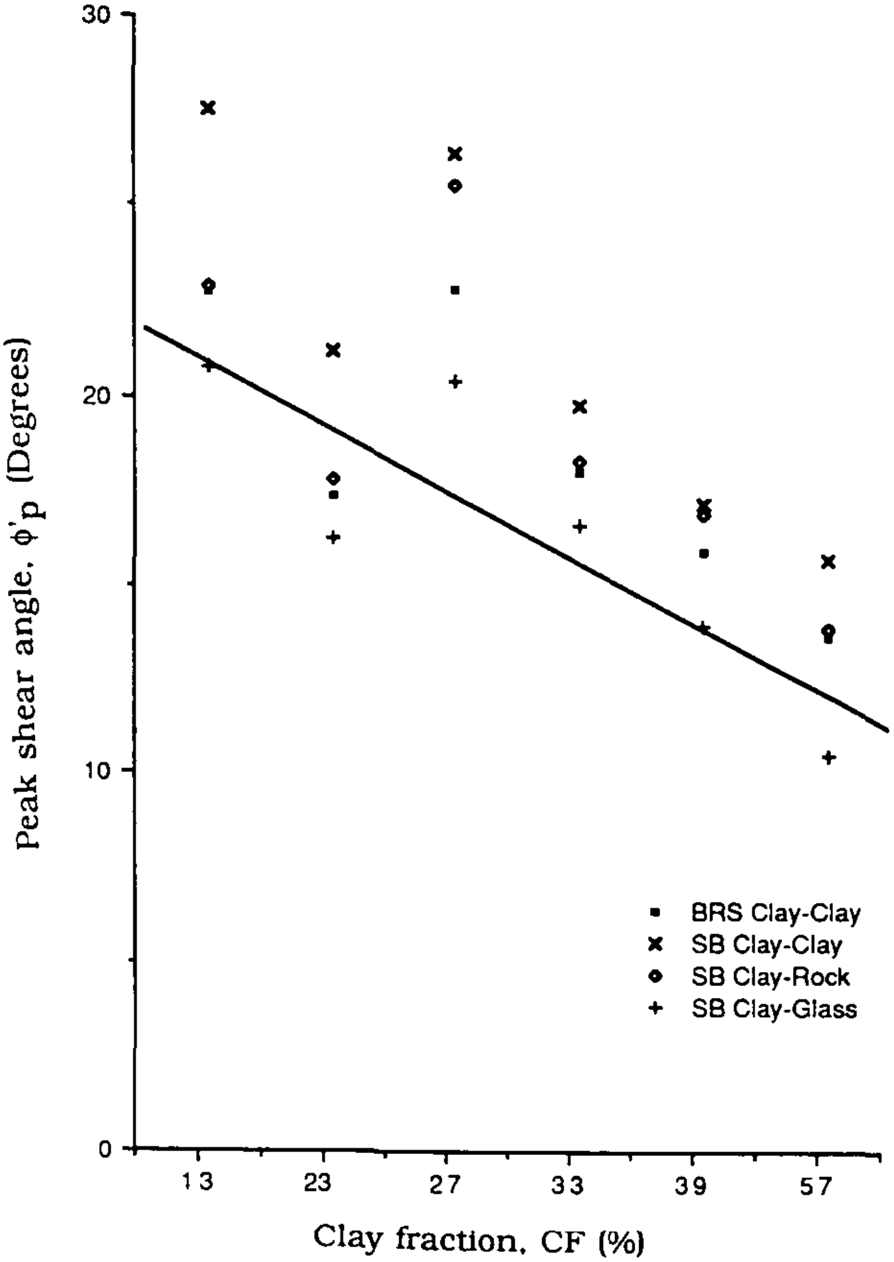


Fig. 8.1 Summary of the peak shear strength, ϕ'_p against clay fraction for all the six clays tested.

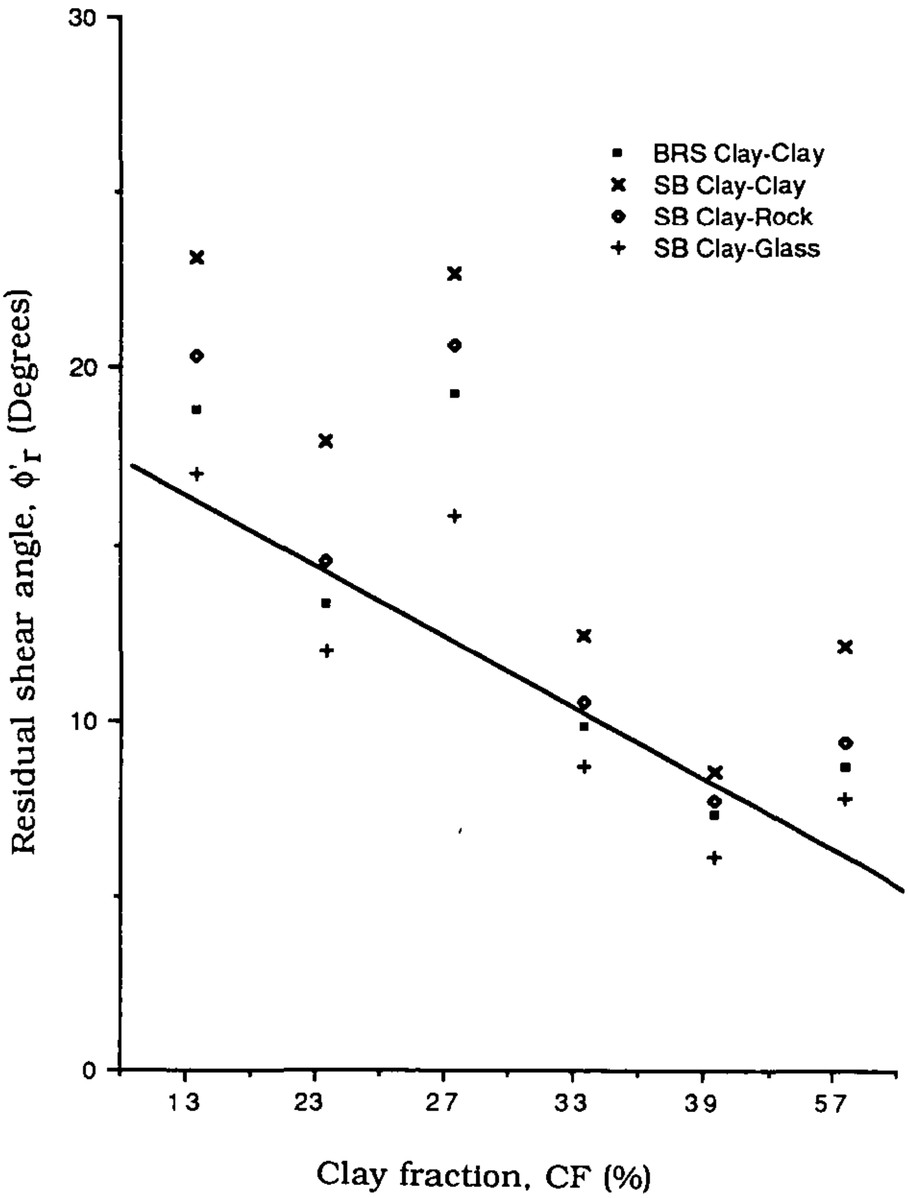


Fig. 8.2 Summary of the residual shear strength, ϕ'_r against clay fraction for all the six clays tested.

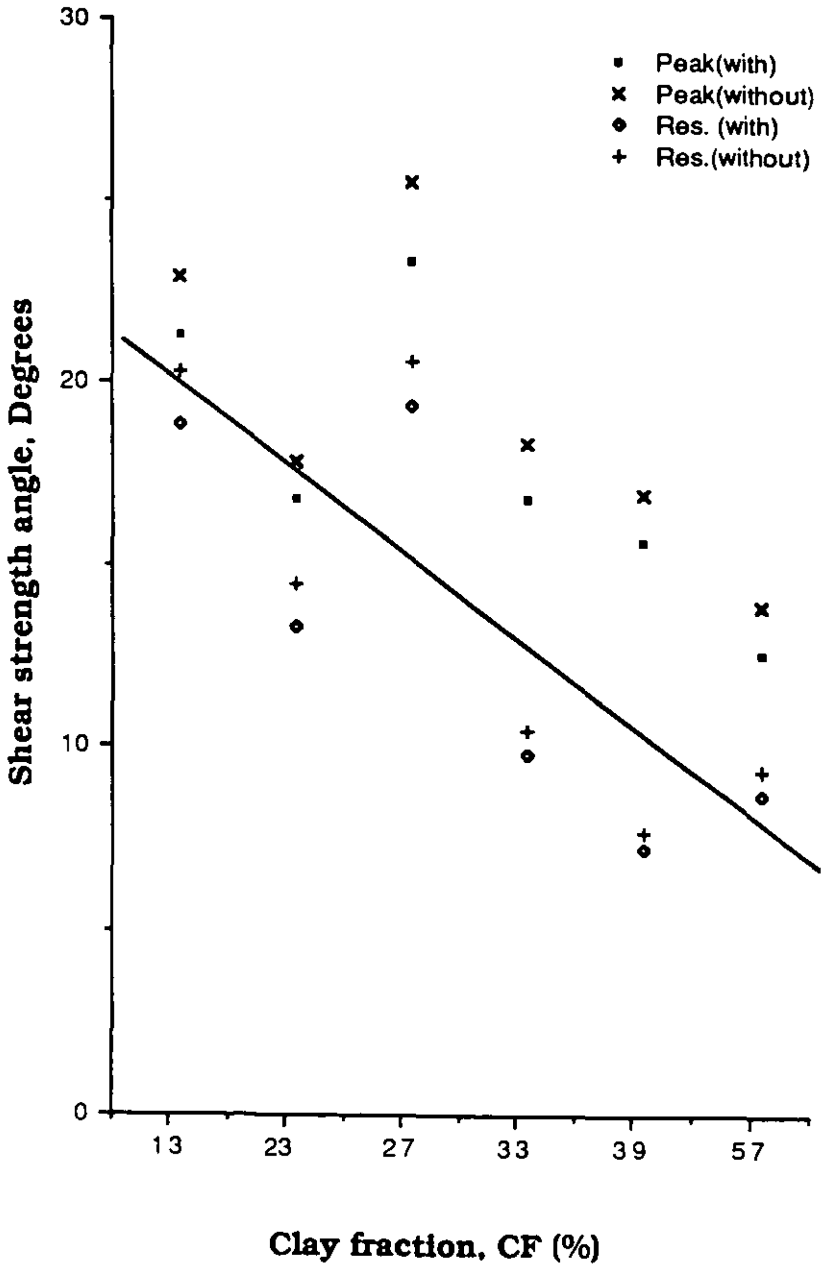


Fig. 8.3 Summary of peak and residual strengths for clay-rock(with and without vibrations, 200 cycles and 10 mm length of travel)

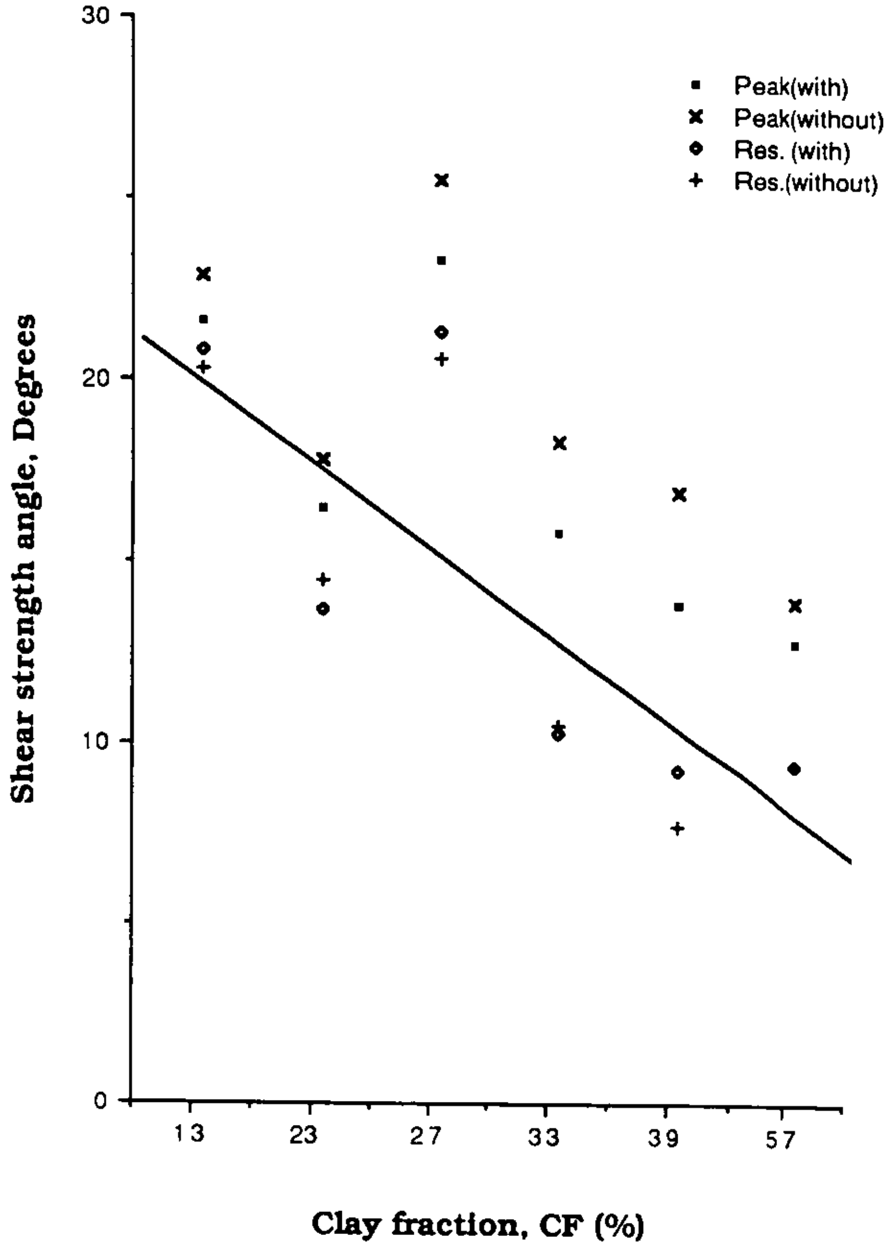


Fig. 8.4 Summary of peak and residual strengths for clay-rock(with and without vibrations, 2000 cycles and 1 mm length of travel)

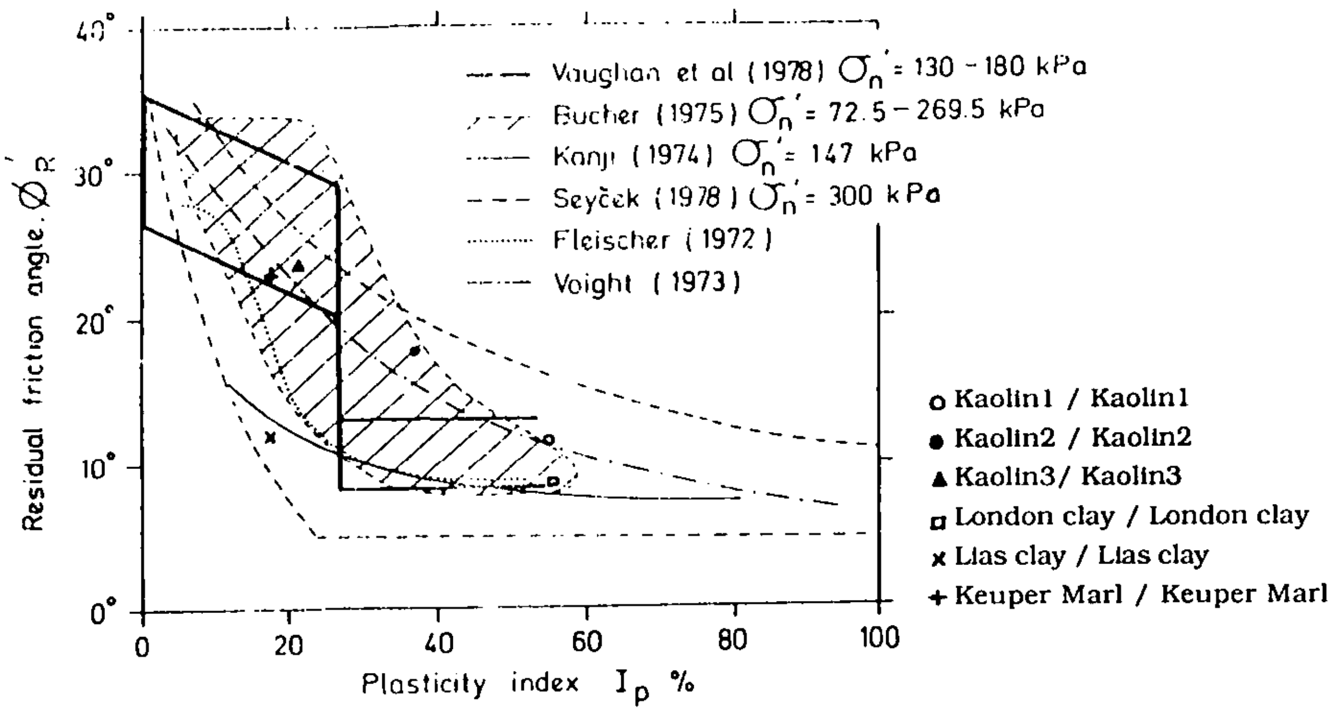


Fig. 8.5 Residual strength : Correlations with plasticity Index

a) Clay against Clay

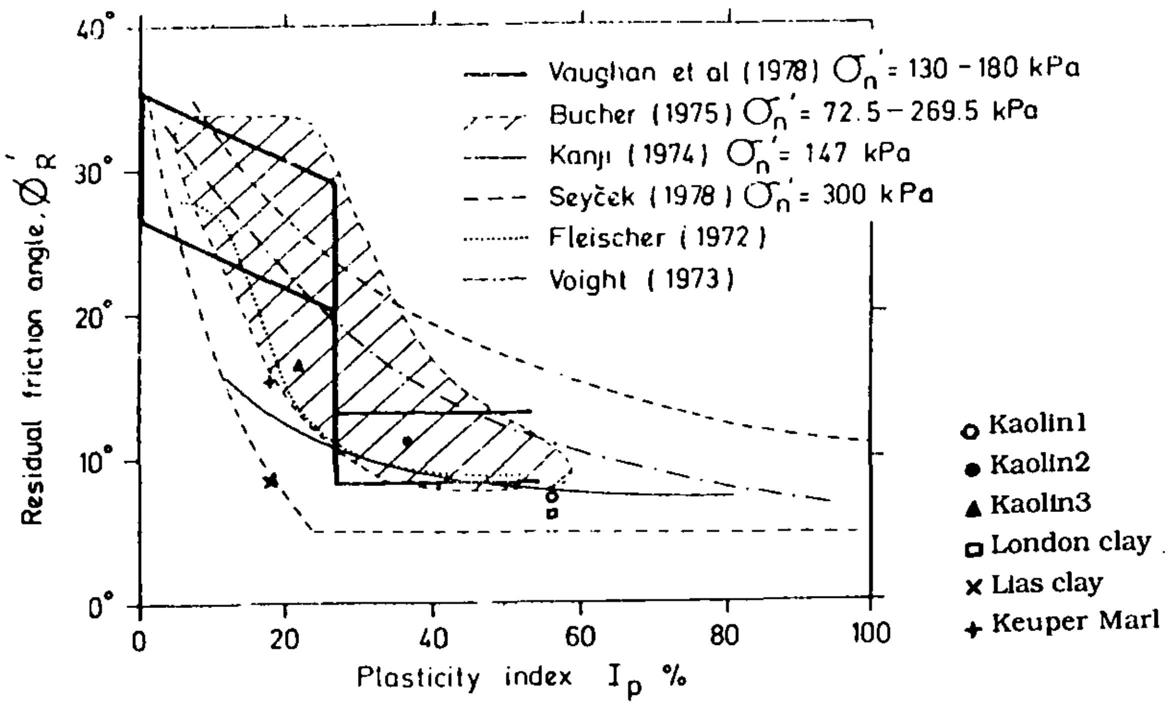


Fig. 8.5 Residual strength : Correlations with plasticity Index

b) Clay against Rock

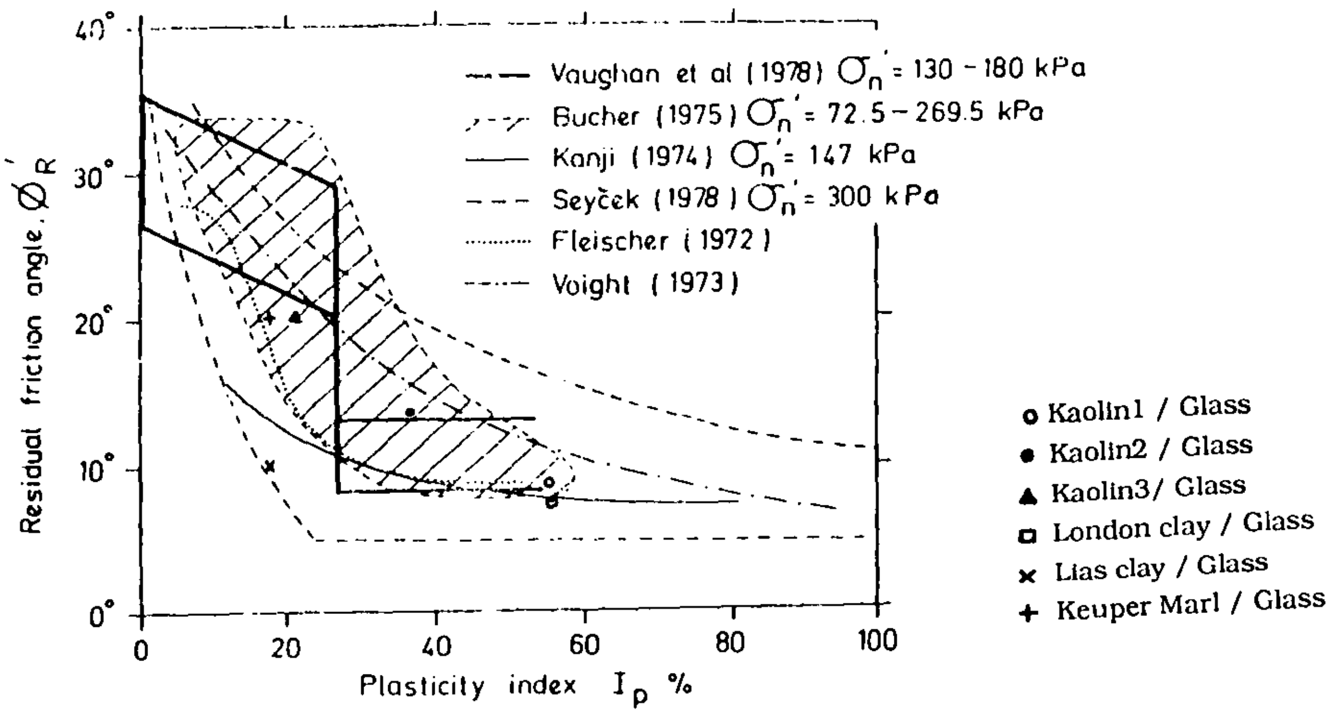


Fig. 8.5 Residual strength : Correlations with plasticity Index
c) Clay against Glass

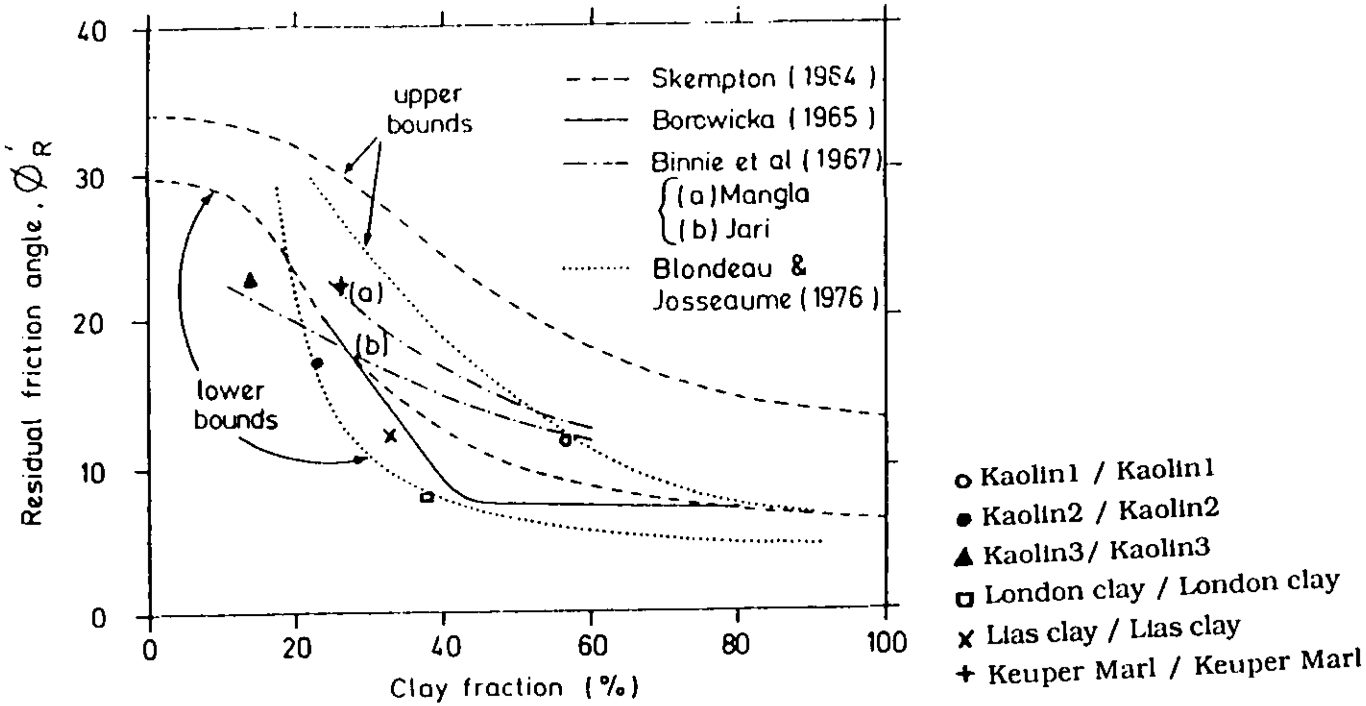


Fig. 8.6 Residual strength : Correlations with Clay fraction

a) Clay against Clay

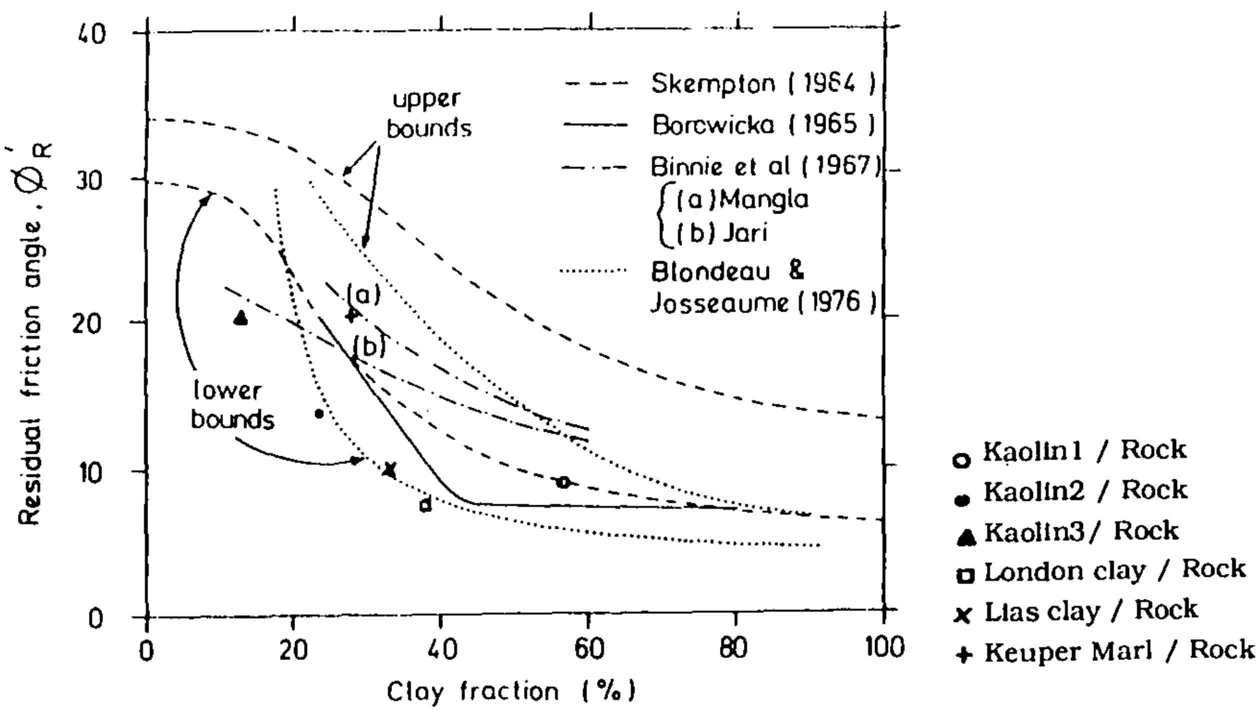


Fig. 8.6 Residual strength : Correlations with Clay fraction
b) Clay against Rock

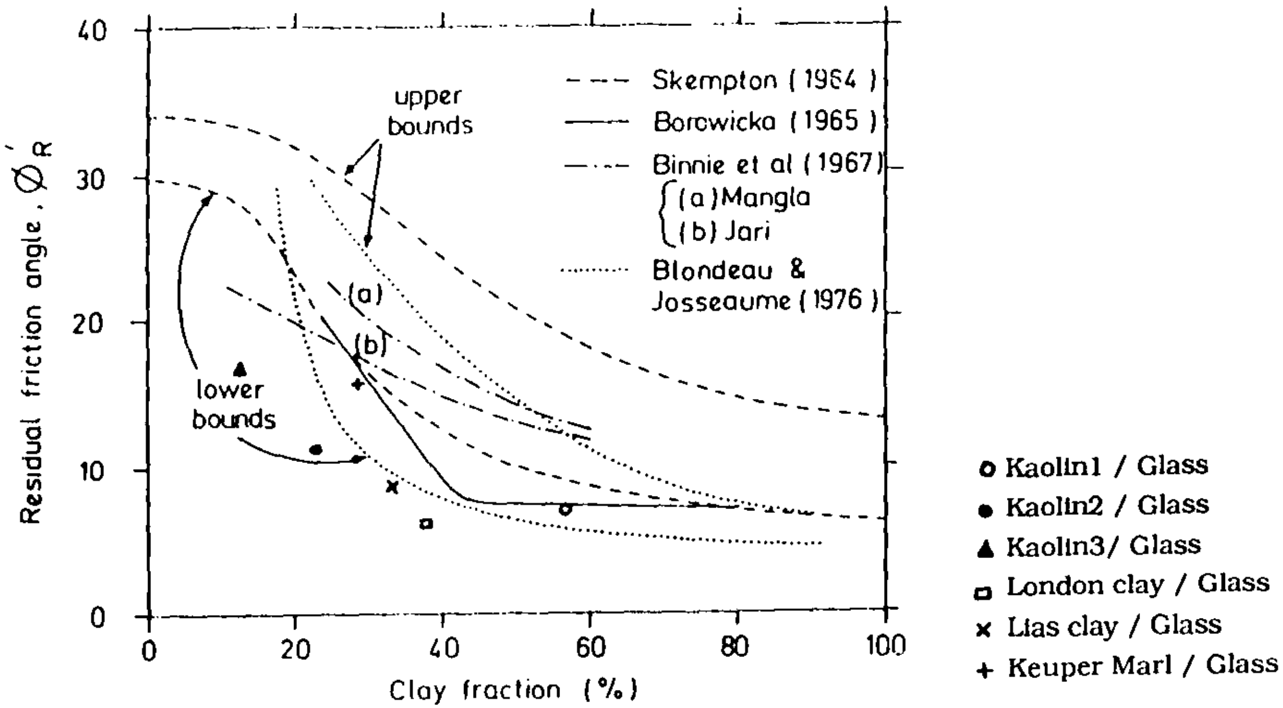


Fig. 8.6 Residual strength : Correlations with Clay fraction
c) Clay against Glass

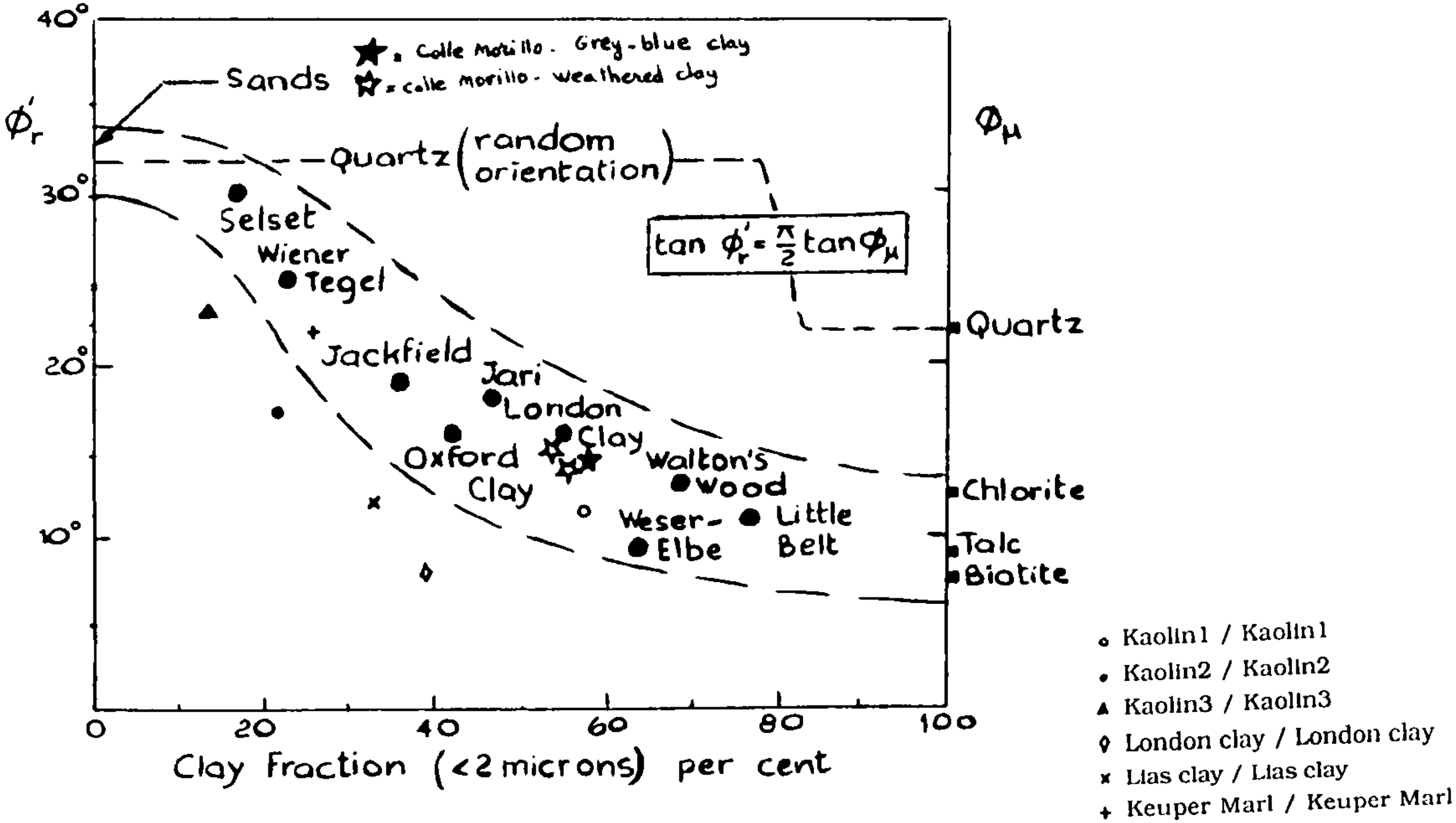


Fig. 8.7 Residual strength : Correlations with Clay fraction
(This investigation and Data by Skempton, 1964)
a) Clay against Clay

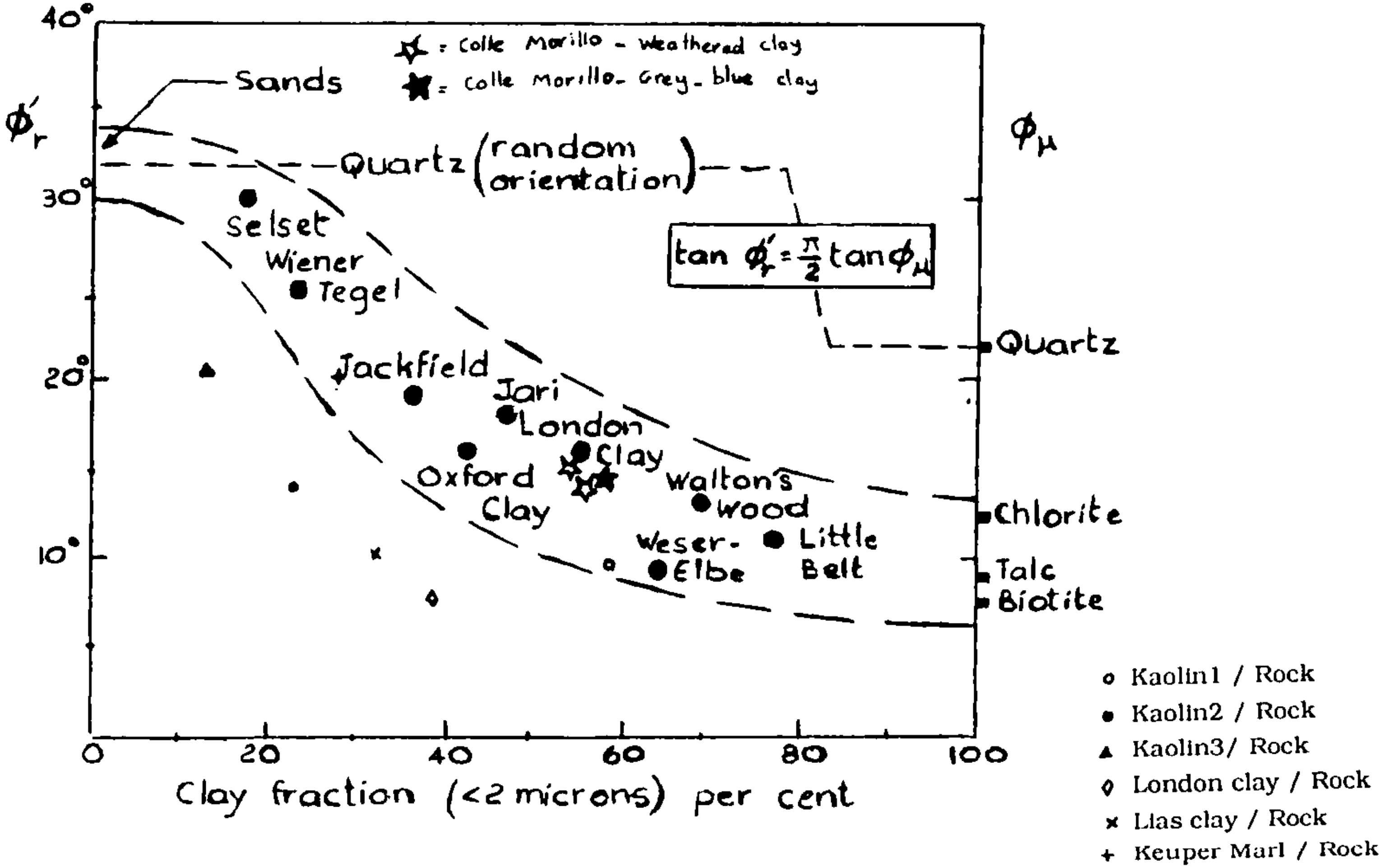


Fig. 8.7 Residual strength : Correlations with Clay fraction
(This investigation and Data by Skempton, 1964)
b) Clay against Rock

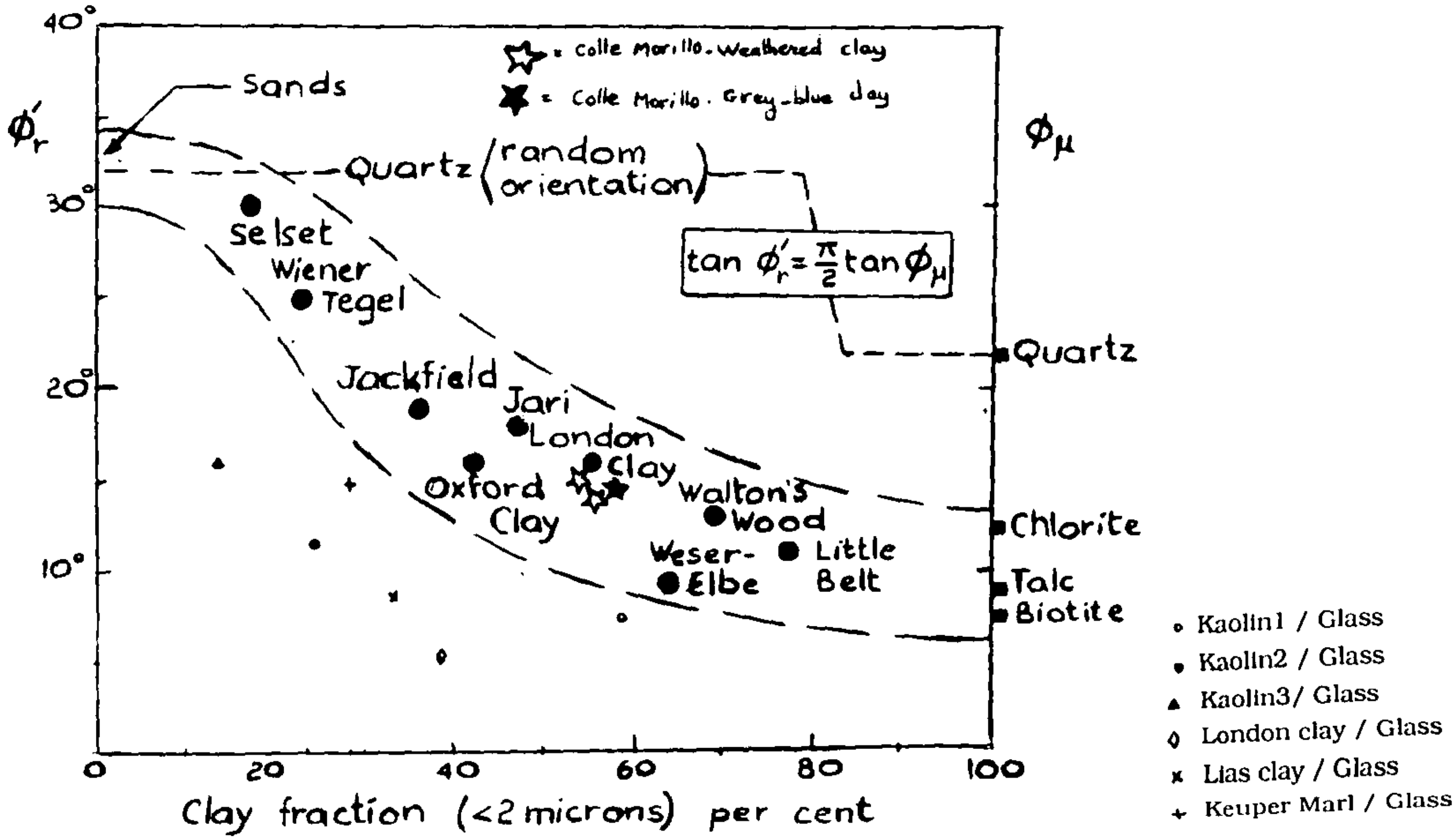


Fig. 8.7 Residual strength : Correlations with Clay fraction
(This investigation and Data by Skempton, 1964)
c) Clay against Glass

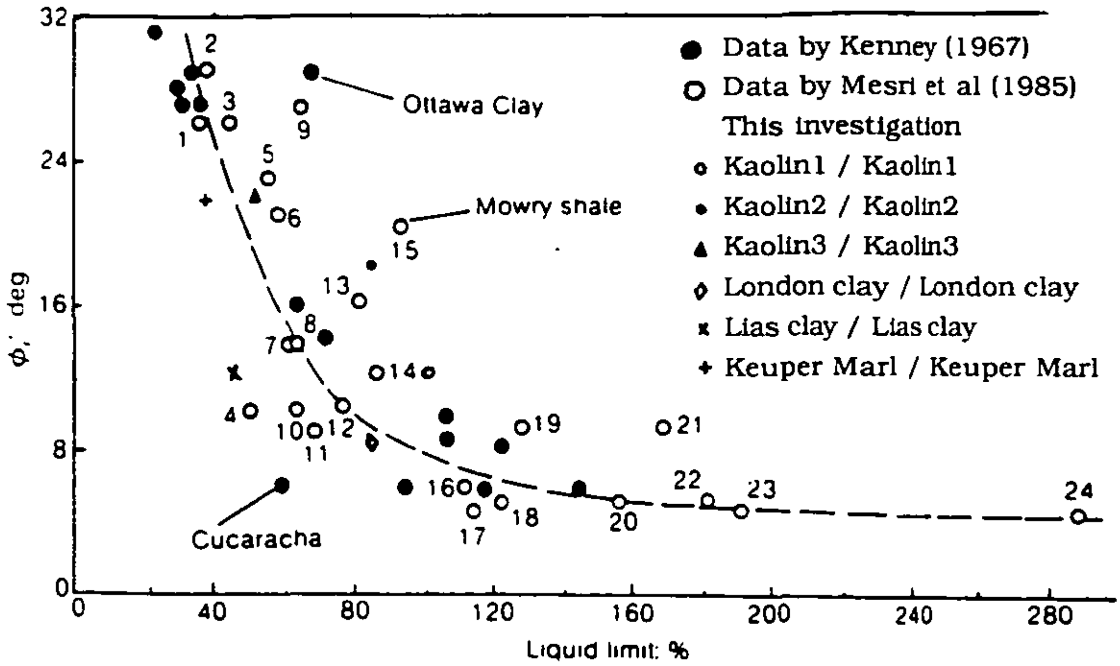


Fig. 8.8 Residual strength : Correlations with Liquid Limit
a) Clay against Clay

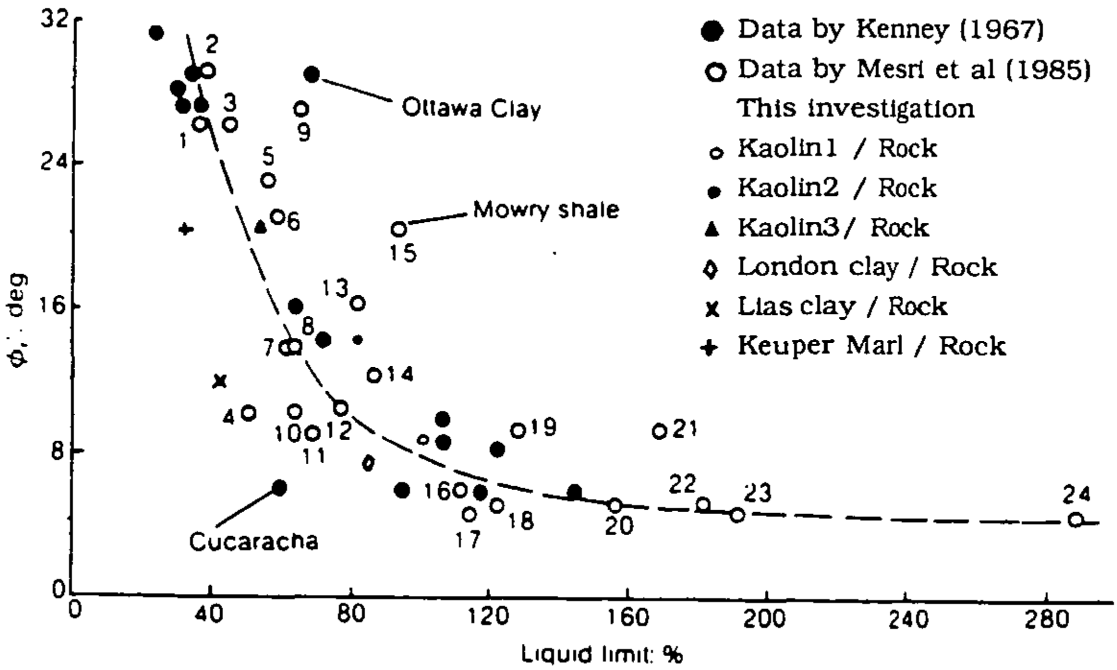


Fig. 8.8 Residual strength : Correlations with Liquid Limit
b) Clay against Rock

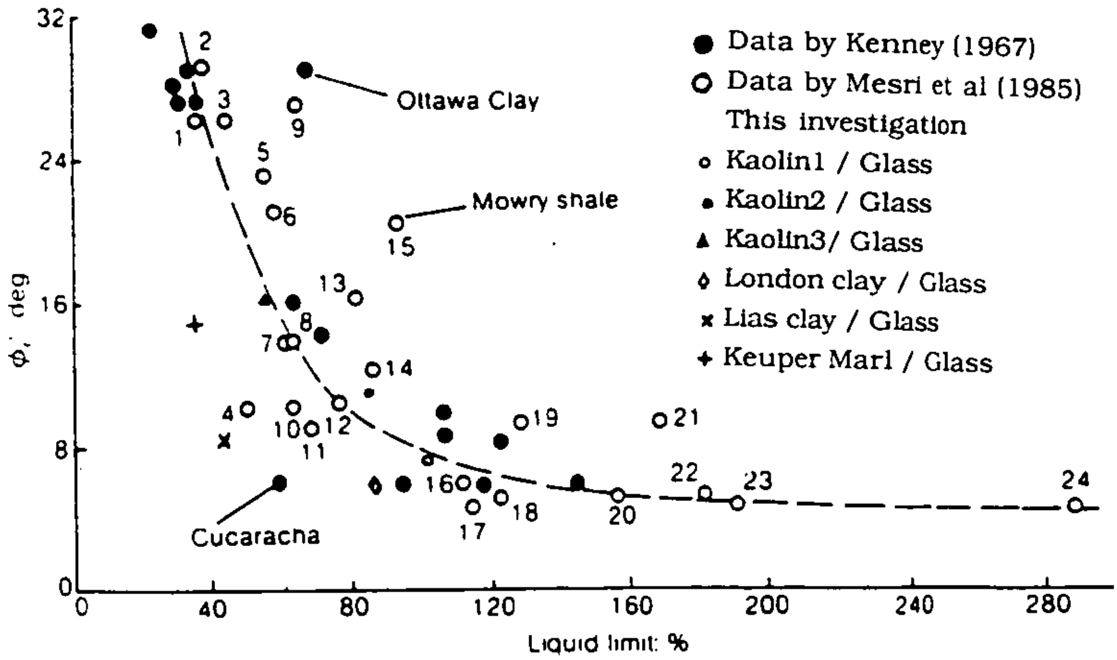


Fig. 8.8 Residual strength : Correlations with Liquid Limit
c) Clay against Glass

CHAPTER NINE

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

9.1 Conclusions

The following conclusions have been drawn from this programme of research :

9.1.1 Equipment

1) An electro-pneumatic converter controls the pressure of the air supply. The pneumatic output from the converter was found proportional to the drive current supplied which is automated by using the B.B.C micro-computer.

2) All measurements that were formerly recorded manually by the manual devices have been replaced by the transducers and a load cell. There is no loss of control over the tests, and the system allows records to be made overnight and during weekends, which can be of considerable advantage when shear tests are being carried out at low rate of shear, and save on manpower.

3) The speed of the motor can be controlled and the direction reversed automatically by generating a number of pulses from the computer and the system can give high speeds of up to 53 mm/min. The speed can be altered for different cycles.

4) The use of a rubber belt with cogs and a reduction gear reduced the stepper motor vibration effects on the readings of the displacement transducers, since the gearbox has a ratio of 375 to 1 together with a further increase of 7 to 1 from the driving belt arrangement between the cogs.

5) The data-logger can be applied to any machine which has similar deformations to that used in this study.

6) The length of shear of the box can be fixed between reversals during the testing to any value between 0 and 10 mm, either forward or backward.

7) The data- recording system, which was developed for laboratory use, will normally be operated in a temperature controlled laboratory. The effect of temperature on the equipment has been studied for various temperatures. No evident problems of temperature instability have been encountered.

8) There some points which can be outlined from these calibration tests, that all the transducers showed sensitivity, they proved to be very stable and to have linear outputs. However, the vertical load cell against the voltage values gave a non-linear curve at low pressures.

9) The automation saves much time and eliminates the need for an operator.

9.1.2 Effect of particle disturbance on the shear zone during reversal

1) The possibility of disturbances to the failure surface during reversal, which is one of the disadvantages of the shearbox, have been minimised by relieving the normal load during the tests. It is worth noting from both the tests, that the reduction in the disturbance during the reversing of the direction of shear reduces the magnitude of the shear strength angle for both London clay and Lias clay. For London clay a reduction of 0.30 degrees was measured, and that for Lias clay was 0.27 degrees.

2) Reversal shear box tests with load off when reversing are recommended as the preferred good method for measuring residual shear strength in the shear box.

9.1.3 Interface test behaviour

From the work reported on the interface tests, it is possible to identify that :

1) A very well defined pattern of peak and residual strengths was found in the tests. In the modified shearbox, the measured strengths gave the following :

Clay-Clay > Clay-Rock > Clay-Glass

The clay sheared against glass gave the lowest values for both the peak and residual shear strength for all tests. The difference between the strengths for clays sheared against sandstone rock and glass is between 1.6 and 4.8 degrees for the residual values and between 1.5 and 5.1 degrees for the peak values. These results show that the peak and residual shear strengths were affected by the same amount.

The clay sheared against clay gave the highest values for peak and residual strengths. The difference between clay-clay and clay-sandstone is between 0.8 and 3.4 degrees for the residual values and between 0.3 and 4.7 degrees for the peak values.

2) From this study it is possible to suggest that if a soil shows a transitional residual mode of behaviour which involes a combination of both turbulent and sliding shear and is sheared against a smooth hard interface (glass used in this study), the residual conditions can be altered to a sliding shear mode involving a low residual shear strength in comparison to the soil sheared alone. This is demonstrated by values given by Kaolin1.

If a soil which shows a sliding residual mode of behaviour, defined by a shear surface which is formed by strongly oriented clay where low residual friction angles are typically in the range from 5 to 12 degrees, is sheared against a smooth hard surface (rock or glass) the residual conditions will be established after small displacement with low residual shear strength, as shown most clearly in the values from London clay and Lias clay.

3) This study showed that there is a divergence between the strength values given by the Bromhead ring shear apparatus and the modified shearbox. The fundamental difference between the two tests could be explained by the fact that the modified shearbox was affected by a large relative displacement interrupted by changes in direction. This may affect the orientation of the clay particles on or close to the shear zone. The values of strength measured using the Bromhead ring shear were found to lie between two well-defined boundaries. The upper boundary is the value of the strength for clay sheared against rock and the lower boundary is the value of the strength for clay sheared against glass. It is clear, therefore, that the conventional shearbox can be used to determine the residual strength of clay soils using interface tests and that the values measured can be confidently related to ring shear measurements.

4) The interface test is a best method to obtain the residual strength of clay soils, constituting a simple, rapid and economical method. This fact is due to easier clay particle orientation at the vicinity of the contact with the interfaces.

9.1.4 Conclusions arising from Vibrationary Loading

There appears to be general agreement on the effect of strength under vibrationary loading. The changes that occurred in the soil during this investigation were :

1) The residual shear strength of cohesive soils was found to be dependent on the vibrationary loading.

2) For soils sheared against rock with vibrations of 2000 cycles and a length of shear of 1mm, there is a reduction in the peak shear strength of between 1.1 and 3.1 degrees compared to the peak strength measured without vibrations. There were no consistent changes in the residual shear strength.

3) For soils sheared against rock with vibrations of 200 cycles and a length of shear of 10mm there is a change in strength for both peak shear strength and residual shear strength. From the work reported in this study, it can be deduced that for design, where soil has been subjected to vibrationary loading with a consistent shear surface, the value of residual shear strength can alter significantly from the value measured using static tests. Lower residual shear strengths should be taken for design in this case.

9.2 SUGGESTION FOR FUTURE RESEARCH

The following recommendations can be made for future study

1) In this investigation only four channels have been used, despite the fact that programme can be used to monitor seven channels. It is possible to extend this study further using the shearbox or ring shear to measure the pore water pressure developments during the test, particularly for rapid loading.

2) Further research is necessary to investigate the effect of vibrations. In particular, it would be interesting to discover the effect of speeds greater that those used in this investigation and to vary the number of cycles and length of travel.

3) This study has considered two interface materials. Further tests using different interfaces are needed to fully investigate the most suitable material which, when sheared against soil using the shearbox, will give suitable values for design. The relationship between the measured values and ring shear values would need to be fully established.

4) As defined in this study the soil-interface test is a convenient and economical way of obtaining the residual shear strength of soils, under the very limited displacement allowed by the modified direct shear box equipment. Further investigations are needed to study the three modes of shearing, defined by Lupini (1981), acting in the interface tests in order to define which mode dominates the results.

5) Further research is necessary to investigate the effect of mineralogy since, as indicated in the literature, residual strength is dependent directly or indirectly on mineral composition of the mixture and the chemical state of the clay mineral.

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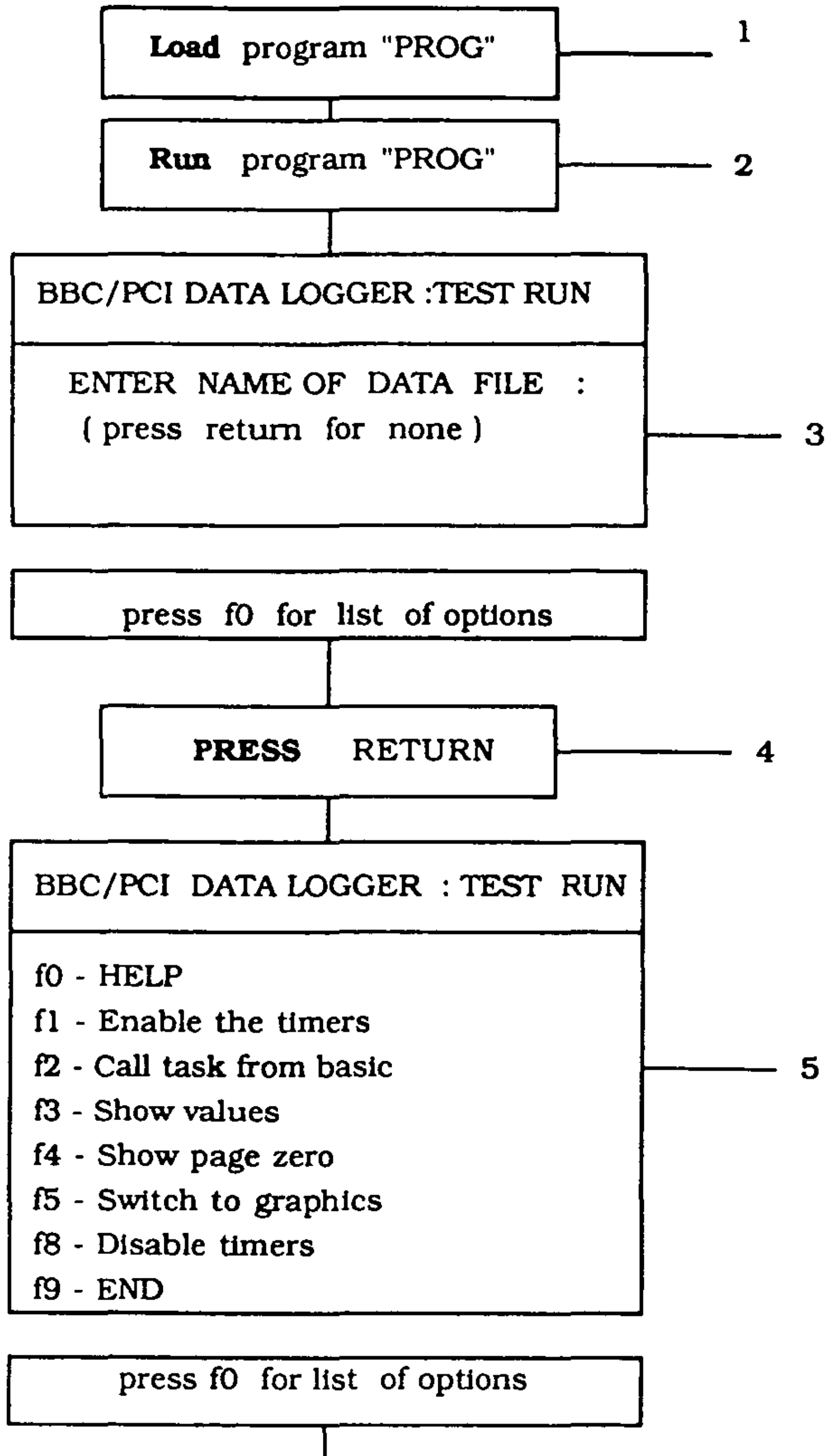
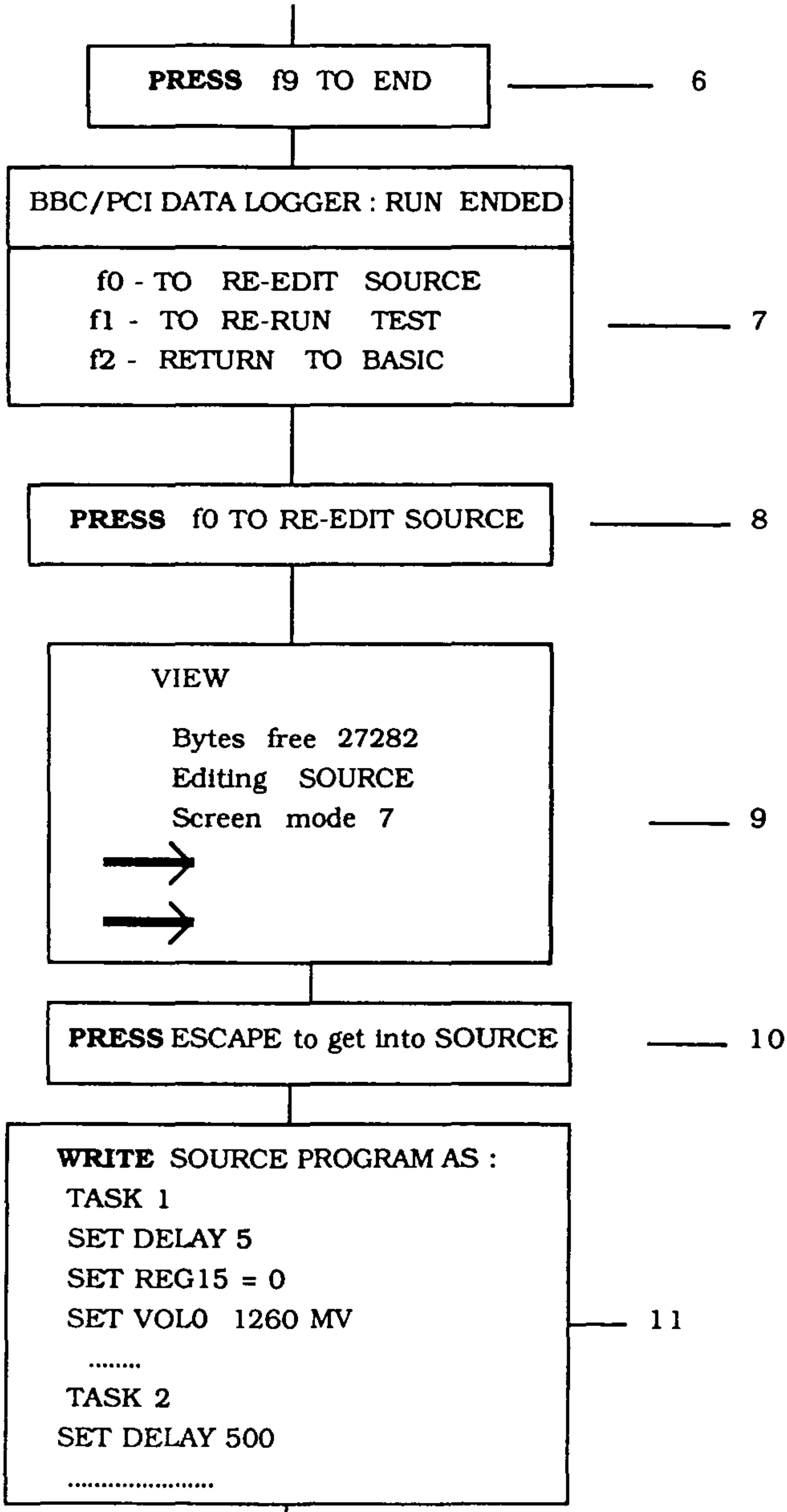
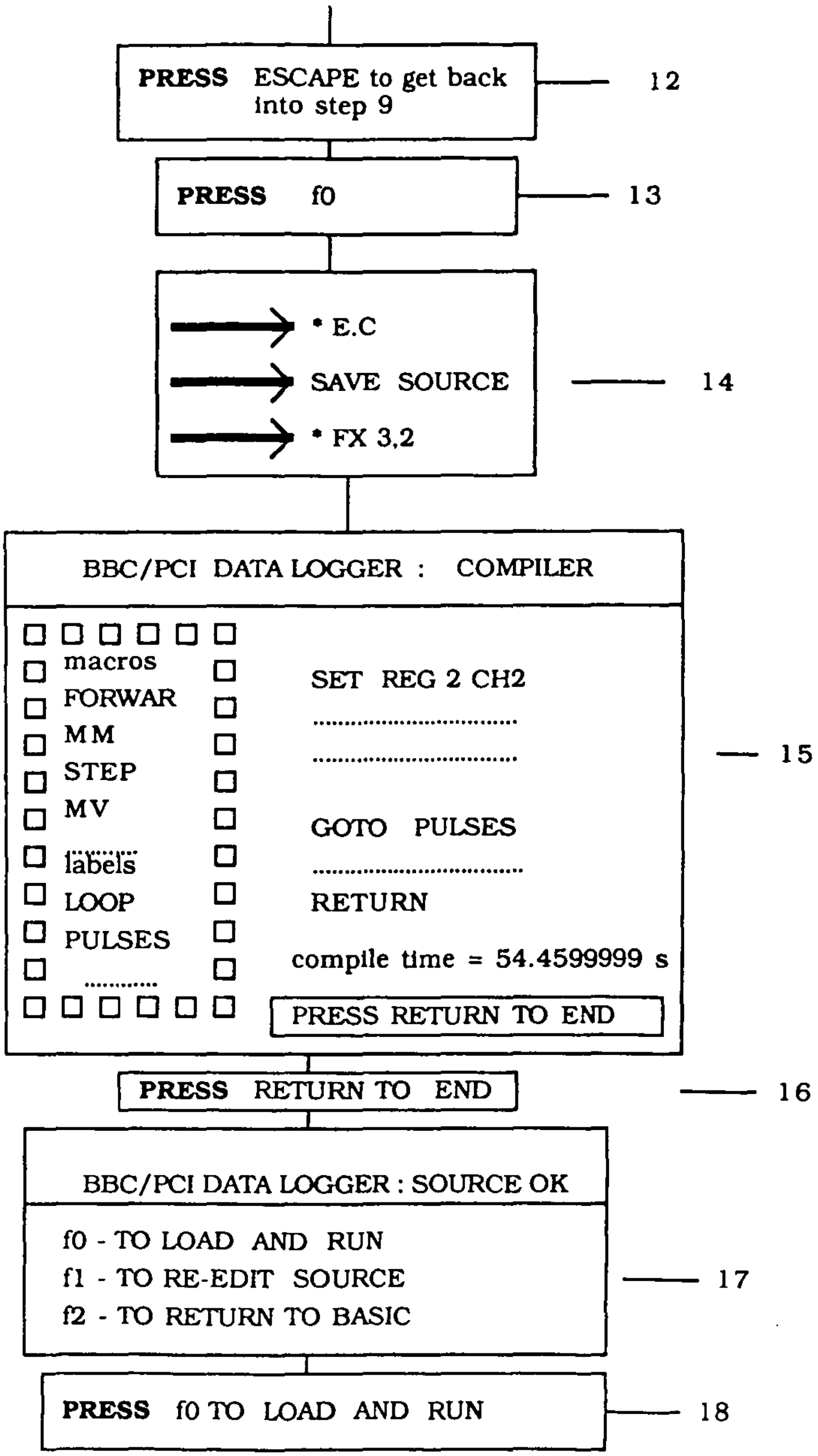
APPENDIX A

STEPS USED TO RUN THE PROGRAM





PRESS f9 TO END
6
BBC/PCI DATA LOGGER : RUN ENDED
f0 - TO RE-EDIT SOURCE
f1 - TO RE-RUN TEST
f2 - RETURN TO BASIC
7
PRESS f0 TO RE-EDIT SOURCE
8
VIEW
Bytes free 27282
Editing SOURCE
Screen mode 7
9
PRESS ESCAPE to get into SOURCE
10
WRITE SOURCE PROGRAM AS :
TASK 1
SET DELAY 5
SET REG15 = 0
SET VOL0 1260 MV
....
TASK 2
SET DELAY 500
....
11


PRESS ESCAPE to get back into step 9
12
PRESS f0
13
* E.C
SAVE SOURCE
* FX 3,2
14
BBC/PCI DATA LOGGER : COMPILER
macros
FORWAR
MM
STEP
MV
labels
LOOP
PULSES
SET REG 2 CH2
GOTO PULSES
RETURN
compile time = 54.4599999 s
PRESS RETURN TO END
15
PRESS RETURN TO END
16
BBC/PCI DATA LOGGER : SOURCE OK
f0 - TO LOAD AND RUN
f1 - TO RE-EDIT SOURCE
f2 - TO RETURN TO BASIC
17
PRESS f0 TO LOAD AND RUN
18

BBC/PCI DATA LOGGER : LOADER

Loading instruction codes

Initialising pointer

Work area

Page zero

Interrupts

19

TASK DRIVERS : f0 - BASIC

f1 - TIMER 1 f2- TIMER 2

TASK 1 DRIVER :

PRESS AS EXAMPLE

f2 then f1

20

BBC/PCI DATA LOGGER : TEST RUN

ENTER NAME OF DATA FILE :

(press return for none)

21

PRESS f0 FOR LIST OF OPTIONS

PRESS RETURN

22

BBC/PCI DATA LOGGER : TEST RUN

f0 - HELP

f1 - Enable timers

f2 - Call task from BASIC

f3 - Show values

f4 - Show page zero

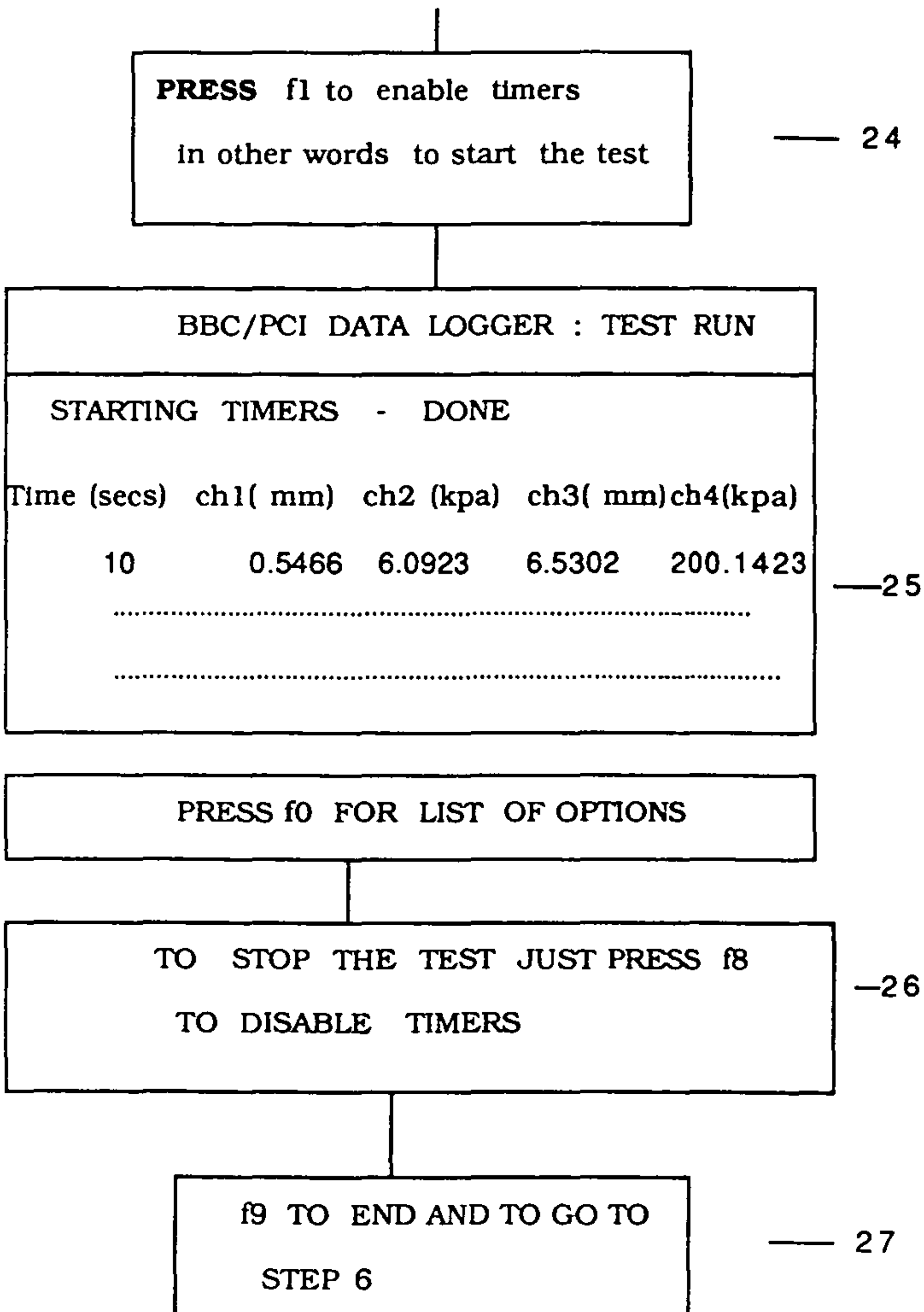
f5 - Switch to graphics

f8 - Disable timers

f9 - END

23

PRESS f0 FOR LIST OF OPTIONS


PRESS f1 to enable timers
in other words to start the test
24
BBC/PCI DATA LOGGER : TEST RUN
STARTING TIMERS - DONE
Time (secs) ch1(mm) ch2 (kpa) ch3(mm) ch4(kpa)
10 0.5466 6.0923 6.5302 200.1423
25
PRESS f0 FOR LIST OF OPTIONS
TO STOP THE TEST JUST PRESS f8
TO DISABLE TIMERS
26
f9 TO END AND TO GO TO
STEP 6
27

APPENDIX B

PROGRAM "PROG"

```
10 REM BBC/PCI BASIC ROUTINES
20 REM resident during PCI operation
45 DIM TYPE$(12),AN$(12)
50 D%=151: E%=135: *FX3,0
70 p%=&E00
90 diskbuff=P% :P%=P%+512 : REM data to disc buffers,2*256
100 subaddtab=&C00 : REM subroutine address table, 256
110 devtab=P% : P%=P% + 64 : REM binary device address , 64
120 mask=P% :P%=P% + 32 :REM binary device bit mask, 32
130 values=P% : P%=P% + 128 : REM device (readings),128
140 selecttab=P% : P%=P% + 9 : REM select table for scanning,9
150 plottab=P% : P%=P% + 9 : REM select table for plotting, 9
160 savetab=P% : P%=P% + 9 : REM item list for saving,9
170 symtab=P% :P%=P% + 64 : REM plotting symbols table, 64
180 intstat=P%=P% + 8 :REM interrupt counters, 8-4 tasks
190 buffstart=P% :P%=P% + 516 :REM plotting buffer , 516
200 enable - addr=P% :P%=P% + 8 :REM interrupt enable
routines
210 int-addr=P% :P%=P% + 4 :REM interrupt enable/disable
address
220 disable-addr=P% : P%=P% + 8 :REM interrupt disabling
routines
230 task table=P% :P%=P% + 64 :REM task tables-work variations
240 stack=P% : P%=P% + 32 :REM task subroutine stack space
260 buffone=diskbuff DIV 256
270 bufftwo=buffone + 1
280 buffoverflow=bufftwo + 1
300 midbuf=buffstart + 258 :REM pointer to the centre
310 midbuf-lo=midbuf MOD 256
320 midbuf-hi=midbuf div 256
330 endbuf=buffstart +516 :REM pointer to the end
340 base=values
380 tskptlo = &70 : REM pointer to the task table
390 tskpthi = &71
400 task-no = &72
410 io-wait = & 73 : REM waiting for pci data-ff=true
420 byt-wait = &74 : REM number of bytes waiting for
430 ttwocount =&75 : REM timer two counter
440 pci-gain = &76
450 bufflo = &77 :REM disc buffer pointer
460 buffhi = &78
470 prntrdy = &79 : REM interrupt vector storage
480 int-lo = &7A
490 int-hi =&7B
500 tsk-accept=&7C :REM task acceptance bytes
520 iplo = &80 :REM instruction pointer
530 iphi = &81
540 palo = &82 :REM parameter A
550 pahi = &83
560 pblo = &84 :REM parameter B
```

```
570 pbhi = &85
580 stacklo = &88  : REM stack pointer
590 stackhi = &89
600 status  = 8A   :REM status flags byte
610 devlo   = &8B    :REM device values table pointer
620 devhi  = &8C
640 mc = P%
650 REM key code received from the machine code
660 REM 40 - plot data in plotting buffer
670 REM 41 - save disc buffer 1
680 REM 42 - save disc buffer 2
690 REM SET UP COMMS **********
750 *FX 5,2
760 *FX7,7
770 *FX8,7
780 VDU2
790 *FX3,7
800 PRINT "B"
810 *FX3,0
820 VDU3
830 *FX5,1
840 *FX2,2
860 *FX225,200
870 U% = 0  REM INSTRUCTION COUNTER
880 REM T% = TASK NO ASSIGNED TO A BASIC CALL
910 PROCscrnfmt
920 PROCenable
930 PROCdata file
970Z=200 : start flag=FALSE :GRAPH-MODE = FALSE
980 REPEAT
990 W = 0 : REM set W = 1 if Z < 200 and Z = valid key
1000 IF Z > 199 AND GRAPH-MODE THEN MODE 7 : HIMEM = H%
:     GRAGH-MODE = FALSE : PROCscrnfmt : *FX 4,0
1004 IF Z = 37 THEN PROCtme-show : W = 1
1005 IF Z = 38 THEN PROCprch : W = 1
1006 IF Z =45 THEN PROCconditions : W = 1
1007 IF Z = 47 THEN PROCplpt : W = 1
1008 IF Z = 46 THEN PROCphp : W = 1
1010 IF Z = 40 THEN PROCplot : W = 1
1020 IF Z = 41 THEN PROCdisc-one : W = 1
1030 IF Z = 42 THEN PROCdisc-two : W = 1
1040 IF Z = 43 THEN  Z = 205
1050 IF Z = 44 THEN  PROCdraw : W = 1
1060 IF Z = 39 THEN  SOUND 1,-14,148,3 : W = 1
1070 IF Z = 135 AND GRAGH-MODE THEN PROCcurs-xy : W = 1
1080 IF Z = 136 AND GRAPH-MODE THEN PROCcurs-left : W = 1
1090 IF Z = 137 AND GRAPH-MODE THEN PROCcurs-right : W = 1
1100 IF Z = 138 AND GRAPH-MODE THEN PROCcurs-down :W = 1
1110 IF Z = 139 AND GRAPH-MODE THEN PROCcurs-up : W = 1
1120 IF Z = 202 THEN PROCstep
```

```
1130 IF Z = 204 THEN PROCpageshow
1140 IF Z = 203 THEN PROCdevshow
1150 IF Z = 201 THEN PROCstart
1160 IF Z = 200 THEN PROChelp
1170 IF Z = 208 THEN PROCfinish
1180 IF Z = 205 THEN MODE4 : HIMEM = H% : GRAPH-MODE =
TRUE : PROCgraphics : W = 1 : *FX4,1
1190 IF Z = 206 THEN PROCpltp
1200 IF Z = 207 THEN PROChelp
1210 IF Z < 200 AND W < > 1 THEN PROCnot-key
1220 Z = GET
1230 UNTIL Z = 209
1240 IF GRAPH-MODE THEN MODE 7 : HIMEM = H% :
GRAPH-MODE = FALSE :PROCscrnfmt : *FX4,0
1250 VDU23,1,1;0;0;0;
1270 PROCfinish
1280 CLOSE£data-stream
1290 *FX225,1
1300 *KEY0 *E.P|M
1310 *KEY1 *E.G|M
1320 *KEY2 VDU26 :CLS : *FX3,0|M
1330 PROCheader : I% = 7 : PROCboxing
1340 PRINTTAB(25,1) ; " RUN ENDED " ;
1350 PRINTTAB(5,4 ) ; "f0 - TO RE-EDIT SOURCE " ;
1360 PRINTTAB (5,6 ); "f1 -TO  RE-RUN TEST ";
1370 PRINTTAB (5,8 ); "f2 - RETURN TO BASIC " ;
1380 PRINTTAB (0,12 );
1390 *FX3,2
1410 END
1450 DEFPROChelp
1460 CLS
1470 PRINT "f0  - help "
1480 PRINT "f1  - enable timers "
1490 PRINT "f2  -call task from basic "
1500 PRINT "f3  -show values "
1510 PRINT "f4  -show page zero "
1520 PRINT "f5  -switch to grapgics "
1530  PRINT
1540 PRINT "f8  -disable timers "
1550 PRINT "f9  -end "
1560 ENDPROC
1580 DEFPROCnot-key
1590 CLS
1600 PRINT "UNRECOGNISED KEY CODE : " ; Z
1610 ENDPROC
1630 DEFPROCgetx ( base , offset )
1640 X% = base?offset + 256* base?(offset + 1 )
1650 IF X% > 32767 THEN X% = X% - ( 2^16 )
1660 ENDPROC
```

```
1680 DEFPROCsigned
1690 PRINT X%
1700 ENDPROC
1720 DEFPROCpageshow
1730 CLS
1740 PRINT "current task = ";?task-no
1750 PRINT "IP pointer  = "; :PROCgetx(&70,iplo-&70):printX%
1760 PRINT
1770 PRINT "task  1 accept   = ";?tsk-accept
1780 PRINT "task  2 accept  = "; tsk-accept?1
1790 PRINT "task  3  accept  = ";tsk-accept?2
1800 PRINT "task  4 accept  = ;tsk-accept?3
1810 PRINT "status byte  = "?status
1820 PRINT "I/O status  =";? io-wait
1830 PRINT "bytes waiting =";?byt-wait
1840 PRINT "T2 count   ="?ttwocount
1850 PRINT "PCI   gain   = ";?pci-gain
1860 PRINT
1870 ENDPROC
1890 DEFPROCdevshow
1900 CLS
1920 FOR  I = 0 TO 7
1930 PRINT "PB "; CHR$ (48 + I );" = " ; :X% = FNPB(I) :PROCsigned
1940 NEXTI
1960 FOR I = 0 TO 3
1970 PRINT "DEL" ; CHR$(49 + I);"="; : X% = FNDEL(I) :
PROCsigned
1980 NEXTI
2000 FOR I =0 TO 3
2010 PRINT "VOL"; CHR$(48 + I);"="; : X% = FNVOL(I) : PROCsigned
2020 NEXTI
2040 Y = 0
2060 FOR I = 0 TO 7
2070 PRINTTAB(19,Y);"REG"; STR$(I)   ;" = "; :X% = FNREG(I)
:PROCsigned
2080 Y = Y + 1
2090 NEXTI
2110 FOR I=0 TO 7
2120 PRINTTAB(19,Y); "CH" ; CHR$ (48 + I ); "      = " ; : X% =
FNCH(I) : PROCsigned
2130 Y = Y + 1
2140  NEXTI
2160 ENDPROC
2200 DEFFNPB(I) : PROCgetx(base,2*(I + 0 )) : = X%
2210 DEFFNDEL(I) : PROCgetx(base,2*(I + 28)) : = X%
2220 DEFFVOL(I) : PROCgetx(base ,2*(I + 48 )) : = X%
2230 DEFFNREG(I) : PROCgetx(base ,2*(I + 32)) : = X%
2240 DEFFNCH(I) : PROCgetx(base , 2*( I + 56)) : = X%
2250 DEFPROCFNREL(I) : PROCgetx(base , 2*(I + 12 )) : = X%
```

```
2280 DEFPROCstep
2290 REM call task from BASIC
2300 X% = T% :REM T% = task no allocated to BASIC
2310 IF X% = 0 THEN PRINT : PRINT "NO TASK ALLOCATED " :
ENDPROC
2320 IF tsk-accept?(X% - 1)=255 THEN CLS : PRINT"TASK
";CHR$(48 + X%) ;" NOT ACCEPTING" : ENDPROC
2340 U% = U% + 1 : task-no?)0 = X%
2350 CLS : PRINT "calling task " ; CHR$(48 + X%) ; "call no.  " ; U%
2360 CALL B%
2370 PRINT "call completed"
2390 ENDPROC
2430 DEFPROCplot
2440 REM send buffer to plotter
2450 VDU2
2460 VDU1,27,1,49
2470 VDU 1,27,1,42,1,5,1,14,1,2
2480 VDU 1,255,1,4,1,4,1,4,1,4
2490 FOR I% = 0 TO 515
2500 VDU1,(bufferstart?I%)
2510 NEXTI%
2520 VDU 1,4,1,4,1,4,1,4,1,255
2530 VDU 1,13
2540 VDU3
2550 ?prntrdy = 0
2560 ENDPROC
2600 DEFPROCheader
2610 REM mode 7 screen formatter
2620 VDU26 :CLS
2630 PRINTCHR$(D%) ; CHR$ (60) ;
STRING$(37,CHR$(44));CHR$(108) ;
2640 PRINTCHR$(D%) ; CHR$ (53) ; CHR$(E%);" BBC/PCI DATA
LOGGER :";
2650 PRINTCHR$(38,1);CHR$(D%);CHR$(106);
2660
PRINTCHR$(D%);CHR$(61);STRING$(37,CHR$(44));CHR$(110);
2670 ENDPROC
2710 DEFPROCboxing
2720 REM mode 7 screen formatter
2730 PRINTTAB(0,3) ; : FOR J% = 1 TO I%
2740 PRINTTAB(D%) ; CHR$(53);CHR$(E%);TAB(38,2 + J%);
CHR$(D%); CHR$9106);
2750 NEXTJ%
2760 PRINTCHR$(D%),CHR$(45); STRING$(37,CHR$(44));
CHR$(46);
2770 ENDPROC
2810 DEFPROCenable
2820 REM SET TASK ACCEPT BYTE FOR BASIC CALL
```

```
2830 IF T% > 0 THEN tsk-accept?(T% - 1) = 0
2840 ENDPROC
2880 DEFPROCstart
2890 IF start-flag THEN ENDPROC
2900 start-flag = TRUE
2920 PRINT : PRINT " STARTING TIMERS ";
2930 I% = ?int-addr + 256*int-addr?1
2940 CALL I%
2950 FOR J% = 0 TO 3
2960 I% = enable-addr?(j% *2) + 256*enable-addr?(j%*2 + 1 )
2970 IF I% > 0 THEN tsk-accept?j% = 0
2980 IF I% > O THEN CALL I%
2990  NEXTJ%
3000 PRINT "  -DONE "
3010 ENDPROC
3050 DEFPROCfinish
3060 IF NOT start-flag THEN ENDPROC
3065 ?&FCOB = 128
3070 PRINT : PRINT "STOPPING TIMERS ";
3080 REM this stops the timers
3090 FOR J% = 0 TO 3
3100 I% = disable-addr?(J%*2) + 256*disable-addr?(j%*2 + 1)
3110 IF I% > 0 THEN tsk-accept?j% = 255
3120 IF I% > 0 THEN CALL I%
3130  NEXTJ%
3140 I% = int-addr?2 + 256*int-addr?3
3150 CALL I%
3160 PRINT "   - DONE"
3170 start-flag = FALSE
3180 ENDPROC
3220 DEFPROCdata-file
3240 PRINTTAB(0,1) ; "ENTER NAME OF DATA FILE :";
3250 PRINTTAB(0,2) ;"(press return for none )";
3260  PRINTTAB(25,1);
3270 INPUT " "A$
3280  IF LEN(A$) > 0 THENdata-stream = OPENOUT(A$)   ELSE
data-stream=0
3290 ENDPROC
3330 DEFPROCdisc-one
3340 REM save disc buffer one
3350 IF data-stream = 0 THEN ENDPROC
3360 FOR I% = 0 TO 255
3370 BPUT£data-stream , diskbuff?I%
3380  NEXTI%
3390 ENDPROC
3430 DEFPROCdisc-two
3440 REM as for disc two
```

```
3450 IF data-stream = 0 THEN ENDPROC
3460 second = discbuff + 256
3470 FOR I% = 0 TO 255
3480 BPUT£data-stream ,second?I%
3490  NEXTI%
3500 ENDPROC
3540 DEFPROCgraphics
3550 REM switch screen to graphics mode
3560 x-div=50 :y-div=10
3570 PROCstart-plot(x-div,y-div) : REM  50 x divisions, 10 y divisions
3580 PROCshow-curs : VDU23,1,0;0;0;0;
3590 ENDPROC
3630 DEFPROCstart-plot(delta-x,delta-y)
3640 x-curr=0 : a-prev=0 : b-prev=0 : c-prev=0 : d-prev=0
3650 MOVE 0,0 : DRAW1279,0 :DRAW1279,1023:DRAW 0,1023 :DRAW 0,0
3660 MOVE 0,44 : MOVE0,(1023-44) : DRAW1279 ,(1023-44)
3670 MOVE 32,76 :DRAW 32,(1023-76)
3680 MOVE 16,76 : DRAW 32,76
3690 MOVE 16, (1023-76) : DRAW 32,(1023-76)
3700 MOVE 48 ,76 : DRAW(1279 - 32) , 76
3710 MOVE 48 ,76 : DRAW 48 ,60
3720 MOVE (1279-32) ,76 : DRAW (1279 - 32 ) , 60
3730 dy = 872/delta-y
3740 dx = 1200/delta-x
3750 y = 76 + dy
3760  REPEAT
3770 MOVE 16 , y : draw 32 , y
3780 y = y + dy
3790 UNTIL y > (1023 - 76 )
3800 x = 48 + dx
3810  REPEAT
3820 MOVE x , 60 : draw x , 76
3830 x = x + dx
3840 UNTIL x > ( 1279 - 32 )
3850 VDU5 : MOVE 32 ,39 : PRINT " f0- HELP arrows-cursor copy-x,y":VDU4
3860 VDU24 ,48 ;80 ; (1279 - 32 ) ; (1023 - 76 ) ;
3870 ENDPROC
3910 DEFPROCdraw
3920 REM draw graph  - USE BASIC 44
3930 IF NOT GRAPH-MODE THEN ENDPROC
3940 IF x-curr = 0 THENPT = TRUE ELSE PT = FALSE
3950 x-prev = x-curr : x-curr = x-curr + dx
3960 IF x-curr > (1279 - 32 ) THEN x-curr = 0 : PT=TRUE : CLG : PROCplot-curs(curs-x,curs-y)
3990  a=FNREG(5)
4000  b=FNREG(6)
4010  c=FNREG(7)
```

```
4020 d=0
4030 REM to draw line - (current , prev , ymax, ymin )
4040 REM to disable line drawing set ymax=ymin
4050 PROCline (a,a-prev, 32767 , -32767 )
4060 PROCline (b,b-prev, 32767 , -32767 )
4070 PROCline (c,c-prev, 32767 , -32767 )
4080 PROCline (d,d-prev,0,0)
4110 a-prev=a : b-prev=b : c-prev=c :d-prev=d
4120 ENDPROC
4160 DEFPROCline (y-curr, y-prev,y-max , y-min )
4170 IF y-max=y-min THEN ENDPROC
4180 yc=y-curr-y-min
4190 yp=y-prev-y-min
4200 y-range=y-max-y-min
4210 y-prev=yp/y-range*872 + 76
4220 y-curr=yc/y-range*872 + 76
4230 IF PT thenplot 69 ,x-curr,y-curr
4240 IF NOT PT THEN MOVE (x-curr-dx) , y-prev : DRAW x-curr ,
y-curr
4250 ENDPROC
4290 DEFPROCscnfmt
4300 PROCheader : I% = 18 : PROCboxing
4310 PRINTTAB (25,1) ; "TEST RUN  " ;
4320 PRINTTAB (0,23) ; CHR$(133) ;CHR$(157) ;CHR$(135);"press
f0 FOR LIST OF OPTIONS"
4330 VDU 28 ,3 , 20 ,37 ,3
4340 ENDPROC
4380 DEFPROCshow-curs
4390 REM switch on the cursor
4400  curs-x=INT(x-div/2)
4410  curs-y=INT(872/2)
4420 PROCplot-curs(curs-x,curs-y)
4430 ENDPROC
4470 DEFPROCcurs-left
4480 REM move cursor left
4490 IF curs-x=0 THEN ENDPROC
4500 PROCplot-curs(curs-x , curs-y)
4510  IF  INKEY(-1)=0  THEN  curs-x=curs_x-1  ELSE
curs_x=curs_x-INT(X_div/5)
4520 IF curs_x < 0 THENcurs_x=0
4530 PROCplot curs(curs_x , curs_y)
4540 ENDPROC
4580 DEFPROCcurs_right
4590 REM move cursor right
4600 IF curs_x=x_div THEN ENDPROC
4610 PROCplot_curs(curs_x , curs_y)
4620 IF INKEY(-1)=0 THENcurs_x=curs_x + 1 ELSE curs_x=curs_x
+ INT(x_div/5)
4630 IF curs_x > x_div THENcurs_x=x_div
4640 PROCplot_curs(curs_x , curs_y)
```

```
4650 ENDPROC
4690 DEFPROCcurs_up
4700 REM move cursor up
4710 IF curs_y=872 THEN ENDPROC
4720 PROCplot_curs(curs_x , curs_y)
4730 IF INKEY(-1)=0 THENcurs_y=curs_y + 4 ELSE curs_y=curs_y
+ INT(872/y_div)
4740 IF curs_y > 872 THENcurs_y = 872
4750 PROCplot_curs(curs_x , curs_y)
4760 ENDPROC
4800 DEFPROCcurs_downIF curs_y=o THEN ENDPROC
4830 PROCplot_curs(curs_x ,curs_y)
4840 IF INKEY(-1)=0 THENcurs_y=curs_y-4 ELSE curs_y -
INT(872/y_div)
4850 IF curs_y < 0 THENcurs_y=0
4860 PROCplot_curs(curs_x , curs_y)
4870 ENDPROC
4910 DEFPROCplot_curs(xp,yp)
4920 xp=48 + (1200*xp/x_div)
4930 yp=76 + yp
4940 MOVE(xp-16) , yp : PLOT 6 ,(xp + 16 ) ,yp
4950 MOVE xp,(yp - 16) : PLOT 6 ,xp,(yp + 16)
4960 ENDPROC
5000 DEFPROCcurs-xy
5010 VDU26 : @%=&20305 : VDU5
5020 MOVE 448,1015 : PRINTSTRING$ (8,CHR$(127))
5030 MOVE192 , 1015 :PRINT "X=";curs_x;
5040 MOVE1048,1015 : PRINTSTRING$(8,CHR$(127))
5050 MOVE728 ,1015 : PRINT"Y=";(curs_y - 436)/436
5060 VDU4 : VDU 24 ,48;80;(1279-32) : (1023 - 76 ); : @% = 10
5070 VDU 23,1,0;0;0;0;
5080 ENDPROC
5120 DEFPROCprch
5125 VDU2
5132 pzcount=pzcount + 1 : IF pzcount > 1 GOTO 5145
5135 PRINT ; " time(secs)        ch1(mm)   ch2(mm)   ch3(KPA)
ch4(KPA)"
5145 FOR IJK=0 TO 3
5150 PROCgetx(base , 2*(IJK + 56) : PROCsigzz
5160 NEXT IJK
5165 PRINT TAB(5) ; AZZ(0) ; TAB(15) ; AZZ(1) ; TAB(30) ; AZZ(2) ;
TAB(40) ; AZZ(3) ; TAB(55) ; AZZ(4)
5170 VDU3
5180 ENDPROC
5200 DEFPROCsigzz
5210 Y% = X%
5220 IF Y% > 32767 THEN Y% = Y% - (2^16)
5222 czz=Y%
5224 IF IJK=0 THEN czz=Y% * (0.0012)
5226 IF IJK = 1 THEN czz=Y% * (0.0012)
```

```
5228 IF IJK = 2 THEN czz=Y% * (0.74624)
5229 IF IJK = 3 THEN czz=Y% * (1.1048)
5230 AZZ(IJK + 1)=czz
5240 ENDPROC
5250 DEFPROCtme_show
5260 VDU2
5265 PROCgetx(base,56)
5270 AZZ(0)=(X% * FNREG(15))
5280 VDU3
5290 ENDPROC
5400 DEFPROCconditions
5430 PROCtake_date
5440 PROCtake_testno
5450 PROCspecimen_name
5460 PROCtake_spec
5470 PROCclay_fraction
5480 PROCmois_content
5490 PROCliquid_limit
5500 PROCplastic_limit
5510 PROCplast_index
5520 PROCload_sequence
5530 PROCrate_ofshear
5540 PROCspec_thick
5550 PROCspec_weight
5560 PROCwater_bath
5570 PROCdist_water
5580 PROCcross_area
5590 PROCsieve_number
5600 PROCroom_temperature
5610 PROCtake_charact
5620 PROCmake_file
5630 ENDPROC
5640 DEFPROCtake_date
5650 PRINTTAB(10) ; " ENTER DATE "
5660 INPUT(20) ; T$
5670 ENDPROC
5680 DEFPROCtake_testno
5690 PRINTTAB(10) ; " ENTER TEST No "
5700 INPUTTAB(23) ; R$
5710 ENDPROC
5720 DEFPROCspecimen_name
5730 PRINTTAB(10) ; "SPECIMEN NAME "
5740 INPUTTAB(23) ; K$
5750 ENDPROC
5760 DEFPROCtake_spec
5770 PRINTTAB(10) ;"SPECIFIC GRAVITY "
5780 INPUTTAB(25) ; F$
5790 ENDPROC
5800 DEFPROCclay_fraction
5810 PRINTTAB(10) ; " CLAY FRACTION "
```

```
5820 INPUTTAB(22) ; M$
5830 ENDPROC
5840 DEFPROCmois_content
5850 PRINTTAB(10) ; "MOISTURE CONTENT "
5860 INPUTTAB(25) ; N$
5870 ENDPROC
5880 DEFPROCliquid_limit
5890 PRINTTAB(10) ; "LIQUID LIMIT  "
5900 INPUTTAB(23) ; B$
5910 ENDPROC
5920 DEFPROCplastic_limit
5930 printtab(10) ; "PLASTIC LIMIT "
5940 INPUTTAB(23) ; A$
5950 ENDPROC
5960 DEFPROCplast_index
5970 PRINTTAB(10) ; " PLASTICITY INDEX "
5980 INPUTTAB(25) ; S$
5990 ENDPROC
6000 DEFPROCload_sequence
6010 PRINTTAB(10) ; "LOAD SEQUENCE "
6020 INPUTTAB(25) ; P$
6030 ENDPROC
6040 DEFPROCrate_of shear
6050 PRINTTAB(10) ; "RATE OF SHEAR "
6060 INPUTTAB(25) ; J$
6070 ENDPROC
6080 DEFPROCspec_thick
6090 PRINTTAB(10) ; "THICKNESS OF SPECIMEN "
6100 INPUTTAB(35) ; W$
6110 ENDPROC
6120 DEFPROCspec_weight
6130 PRINTTAB(10) ; "WEIGHT OF SPEC."
6140 INPUTTAB(28) ; Z$
6150 ENDPROC
6160 DEFPROCwater_bath
6170 PRINTTAB(10) ; "WATER BATH "
6180 INPUTTAB(25) ; Y$
6190 ENDPROC
6200 DEFPROCdist_water
6210 PRINTTAB(10) ; "DISTILLED WATER "
6220 INPUTTAB(25) ; X$
6230 ENDPROC
6240 DEFPROCcross_area
6250 PRINTTAB(10) ; "CROSS SECT.AREA "
6260 INPUTTAB(23) ; Q$
6270 ENDPROC
6280 DEFPROCsieve_number
6290 PRINTTAB(10) ; "SIEVE NUMBER "
6300 INPUTTAB(25) ; O$
```

```
6310 ENDPROC
6320 DEFPROCroom_temperature
6330 PRINTTAB(10) ; "ROOM TEMPERATURE "
6340 INPUTTAB (23) ; L$
6350 ENDPROC
6360 DEFPROCtake_charact
6370 PRINT " SPEC.CONDITIONS "
6380 TYPE$(1) = "60*60*25"
6390 TYPE$(2) = "100*100*25"
6400 TYPE$(3) = "REMOULDED"
6410 TYPE$(4) = "COMPACTED"
6420 TYPE$(5) = "UNDISTURBED"
6430 TYPE$(6) = "PRE_CUT"
6440 TYPE$(7) = "DRY"
6450 TYPE$(8) = "CONS.UNDR"
6460 TYPE$(9) = "CONS.DRA."
6470 TYPE$(10) = "UNDRAINED"
6480 TYPE$(11) = "WATER AROUND"
6490 TYPE$ (12) = "DAMP CLOTH"
6500 FOR aa% = 1 TO 12
6510 PRINT TYPE$(aa%)
6520 INPUT "IS THIS O.K " ; AN$(aa%)
6530 NEXT aa%
6540 PRINT "SPEC.CONDITIONS"
6550 FOR aa% = 1 TO 12
6560 IF AN$(aa%) = "Y" THEN PRINT TYPE$(aa%)
6570 NEXT aa%
6580 ENDPROC
6590 DEFPROCmake_file
6600 PRINT"NAME OF"
6610 INPUT "YOUR DATA FILE " , file$
6620 te = OPENOUT(FILE$)
6630 PRINT£te , "DATE", T$ : VDU2 : PRINT "DATE ",T$ :VDU3
6640 PRINT£te, "TEST NO " , R$ : VDU2 : PRINT "TEST NO",R$ :
VDU3
6650 PRINT£te,"SPEC.NAME",K$ : VDU2 : PRINT "SPEC.NAME "
,K$ : VDU3
6660 PRINT£te,"SPEC.GRAVITY",F$ : VDU2:PRINT"SPEC.GRAVITY"
,F$:VDU3
6670 PRINT£te,"CLAY FRACTION ",M$ :VDU2:PRINT"CLAY
FRACTION",M$:VDU3
6680 PRINT£te,"MOISTURE
CONTENT",N$:VDU2:PRINT"MOISTURE CONTENT",N$:VDU3
6690 PRINT£te,"LIQUID LIMIT",B$:VDU2:PRINT"LIQUID
LIMIT",B$:VDU3
6700 PRINT "M130,1970 "
6702 PRINT "P70"
6704 PRINT "P70"
6710 PRINT£te,"PLASTICITY INDEX",S$:VDU2:PRINT"PLASTICITY
INDEX ",S$:VDU3
```

```
6720 PRINT£te,"LOAD SEQUENCE ",P$ : VDU2 : PRINT "LOAD SEQUENCE ",P$ :VDU3
6730 PRINT£te,"RATE OF SHEAR ",J$ :VDU2 :PRINT "RATE OF SHEAR ",J$:VDU3
6740 PRINT£te,"THICKNESS OF SPEC.",W$:VDU2 : PRINT"THICKNESS OF SPEC.",W$ : VDU3
6750 PRINT£te,"WEIGHT OF SPEC.",W$:VDU2:PRINT"WEIGHT OF SPEC.",W$:VDU3
6760 PRINT£te,"WATER OF BATH.",Y$:VDU2 : PRINT "WATER BATH ",Y$ : VDU3
6770 PRINT£te,"CROSS SECT.AREA",Q$:VDU2:PRINT"CROSS SECT.AREA",Q$:VDU3
6780 PRINT£te,"ROOM temperature ",L$:VDU2:PRINT"ROOM TEMPERATURE ",L$:VDU3
6790 VDU2 :PRINT "SPEC.CONDITIONS ":VDU3
6800 FOR aa% =1 TO 12
6810 IF AN$(aa%) ="Y" THEN PRINT£te,TYPE$(aa%):VDU2:PRINTTYPE$(aa%):VDU3
6820 NEXT aa%
6830 CLOSE£te
6840 ENDPROC
6850 DEFPROCpltp
6851 VDU2
6852 PRINT "M200,200"
6853 PRINT "X1 ,250,10 "
6854 PRINT"M200,200"
6855 PRINT"X0 ,250,8"
6856 PRINT" Q0 "
6857 PRINT" S4 "
6858 PRINT "M440 ,150 "
6859 PRINT " P1 "
6860 PRINT "M690 ,150 "
6861 PRINT " P2 "
6862 PRINT "M940 ,150 "
6863 PRINT " P3 "
6864 PRINT "M1190 ,150 "
6865 PRINT " P4 "
6866 PRINT "M1420 ,150 "
6867 PRINT "P5 "
6868 PRINT "M1670 ,150 "
6869 PRINT "P6"
6870 PRINT "M1920 , 150 "
6871 PRINT "P7"
6872 PRINT "M2170 ,150 "
6873 PRINT "P8"
6874 PRINT "M2430 ,150 "
6875 PRINT "P9"
6876 PRINT "M2680 ,150 "
6877 PRINT "P10"
6878 PRINT "M550 ,80 "
```

```
6879 PRINT "S5"
6880 PRINT "PHOR.DISPL.MM"
6882 PRINT"S4"
6884 PRINT "M130 ,470 "
6886 PRINT " P10"
6888 PRINT"M130 ,720"
6889 PRINT "P20"
6890 PRINT "M130 ,970 "
6891 PRINT "P30"
6892 PRINT "M130,1220"
6893 PRINT "P40"
6894 PRINT "M130 ,1470 "
6895 PRINT "P50 "
6897 PRINT "M130,1720 "
6898 PRINT "P60"
7000 PRINT "M130.1970"
7004 PRINT "P70"
7176 PRINT"M60,600"
7178 PRINT "Q1"
7180 PRINT "S5"
7182 PRINT "PSHEAR STRESS KPA"
7184 VDU3
7185 ENDPROC
7188 VDU2
7190 PRINT "M200,200"
7191 PROCgetx(base,114) : X=ABS(-X%)*0.3 + 200
7192 PROCgetx(base ,116) : X=ABS(-X%)*0.13884 + 200
7194 a2$= "M" + STR$(X) + ", " +STR$(Y)
7196 PRINTa2$
7198 PRINT"N1"
7200 VDU3
7220 ENDPROC
```

APPENDIX C

PROGRAM " LOADER "

```
10 REM BBC/PCI CODE LOADER AND INITIALISATION
40 *FX3,0
60 REM now the instruction codes
80  X%=OPENIN("CODE")
90  Y%=BGET#X%+BGET#X%*256
100 PTR#X%=10
120  HIMEM=&5800-Y%-2
130  H%=HIMEM
160  D%=151:E%=135
170 PROCheader:I%=8:PROCboxing
180 PRINTTAB(25,1);"LOADER    ";
190 PRINTTAB(5,4);"Loading instruction codes";
200 *LOAD MCCODE 0E00
210 *LOAD JSRTAB 0C00
230 P%=&E00
250 diskbuff=P%     :P%=P%+512: REM Data to disc buffers, 2*256
260 subaddtab=&C00            : REM subroutine address table, 256
270 devtab=P%       :P%=P%+64 : REM binary device address, 64
280 mask=P%         :P%=P%+32 : REM binary device bit mask, 32
290 values=P%       :P%=P%+128: REM device values (readings), 128
300 selecttab=P%    :P%=P%+9  : REM select table - for scanning, 9
310 plottab=P%      :P%=P%+9  : REM select table - for plotting, 9
320 savetab=P%      :P%=P%+9  : REM table of items to be saved, 9
330 symbtab=P%      :P%=P%+64 : REM plotting symbols table, 64
340 intstat=P%      :P%=P%+8  : REM Interrupt counters, 8 - 4 tasks
350 buffstart=P%    :P%=P%+516: REM Plotting buffer, 516
360 enable_addr=P% :P%=P%+8   : REM Interrupt enable routines
370 int_addr=P%     :P%=P%+4  : REM Interrupt enable/disable addr
380 disable_addr=P%:P%=P%+8   : REM Interrupt disabling routines
390 task_table=P%  :P%=P%+64  : REM Task tables - work variables
400 stack=P%        :P%=P%+32 : REM Task subroutine stack space
420 buffone=diskbuff DIV 256
430 bufftwo=buffone + 1
440 buffoverflow=bufftwo + 1
460 midbuf=buffstart+258  : REM Pointer to the centre
470 midbuf_lo=midbuf  MOD 256
480 midbuf_hi=midbuf DIV 256
490 endbuf=buffstart+516  : REM Pointer to the end
510 REM  page 0 values
 530 tskptlo  = &70  : REM pointer to task table
540 tskpthi  = &71
550 task_no   = &72
```

```
560 io_wait   = &73  : REM waiting for PCI data - FF=true
570 byt_wait  = &74  : REM number of bytes waiting for
580 ttwocount = &75  : REM timer two counter
590 pci_gain  = &76
600 bufflo    = &77  : REM disc buffer pointer
610 buffhi    = &78
620 prntrdy   = &79  : REM printer ready 0=OK FF=waiting
630 int_lo    = &7A  : REM interrupt vector storage
640 int_hi    = &7B
650 tsk_accept= &7C  : REM task acceptance bytes
670 iplo      = &80  : REM instruction pointer
680 iphi      = &81
690 palo      = &82  : REM parameter A
700 pahi      = &83
710 pblo      = &84  : REM parameter B
720 pbhi      = &85
730 stacklo = &88  : REM stack pointer
740 stackhi = &89
750 status  = &8A  : REM status flags byte
760 devlo   = &8B  : REM device values table pointer
770 devhi   = &8C
790  mc=P%
840  PROCinload
850   PPRINTTAB(5,5);"Initialising Pointers";
870  PROCpointers P.TAB(5,6);"            Work area";
880  PROCwork_area
890  PRINTTAB(5,7);"            Page Zero";
900  PROCpage_zero
910  PRINTTAB(5,8);"            Interrupts";
920  PROCint_setup
930 PROCplotchar
940  PRINTTAB(5,9);"Done";
950 CHAIN "PROG"
970 END
1020 DEFPROCjump
1040  dest=P%?2+P%?3*256
1050 P%?2=instr(dest) MOD 256
1060 P%?3=instr(dest) DIV 256
1080 ENDPROC
1120 DEFPROCalt
1140  dest=P%?3+P%?4*256
1150 P%?3=instr(dest) MOD 256
1160 P%?4=instr(dest) DIV 256
1180 ENDPROC
1220 DEFPROCpointers
1240 REM set up task pointers
1260 FOR I%=0TO63
1270  task_table?I%=0
```

```
1280 NEXT I%
1300 PTR#X%=2
1310 PROCpt(0)
1320 PROCpt(16)
1330 PROCpt(32)
1340 PROCpt(48)
1360 CLOSE£0
1380 ENDPROC
1420 DEFPROCpt(i)
1440 I%=BGET#X%+BGET#X%*256+H%
1450 task_table?i=I% MOD 256
1460 task_table?(i+1)=I% DIV 256
1480 ENDPROC
1520 DEFPROCinit(A%,B%,C%)
1540 FOR I%=0 TO (B%-1):A%?I%=C%:NEXTI%
1560 ENDPROC
1600 DEFPROCtset(A,B)
1610 :
1620 task_table?A=B MOD 256
1630 task_table?(A+1)= B DIV 256
1650 ENDPROC
1690 DEFPROCbinset
1710 REM set up binary devices
1720 REM first initialise the PIA
1730 ?&FC02=255
1740 ?&FC03=255
1750 ?&FC0C=&C0
1760 REM this sets PA AND PB as outputs
1780 FORI%=0TO7
1790  devtab?(I%*2)=&01
1800  devtab?(I%*2+1)=&FC
1810  mask?I%=2^I%
1820  NEXTI%
1840 REM TRIP BIT
1850 devtab?32=status
1860  mask?16=128
1880 REM now CB2
1890  devtab?22=&0C
1900  devtab?23=&FC
1910 mask?11  =32
1940 ENDPROC
1980 DEFPROCinload
2010 REM Load  in the instruction codes
2030 DIM instr(256)
2050 P%=HIMEM
2060 I%=0
2080 REPEAT
2090  instr(I%)=P%
```

```
2100 I%=I%+1
2110 com=BGET#X%
2120 par=BGET#X%
2140 ?P%=com
2150 P%=P%+1
2160 ?P%=par
2170 P%=P%+1
2190 IF par>0 THEN FOR J%=1 TO par:?P%=BGET#X%:P%=P%+1:NEXT J%
2210 UNTIL (P%-HIMEM)>=Y%-1
2240 REM - NOW SORT OUT JUMPS
2270 P%=H%
2280 K%=1
2300 REPEAT
2310 K%=K%+1
2320 com=?P%
2330 IF com=16 OR com=17 PROCjump
2340 IF com=6 THEN PROCalt
2350 P%=P%+1
2360 par=?P%
2370 P%=P%+par+1
2380 UNTIL K%=I%
2400 ENDPROC
2440 DEFPROCwork_area
2470 REM initialise the work areas
2490 PROCinit(selecttab,9,255)
2500 PROCinit(plottab,9,255)
2510 PROCinit(savetab,9,255)
2520 PROCinit(mask,32,0)
2530 PROCinit(devtab,64,0)
2540 PROCinit(intstat,8,0)
2550 PROCinit(enable_addr,8,0)
2560 PROCinit(disable_addr,8,0)
2570 PROCinit(values,128,0)
2580 PROCinit(diskbuff,512,0)
2590 PROCinit(buffstart,516,0)
2600 REM set up task tables
2610 PROCtset(devlo-&80+0,values)
2620 PROCtset(devlo-&80+16,values)
2630 PROCtset(devlo-&80+32,values)
2640 PROCtset(devlo-&80+48,values)
2650 PROCtset(stacklo-&80+0,stack+6)
2660 PROCtset(stacklo-&80+16,stack+14)
2670 PROCtset(stacklo-&80+32,stack+22)
2680 PROCtset(stacklo-&80+48,stack+30)
2690 values?56=1:REM delay count - set to one
2700 values?58=1
2710 values?60=1
```

```
2720 values?62=1
2730 intstat?0=1
2740 intstat?2=1
2750 intstat?4=1
2760 intstat?6=1
2780 ENDPROC
2820 DEFPROCpage_zero
2840 REM set up page zero variables
2860 J%=&70
2880 FOR I%=0 TO 15
2890 J%?I%=0
2900 NEXT I%
2920 PROCbinset
2940 ?ttwocount=20
2950 tsk_accept?0=255
2960 tsk_accept?1=255
2970 tsk_accept?2=255
2980 tsk_accept?3=255
2990 bufflo?0=diskbuff MOD 256
3000 buffhi?0=diskbuff DIV 256
3010 ?status=0
3020 ?tskptlo=task_table MOD 256
3030 ?tskpthi=task_table DIV 256
3050 ENDPROC
3090 DEFPROCplotchar
3110 REM set up the plotting characters
3130 FORI%=0 TO 7
3140 FORJ%=0 TO 4
3150 READ K%
3160 symbtab?(I%*8+J%)=K%
3170 NEXTJ%
3180 NEXTI%
3200 DATA 4,4,31,4,4
3210 DATA 17,10,4,10,17
3220 DATA 31,17,17,17,31
3230 DATA 2,6,10,6,2
3240 DATA 16,8,3,8,16
3250 DATA 1,2,24,2,1
3260 DATA 2,2,30,2,2
3270 DATA 8,12,10,12,8
3280 :
3290 ENDPROC
3330 DEFPROCheader
3340 VDU2:CLS
3350
PRINTCHR$(D%);CHR$(60);STRING$(37,CHR$(44));CHR$(108);
3360 PRINTCHR$(D%);CHR$(53);CHR$(E%);" BBC/PCI DATA
LOGGER :"; 3370 PRINTTAB(38,1);CHR$(D%);CHR$(106);
3380PRINTCHR$(D%);CHR$(61);STRING$(37,CHR$(44));
CHR$(110);
```

```
3390 ENDPROC
3430 DEFPROCboxing
3440 PRINTTAB(0,3);:F.J%=1TOI%
3450
PRINTCHR$(D%);CHR$(53);CHR$(E%);TAB(38,2+J%);CHR$(D%);
CHR$(106);
3460 NEXTJ%
3470
PRINTCHR$(D%);CHR$(45);STRING$(37,CHR$(44));CHR$(46);
3480 ENDPROC
3520 DEFPROCinterrupts
3540 stat%=&FE6D
3550 ctrl%=&FE6E
3560 auxc%=&FE6B
3580 in=?(PAGE-2)+?(PAGE-1)*256
3590 FORI=0TO2STEP2
3600 P%=in
3610 [OPTI
3630 .main PHP:PHA:TXA:PHA:TYA:PHA
3640      LDA task_no:PHA
3650      LDA #&40  \ test timer 1
3660      BIT stat%
3670      BEQ nexta
3680      LDA #tone_task_no
3690      BEQ nexta
3700      STA task_no
3710      JSR tone_resp
3720 .nexta LDA #&20  \ test timer 2
3730      BIT stat%
3740      BEQ nextb
3750      LDA #ttwo_task_no
3760      BEQ nextb
3770      STA task_no
3780      JSR ttwo_resp
3790 .nextb PLA:STA task_no  \ restore task no & return
3800      PLA:TAY:PLA:TAX:PLA:PLP
3810      JMP (int_lo)
3850 .gotask SEC:SBC #1:ASLA:ASLA:ASLA:ASLA
3860      CLC:ADC #(task_table MOD 256)
3870      STA tskptlo
3880      LDA #(task_table DIV 256):ADC #0
3890      STA tskpthi:JMP mc
3910 .endint PHP:PHA:SEI:LDA int_lo:STA &0204
3920      LDA int_hi:STA &0205:CLI:PLA:PLP
3930      RTS
3950 .startint PHP:PHA:SEI:LDA &0204:STA int_lo
3960      LDA &0205:STA int_hi:LDA #(main MOD 256)
3970      STA &0204:LDA #(main DIV 256):STA &0205
3980      CLI:PLA:PLP
3990      RTS
```

```
4010 .tone_en LDA auxc%:AND #&3F:ORA #&40
4020          STA auxc%:LDA #&C0:STA ctrl%:LDA #&40
4030          STA stat%:LDA #&50:STA &FE64:LDA #&C3
4040          STA &FE65:RTS
4060 .tone_dis LDA auxc%:AND #&3F:STA auxc%
4070           LDA #&40:STA ctrl%:LDA #0:STA &FE64
4080           STA &FE65:LDA #&40:STA stat%:RTS
4100 .ttwo_en LDA auxc%:AND #&DF:STA auxc%
4110          LDA #&A0:STA ctrl%:LDA #&20:STA stat%
4120          LDA #&50:STA &FE68:LDA #&C0:STA &FE69
4130          RTS
4150 .ttwo_dis LDA #&20:STA ctrl%:LDA #0:STA &FE68
4160           STA &FE69:LDA #&20:STA stat%:RTS
4180 .tone_resp LDA #&40:STA stat%
4200 .start SEC:LDA task_no
4230       SBC #1:ASLA:TAX:SEC:LDA intstat,X
4240       SBC #1:STA intstat,X:BNE return
4230       INX:LDA intstat,X:SBC #0:BEQ done
4240       STA intstat,X
4260 .return RTS
4280 .done  DEX:TXA:CLC
4290       ADC #56:TAY:LDA values,Y:STA intstat,X
4300       INX:INY:LDA values,Y:STA intstat,X
4310       LDA task_no:SEC:SBC #1:TAX
4320       LDA tsk_accept,X:BMI return
4330       LDA task_no:JSR gotask:RTS
4350 .ttwo_resp LDA #&20:STA stat%:LDA #&50
4360           STA &FE68:LDA #&C0:STA &FE69
4370           DEC ttwocount:BEQ ttwogo:RTS
4390 .ttwogo LDA #20:STA ttwocount:JMP start
4410 .B%    TXA:JMP gotask \ BASIC entry point
4420 ]
4430 NEXTI
4440 IF P%>PAGE TH.P."OUT OF ROOM FOR MACHINE CODE":END
4460 int_addr?0=startint MOD 256
4470 int_addr?1=startint DIV 256
4480 int_addr?2=endint   MOD 256
4490 int_addr?3=endint   DIV 256
4510IFtone_task_no>0THENenable_addr?((tone_task_no-1)*2)=ton
e_en       MOD 256
4520IFtone_task_no>0THENenable_addr?((tone_task_no-1)*2+1)=t
one_en     DIV 256
4530IFtone_task_no>0THENdisable_addr?((tone_task_no-1)*2)=to
ne_dis     MOD 256
4540IFtone_task_no>0THENdisable_addr?((tone_task_no-1)*2+1)=
tone_dis  DIV 256

4560IFttwo_task_no>0THENenable_addr?((ttwo_task_no-1)*2)=ttw
o_en       MOD 256
```

```
4570IFttwo_task_no>0THENenable_addr?((ttwo_task_no-1)*2+1)=t
two_en      DIV 256
4580IFttwo_task_no>0THENdisable_addr?((ttwo_task_no-1)*2)=tt
wo_dis      MOD 256
4590IFttwo_task_no>0THENdisable_addr?((ttwo_task_no-1)*2+1)=
ttwo_dis  DIV 256
4610 ENDPROC
4650 DEFPROCint_setup
4670 REM setup the task interrupts
4680 *KEY0 BASIC|M
4690 *KEY1 TIMER1|M
4700 *KEY2 TIMER2|M
4710 PRINTTAB(0,13);:PROChighlight
4720 PRINT"TASK DRIVERS: f0 - Basic";
4730 PRINTTAB(0,14);:PROChighlight
4740 PRINT"f1 - Timer 1   f2 - Timer 2";
4750 ba=0:ta=0:tb=0
4760 locn=16
4770 FOR I=0TO3
4780 addr=task_table+I*16
4790 jmpaddr=addr?0+256*addr?1
4800 IF jmpaddr>HIMEM TH.PROCdriver:locn=locn+1
4810 NEXT I
4820 tone_task_no=ta
4830 ttwo_task_no=tb
4840 T%=ba
4850 PROCinterrupts
4870 ENDPROC
4910 DEFPROCdriver
4920 REPEAT
4930 PRINTTAB(5,locn);"TASK ";CHR$(49+I);" DRIVER :";
4940 INPUT""A$
4950 IF A$="BASIC" AND ba=0 TH. ba=I+1:UNTIL TRUE:ENDPROC
4960 IF A$="TIMER1"AND ta=0 TH. ta=I+1:UNTIL TRUE:ENDPROC
4970 IF A$="TIMER2" AND tb=0 TH. tb=I+1:UNTIL TRUE:ENDPROC
4980 IF A$<>"BASIC" AND A$<>"TIMER1" AND A$<>"TIMER2"
TH.E=1 ELSE      E=2
4990 IF E=1TH.P.TAB(5,locn+1);"USE THE FUNCTION KEYS";
5000  IF  E=2TH.P.TAB(5,locn+1);"THIS  DRIVER  ALREADY
ALLOCATED";     5010 TIME=0:REPEAT:UNTIL TIME=150
5020 PRINTTAB(5,locn);STRING$(30," ")
5030 PRINTTAB(5,locn+1);STRING$(30," ")
5040 UNTIL FALSE
5050 ENDPROC
5090 DEFPROChighlight
5100 PRINTCHR$(132);CHR$(157);CHR$(135);
5110 ENDPROC
```

APPENDIX D

PROGRAM " COMPILE "

```
10   REM BBC/PCI COMPILER
30   *LOAD DAMMC  C00
40    D%=151:E%=135:V%=132:U%=134:*FX3,0
50    PROCheader:PRINTTAB(25,1);"COMPILER";
60   I%=16:PROCboxing:PROCinit:PROCwin(0):CLS
90    srcfil=OPENIN("SOURCE")
100   filout=0
110   obuff%=&3000
120   TIME=0
130  PROCpassone
140  CLOSE#0
150   ibuff%=&3000
160   obuff%=&5800
170  PROCpasstwo
180  CLOSE#0
190   ibuff%=&5800
200   filout=OPENOUT("CODE")
210  PROCpassthree
220  CLOSE#0
240   PROCtxtout("")
250   PROCtxtout(" Compile time="+STR$(TIME/100)+" s ")
260        PRINT:PRINTCHR$(V%);CHR$(157);CHR$(U%);"PRESS
RETURN TO          END":*FX15,1
270           I=GET:PROCheader:PRINTTAB(25,1);"SOURCE
OK";:I%=7:PROCboxing
280  *KEY0 *E. G|M
290  *KEY1 *E. P|M
300  PRINTTAB(5,4);"f0 - TO LOAD AND RUN";
310  PRINTTAB(5,6);"f1 - TO RE-EDIT SOURCE";
320  PRINTTAB(5,8);"f2 - TO RETURN TO BASIC";TAB(0,12);
330  *FX3,2
340  *KEY2 *FX3,0|M
350  END
390  REM THE COMPILER ...
400  REM (due to space - reduced rems )
420  DEFPROCfail(A$,C$,X)
440  LOCALB$:B$=" "+A$+C$:PROCfailtxt(B$)
450CLOSE#0:PRINT:PRINTCHR$(129);CHR$(157);CHR$(U%);"Press
   any key ";:*FX15,1
460 I=GET:PROCheader:PRINTTAB(25,1);"FAILED
";:I%=5:PROCboxing
470  PRINTTAB(5,4);"f0 - TO RE-EDIT THE SOURCE";
480  PRINTTAB(5,6);"f2 - TO RETURN TO BASIC";TAB(0,10);
490  *KEY0 *E.P|M
500  *KEY2 *FX3,0|M
510  *FX3,2
520  END
```

```
540  ENDPROC
570  DEFPROCinit
590  pout=32: REM no. of bytes/instr
600  nreg=15: REM no. of registers
610  nbbc=12: REM no. of BBC PORT bits
620  ndev=15: REM no. of PCI devices
630  ncom%=19: REM no. of commands -1
640  nmac%=10: REM no. of macros (max)
650  nlab%=10: REM no. of labels (max)
660  NB =16: REM no. of parameters in txt manipulation
680DIMcom$(ncom%),comc(ncom%),mac$(nmac%),macls(nmac%),
macle(nmac%)
690   DIM lab$(nlab%),labl(nlab%),code(ncom%),npar(ncom%)
700   DIM B$(NB),D$(NB),parray(pout)
710   DIM REG$(nreg),rcode(nreg)
720   DIM BBC$(nbbc),bcode(nbbc)
730   DIM DEV$(ndev),dcode(ndev),dtyp(ndev)
750  FOR i=0 TO ndev
760   READ DEV$(i),dcode(i),dtyp(i)
770  NEXT i
790  FOR i=0 TO nbbc
800   READ BBC$(i),bcode(i)
810  NEXT i
830  FOR i=0 TO nreg
840    REG$(i)="REG"+STR$(i):rcode(i)=i+32
850  NEXT i
870  FOR i=0 TO ncom%
880   READ com$(i),code(i),npar(i)
890  NEXT i
910  FOR i=0 TO nmac%
920  mac$(i)="        ":mac$(i)=""
930  NEXT i
950  FOR i=0 TO nlab%
960  lab$(i)="        ":lab$(i)=""
970  NEXT i
990  FOR i=0 TO NB
1000  B$(i)=STRING$(16," "):B$(i)=""
1010  D$(i)=STRING$(16," "):D$(i)=""
1020 NEXT i
1040 PROCinitwin
1060 ENDPROC
1090 REM devices and commands data
1110 DATA "VOL0",48,1
1120 DATA "VOL1",49,1
1130 DATA "VOL2",50,1
1140 DATA "VOL3",51,1
1150 DATA "REL0",12,0
1160 DATA "REL1",13,0
1170 DATA "REL2",14,0
```

```
1180 DATA "REL3",15,0
1190 DATA "CH0",56,-1
1200 DATA "CH1",57,-1
1210 DATA "CH2",58,-1
1220 DATA "CH3",59,-1
1230 DATA "CH4",60,-1
1240 DATA "CH5",61,-1
1250 DATA "CH6",62,-1
1260 DATA "CH7",63,-1
1270 REM BBC DEVICES
1280 DATA "CA1",8
1290 DATA "CA2",9
1300 DATA "CB1",10
1310 DATA "CB2",11
1320 DATA "PA0",0
1330 DATA "PA1",1
1340 DATA "PA2",2
1350 DATA "PA3",3
1360 DATA "PA4",4
1370 DATA "PA5",5
1380 DATA "PA6",6
1390 DATA "PA7",7
1400 DATA "TRIP",16
1420 DATA "TASK",0,-1
1430 DATA "SET",128,-1
1440 DATA "IF",72,-1
1450 DATA "IFT",64,-1
1460 DATA "INC",112,-1
1470 DATA "DEC",96,-1
1480 DATA "HALT",9,0
1490 DATA "WAIT",8,0
1500 DATA "SCANLIST",36,-1
1510 DATA "ALT",4,-1
1520 DATA "GOTO",16,2
1530 DATA "GOSUB",17,2
1540 DATA "RETURN",18,0
1550 DATA "PLOTLIST",48,-1
1560 DATA "PLOT",49,0
1570 DATA "SCAN",40,0
1580 DATA "SAVE",41,0
1590 DATA "SAVELIST",44,-1
1600 DATA "FLUSH",42,0
1610 DATA "BASIC",43,1
1640 DEFPROCpassone
1660 REM first compiler pass
1670 REM collect Macro names & convert SAM to DAM
1690 PROCsrctxt(STRING$(8,CHR$(255)))
1700  PROCsrctxt(CHR$(255)+"macros"+CHR$(255))
1710 PROCsrctxt(CHR$(255)+"        "+CHR$(255))
```

```
1720  PROCtxtout(CHR$(157)+CHR$(156)+"PASS  1"+CHR$(157))
    :PROCtxtout("")
1730  linout=0:emflag=FALSE : vlflag=FALSE
1750  REPEAT
1760  PROCsamin:PROCsplit(A$)
1770   IF  B$(0)<>""  AND  B$(0)<>"REM"  AND  B$(0)<>"rem"  TH.
PROCintrp
1780  UNTIL EOT OR B$(0)="END"
1790
CLOSE#srcfil:A$=STR$(linout+1):PROCdamaout(0):CLOSE#filout
1810  ENDPROC
1840  DEFPROCintrp
1860  REM interpret a line, pass one
1880  linout=linout+1
1890  IF B$(0)="MACRO" TH.mac=TRUE ELSE mac=FALSE
1900  IF B$(0)="ENDMACRO" TH.emac=TRUE ELSE emac=FALSE
1910  IF mac AND emflag TH.PROCfail("Nested macro
   definitions:",B$(1),1)
1920  IF emac AND vlflag TH.PROCfail("No code in macro:",B$(1),2)

1930  IF emac AND NOT emflag TH.PROCfail("No start of macro
      definition"," ",3)
1940  IF B$(0)="MACRO" AND B$(1)="" TH.PROCfail("Missing macro
       name","",4)
1950    IF   mac   TH.PROCismac(B$(1)):IF   imac%>=0   TH.
PROCfail("Already         defined:",B$(1),5)
1960  IF mac TH.PROCaddmac(B$(1)):emflag=TRUE:vlflag=TRUE
1970  IF emac TH.emflag=FALSE:macle(imac%)=linout
1980  IF NOT mac AND NOT emac AND vlflag THENvlflag=FALSE
1990   IF B$(0)="IF"ORB$(0)="IFT"ORB$(1)="IF"ORB$(1)="IFT"
   THENPROCifsplit
2010  PROCdamout(linout)
2030  ENDPROC
2060  DEFPROCsplit(A$)
2080   FORI%=0TONB:B$(I%)="":NEXTI%
2090   N%=0:L%=0:M%=LEN(A$):IF M%=0 THENENDPROC
2110  REPEAT
2120  REPEAT
2130  L%=L%+1
2140  UNTIL MID$(A$,L%,1)<>" " OR L%>M%
2150  IF L%>M% THENUNTIL TRUE:ENDPROC
2160  C$=MID$(A$,L%,1):PROCnumeric(C$):PROCseparate(C$)
2170  IF NUM TH.PROCnumb ELSE IF NOT SEP TH.PROCtext ELSE
K%=0:J%=0                    2180                 IF
K%<>J%TH.B$(N%)=MID$(A$,J%,(K%-J%)):N%=N%+1
2190  UNTIL L%=M%
2210  ENDPROC
2230  DEFPROCsplitsp(A$)
2250   M%=LEN(A$):L%=1:N%=0
2260  IF MID$(A$,1,1)<>" "THENL%=0
2270  REPEAT
```

```
2280  J%=L%+1
2290  REPEAT
2300  L%=L%+1
2310  UNTIL MID$(A$,L%,1)=" "OR L%=M%
2320  IF L%=M%TH.K%=L%+1ELSE K%=L%
2330  B$(N%)=MID$(A$,J%,(K%-J%)):N%=N%+1
2340  UNTIL L%=M%
2350  IF N%<NB THENFORI%=N%TONB:B$(I%)="":NEXTI%
2370  ENDPROC
2400  DEFPROCnumb
2420  J%=L%:IF L%=M%TH.K%=M%+1:ENDPROC
2430  REPEAT
2440                              L%=L%+1:IF
L%<=M%TH.C$=MID$(A$,L%,1):PROCnumeric(C$)
    :PROCsign(C$)
2450  UNTIL NOT NUM OR L%>M% OR SIGN
2460  K%=L%:IF L%>M% TH.L%=M% ELSE L%=L%-1
2480  ENDPROC
2510  DEFPROCtext
2530  J%=L%:IF L%=M% THENK%=M%+1:ENDPROC
2540  PROCbrackets(C$):IF BRKT THENK%=L%+1:ENDPROC
2550  REPEAT
2560                              L%=L%+1:IF
L%<=M%TH.C$=MID$(A$,L%,1):PROCseparate(C$)
    :PROCbrackets(C$:PROCsign(C$)
2570  UNTIL L%>M% OR BRKT OR SIGN OR SEP
2580  K%=L%:IF L%>M% TH.L%=M% ELSE L%=L%-1
2600  ENDPROC
2630  DEFPROCsign(C$)
2650  C$=LEFT$(C$,1)
2660  IF INSTR("+-",C$)>0TH.SIGN=TRUE ELSE SIGN=FALSE
2680  ENDPROC
2710  DEFPROCnumeric(C$)
2730  C$=LEFT$(C$,1)
2740  IF INSTR("0123456789.+-",C$)>0 THENNUM=TRUE ELSE
NUM=FALSE
2760  ENDPROC
2790  DEFPROCseparate(C$)
2810  IF INSTR(", =",C$)>0 TH.SEP=TRUE ELSE SEP=FALSE
2830  ENDPROC
2870  DEFPROCifsplit
2890  REM split the IF clause
2910  i=0
2920  REPEAT
2930  i=i+1
2940  UNTIL B$(i)="THEN"OR B$(i)=""
2950  IF B$(i)=""THENEENDPROC
2970  B$(i)="":isplit=i:PROCdamout(linout):linout=linout+1
    :i=isplit+1:j=0
2980  FORS%=0TOisplit:B$(S%)="":NEXTS%
```

```
2990 REPEAT
3000  B$(j)=B$(i):B$(i)=""
3010 j=j+1:i=i+1
3020  UNTIL B$(i)=""
3040 ENDPROC
3080 DEFPROCpasstwo
3100 REM compiler pass two
3110 REM macro expansion and label collection
3130 PROCsrctxt(CHR$(255)+"       "+CHR$(255))
     :PROCsrctxt(CHR$(255)+"labels"+CHR$(255))
3140 PROCsrctxt(CHR$(255)+"       "+CHR$(255)):PROCtxtout(" ")
3150  PROCtxtout(CHR$(157)+CHR$(156)+"PASS 2 "+CHR$(157))
    :PROCtxtout("")
3160  PROCdamin(0):endofmac=VAL(A$)
3170  linein=1:lineout=1:param$=""
3180 PROCexpand(linein,endofmac,param$)
3190 A$=STR$(lineout):PROCdamaout(0):CLOSE#filout
3200 PROCsrctxt(CHR$(255)+"       "+CHR$(255))
     :PROCsrctxt(STRING$(8,CHR$(255)))
3220 ENDPROC
3250 DEFPROCexpand(linin,endin,parm$)
3270 REM macro expansion routine, recursive
3290 LOCAL linein,endofmac,param$,imac%,iparin%,iparout%
3300 LOCAL Bold$,Dold$
3310 PROCsave
3330 REM REPEAT
3340      PROCmacjump:IF    linin=endin    TH.UNTIL
TRUE:PROCrestore:ENDPROC
3350 PROCdamin(linin):PROCsplitsp(A$):iparout%=0:iparin%=0
3360 REPEAT
3370 IF INSTR(B$(iparin%),"PARAM")>0 TH. PROCparins
3380 iparin%=iparin%+1
3390 UNTIL iparin%>NB OR B$(iparin%)=""
3400 iparin%=0:LOCAL subst:subst=FALSE
3420 REPEAT
3430 PROCismac(B$(iparin%))
3440 IF imac%>=0TH.PROCexpmac:iparin%=iparin%+1
3450 IF imac%<0THENPROCcompute:D$(iparout%)=B$(iparin%):
B$(iparin%)="":PROClabel:iparin%=iparin%+1:iparout%=iparout%+1
3460 UNTIL iparin%>NB OR B$(iparin%)=""
3480 iparin%=0
3490  IF  D$(0)<>""TH.PROCnumeric(D$(0)):IF  NUM  THEN
retval$=D$(0)          :D$(0)="":iparin%=1
3500 iparout%=0
3520 REPEAT
3530 B$(iparout%)=D$(iparin%):D$(iparin%)=""
3540 iparin%=iparin%+1:iparout%=iparout%+1
3550 UNTIL iparin%>NB OR D$(iparin%)=""
```

```
3570 IF B$(0)<>""TH.PROCdamout(lineout):lineout=lineout+1

3580 linin=linin+1
3600  UNTIL linin=endin
3620  PROCrestore
3640  ENDPROC
3670  DEFPROCexpmac
3690  IF macle(imac%)=endin TH.PROCfail("Recursive macro
      definition",mac$(imac%),8)
3700 IF iparout%>0TH.param$=D$(iparout%-1) ELSE param$=""

3710 linein=macls(imac%)+1:endofmac=macle(imac%):retval$=""
    :B$(iparin%)=""
3720 PROCexpand(linein,endofmac,param$)
3730IF subst AND
iparout%>0TH.D$(iparout%-1)="":iparout%=iparout%-1
3740 IF retval$<>"" AND iparout%>0TH.D$(iparout%)=retval$
    :iparout%=iparout%+1
3760 ENDPROC
3790 DEFPROCcompute
3810 LOCAL ip,pi
3830 IF B$(iparin%)<>"(" THENENDPROC
3840 ip=iparin%+1
3850 IF B$(ip)=")" OR B$(ip)=""TH.PROCfail("Empty ( .. )
    exprn.","",9)
3860 A$=""
3870 REPEAT
3880 A$=A$+B$(ip):B$(ip)=""
3890 ip=ip+1
3900 UNTIL B$(ip)=")" OR B$(ip)=""
3920  B$(iparin%)=STR$(INT(EVAL(A$)))
3930 IF B$(ip)=""THENENDPROC
3940 ip=ip+1:pi=iparin%+1
3960 REPEAT
3970  B$(pi)=B$(ip):B$(ip)=""
3980 ip=ip+1:pi=pi+1
3990 UNTIL B$(ip)="" OR ip>NB
4010 ENDPROC
4040 DEFPROCiscom(A$)
4060 icom%=-1:S%=0
4070 REPEAT
4080 IF A$=com$(S%)THENicom%=S% ELSE S%=S%+1
4090 UNTIL icom%>=0 OR S%>ncom%
4110 ENDPROC
4140 DEFPROCismac(A$)
4160 LOCAL B$:B$=LEFT$(A$,6):imac%=-1:S%=0
4170 REPEAT
4180 IF B$=mac$(S%)TH.imac%=S% ELSE S%=S%+1
4190 UNTIL imac%>=0 OR S%>nmac%
4210 ENDPROC
4240 DEFPROCaddmac(A$)
4260 imac%=-1
```

```
4270 REPEAT
4280 imac%=imac%+1
4290 UNTIL macls(imac%)=0 OR imac%=nmac%
4310 IF macls(imac%)>0TH.PROCfail("Macro table full","",6)
4320 A$=LEFT$(A$,6):macls(imac%)=linout:mac$(imac%)=A$
4330 IF LEN(A$)<6TH.A$=A$+STRING$(6-LEN(A$)," ")

4340 PROCsrctxt(CHR$(255)+A$+CHR$(255)):PROCtxtout("")
4360 ENDPROC
4390 DEFPROCislab(A$)
4410 LOCAL B$:B$=LEFT$(A$,6):ilab%=-1:S%=0
4420 REPEAT
4430 IF B$=lab$(S%)THENilab%=S% ELSE S%=S%+1
4440 UNTIL ilab%>=0 OR S%>nlab%
4460 ENDPROC
4490 DEFPROClabel
4510 IF iparin%>0 THENENDPROC
4520 PROCiscom(D$(0)):IF icom%>=0THENENDPROC
4530 c$=MID$(D$(0),1,1)
4540 PROCnumeric(c$):IF NUM THENENDPROC
4550 PROCbrackets(c$):IF BRKT THENENDPROC
4560 PROCislab(D$(0)):IF ilab%>=0THENPROCfail("Multiple label
     definitions :",D$(0),10)
4570 IF B$(iparin%+1)=""TH.PROCfail("No instr. on label line
  :",D$(0),53)
4580 PROCaddlab(D$(0)):D$(0)="":iparout%=iparout%-1
4600 ENDPROC
4630 DEFPROCaddlab(A$)
4650 ilab%=-1
4660 REPEAT
4670 ilab%=ilab%+1
4680 UNTIL labl(ilab%)=0 OR ilab%>nlab%
4690 IF ilab%>nlab% TH.PROCfail("Label table full","",11)
4700 lab$(ilab%)=LEFT$(A$,6):labl(ilab%)=lineout
4710 IF LEN(A$)<6TH.A$=A$+STRING$(6-LEN(A$)," ")

4720 PROCsrctxt(CHR$(255)+LEFT$(A$,6)+CHR$(255))
    :PROCtxtout(CHR$(V%)+CHR$(157)+CHR$(U%)+A$)
4740 ENDPROC
4780 DEFPROCsamin
4800 A$=""
4810 REPEAT
4820 I%=BGET#srcfil:IF I%<>13THENA$=A$+CHR$(I%)
4830 UNTIL I%=13 OR EOF#srcfil
4840 IF EOF#srcfil TH.EOT=TRUE ELSE EOT=FALSE
4860 ENDPROC
4890 DEFPROCdamaout(line)
4910
?&72=(obuff%+line*80)MOD256:?&73=(obuff%+line*80)DIV256
 4920 $&C00=A$:CALL &C50
4940 ENDPROC
```

```
4970 DEFPROCdamin(line)
4990?&70=(ibuff%+line*80)MOD256:?&71=(ibuff%+line*80)
DIV256
5000 CALL &C60:A$=$&C00
5020 ENDPROC
5050 DEFPROCdamout(line)
5070  PROCbmerge:PROCdamaout(line)
5080   A$=CHR$(U%)+MID$(A$,2):PROCtxtout(A$)
5100  ENDPROC
5130  DEFPROCbmerge
5150   I%=0:A$=""
5160   REPEAT
5170   A$=A$+" "+B$(I%):I%=I%+1
5180   UNTIL LEN(A$)>61 OR B$(I%)=""
5190  IF B$(I%)<>""TH.PROCfail("Output line > 60 chars","",7)
5210  ENDPROC
5240  DEFPROCrestore
5260  PROCsplitsp(Dold$):FOR I%=0TO NB:D$(I%)=B$(I%)
    :NEXTI%:PROCsplitsp(Bold$)
5270  FORI%=0TO NB
5280   IFB$(I%)="|"THENB$(I%)=""
5290   IFD$(I%)="|"THEND$(I%)=""
5300  NEXTI%
5320 ENDPROC
5340 DEFPROCsave
5360 REM save B$() and D$() into LOCAL
5370 REM variables Bold$ and Dold$
5390 Bold$=""
5400 Dold$=""
5410 FOR I%=0 TO NB
5420  IF  B$(I%)=""TH.Bold$=Bold$+"  |"  ELSE  Bold$=Bold$+"
"+B$(I%)
5430  IF  D$(I%)=""TH.Dold$=Dold$+"  |"  ELSE  Dold$=Dold$+"
"+D$(I%)
5440  B$(I%)="":D$(I%)=""
5450 NEXT I%
5470 ENDPROC
5500 DEFPROCjump
5520 j=-1
5530 FOR I%=0 TO nmac%
5540 IF macls(I%)=linin THEN j=I%
5550  NEXTI%
5560 IF j>=0 THEN linin=macle(j)+1
5580 ENDPROC
5610 DEFPROCmacjump
5630 REPEAT
5640 lin=linin:PROCjump
5650 UNTIL lin=linin
5670 ENDPROC
5720 DEFPROCbrackets(C$)
5740 C$=LEFT$(C$,1)
```

```
5750 IF INSTR("<>()",C$)>0TH.BRKT=TRUE ELSE BRKT=FALSE
5770 ENDPROC
5800 DEFPROCparins
5820 subst=TRUE:LOCAL blen,a$,b$,c$
5830  blen=LEN(B$(iparin%))
5840  i=INSTR(B$(iparin%),"PARAM")
5850 IF i=1TH.a$="" ELSE a$=MID$(B$(iparin%),1,(i-1))
5860  b$=parm$
5870 IF (i+4)=blen TH.c$="" ELSE c$=MID$(B$(iparin%),(i+5),blen)
5880  B$(iparin%)=a$+b$+c$
5900 ENDPROC
5930 DEFPROCbyte(C$)
5950 IF C$=""TH.PROCfail("Not a number:",C$,55)
5960  I%=EVAL(C$)
5970 IF I%<0TH.PROCfail("Not a byte:",C$,13)
5980 IF I%>255TH.PROCfail("Not a byte:",C$,13)
6000 ENDPROC
6030 DEFPROCword(C$)
6050 IF C$=""TH.PROCfail("Not a number:",C$,55)
6060  I%=EVAL(C$)
6070  IF  I%>65535  OR  I%<-32768TH.PROCfail("Value  >  16  bits
:",C$,14)
6080 IF I%>32767THENPROCtxtout(" (Arg not valid if +/-)")
6100 ENDPROC
6130 DEFPROClohi(C$)
6150 LOCAL I:I=0
6160 IF C$="ON" OR C$="HI" OR C$="CLOSED"THENhi=TRUE:I=1
6170 IF C$="OFF" OR C$="LO" OR C$="OPEN"THENhi=FALSE:I=1
6180 IF I=0 THENPROCfail("Not valid arg. :",C$,15)
6200 ENDPROC
6230 DEFPROCoutpar
6250 REM put one byte parameter into code parameter array
6270  parray(iout)=I%:iout=iout+1
6280 IF iout>pout THENPROCfail("CODE parameter array full","",17)

6290  parray(1)=iout-2
6310 ENDPROC
6340 DEFPROCoutval
6360 REM output a two byte value into parameter array
6380 !&70=I%:parray(iout)=?&70:parray(iout+1)=?&71
6390  parray(1)=iout:iout=iout+2
6400 IF iout>pout THENPROCfail("Parameter array full ","",17)
6420 ENDPROC
6450 DEFPROCclrparray
6470 FOR I%=0 TO  pout:parray(I%)=-1:NEXTI%
6490 ENDPROC
6520 DEFPROCisdev(A$)
6540  dev=-1:S%=0
6550  REPEAT
6560 IF A$=DEV$(S%)THENdev=S% ELSE S%=S%+1
6570 UNTIL dev>=0 OR S%>ndev
```

```
6590 ENDPROC
6620 DEFPROCisbbc(A$)
6640 bbc=-1:S%=0
6650 REPEAT
6660 IF A$=BBC$(S%)TH.bbc=S% ELSE S%=S%+1
6670 UNTIL bbc>=0 OR S%>nbbc
6690 ENDPROC
6720 DEFPROCisreg(A$)
6740 reg=-1:S%=0
6750 REPEAT
6760 IF A$=REG$(S%)THENreg=S%ELSE S%=S%+1
6770 UNTIL reg>=0 OR S%>nreg
6790 ENDPROC
6820 DEFPROCpassthree
6840 REM third pass - convert mnemonics to instruction codes
6860 T%=0: REM task number
6870 PROCtxtout(""):PROCtxtout(CHR$(157)+CHR$(156)+"PASS 3
    "+CHR$(157))
6880 PROCtxtout("")
6890 PROCdamin(0):endin=VAL(A$)
6900 linein=1:prog=0: REM prog is byte counter
6910 FOR I%=1TO10:BPUT#filout,0:NEXTI%
6920 PROCtxtout(" TASK 1"):PROCconv("TASK 1")
6940 REPEAT
6950
PROCdamin(linein):PROCtxtout(A$):PROCconv(A$):linein=linein+1
6960 UNTIL linein=endin
6980 BPUT#filout,0:BPUT#filout,0:prog=prog+2
6990 PTR#filout=0
7000 BPUT#filout,(prog MOD 256):BPUT#filout,(prog DIV 256)
7020 ENDPROC
7050 DEFPROCconv(A$)
7070 PROCsplitsp(A$):PROCiscom(B$(0))
7080 IF icom%<0 TH. PROCfail("Not a command :",B$(0),18)
7100 PROCclrparray:iout=2:parray(0)=code(icom%):parray(1)=0
7110 IF npar(icom%)=0 TH. PROCwrite:Endproc
7120 IF B$(1)=""THENPROCfail("Missing argument(s) :",B$(0),35)
7130 IFnpar(icom%)=1 OR
npar(icom%)=2THENPROCnumeric(B$(1)):IF NUM THEN
PROCbyte(B$(1)):PROCoutpar:PROCwrite:ENDPROC
7140 IF npar(icom%)=2TH.PROCislab(B$(1)):IF ilab%<0 THEN
PROCfail("Undefined argument :",(B$(0)+" "+B$(1)),19)
7150 IF
npar(icom%)=2TH.I%=labl(ilab%):PROCoutval:PROCwrite:ENDPROC
7160 IF B$(0)="ALT" THEN PROCalt:EENDPROC
7170 IF B$(0)="TASK" THENPROCtask:ENDPROC
7180 IF B$(0)="PLOTLIST" OR B$(0)="SAVELIST" THEN
   PROCstartplot:ENDPROC
7190 IF B$(0)="INC" OR B$(0)="DEC" THEN PROCinc:ENDPROC
7200 IF B$(0)="SCANLIST" THEN PROCselect:ENDPROC
7210 IF B$(0)="IF" OR B$(0)="IFT" THENPROCif:ENDPROC
```

```
7220 IF B$(0)="SET" THEN PROCset:ENDPROC
7240 ENDPROC
7270 DEFPROCwrite
7290 FOR S%=0 TO (iout-1)
7300 REM PROCtxtout("  "+STR$(S%)+"="+STR$(parray(S%)))
7310 BPUT#filout,parray(S%):prog=prog+1
7320 NEXT S%
7340 ENDPROC
7370 DEFPROCalt
7390 PROCnumeric(B$(1)):IF NOT NUM TH.PROCfail("Not a task number    :",B$(1),51)
7400 PROCbyte(B$(1)):IF I%<1 OR I%>4TH.PROCfail("Not a task number    :",B$(1),51)
7410 PROCoutpar
7420 IF B$(2)="+" TH. parray(0)=parray(0)+1:PROCwrite:E.
7430 IF B$(2)="HALT" TH. PROCwrite:E.
7440 IF B$(2)="" TH. PROCfail("Missing argument - ALT","",52)
7450 PROCislab(B$(2)):IF ilab%<0 TH. PROCfail("Incorrect argument :",B$(2),52)
7460 parray(0)=parray(0)+2:I%=labl(ilab%):PROCoutval:PROCwrite
7480 ENDPROC
7510 DEFPROCstartplot
7530 i=1
7540 REPEAT
7550 PROCisreg(B$(i)):IF reg>=0 TH. I%=rcode(reg):PROCoutpar

7560 IF reg<0 THEN PROCisdev(B$(i)):IF dev<0 THEN PROCfail("Incorrect argument :",(B$(0)+" "+B$(i)),22)
7570 IF reg<0 THEN IF dev>=0 THEN I%=dcode(dev):PROCoutpar:dev=-1
7580 i=i+1
7590 UNTIL i>8 OR B$(i)=""
7610IFi>8 AND B$(i)<>"" TH.PROCfail("Too many arguments:",B$(0),23)
7620 PROCwrite
7640 ENDPROC
7670 DEFPROCinc
7690 PROCisdev(B$(1))
7700 IF dev<0 TH. PROCfail("Invalid parameter :",(B$(0)+" "+B$(1)),27)
7710 i=dcode(dev)
7720 IF i<48 OR i>51 TH. PROCfail("Invalid device :",(B$(0)+" "+B$(1)),24)
7730 parray(0)=parray(0)+(i-48)
7740 IF B$(2)="" TH. PROCfail("Missing change value :",B$(0),25)
7750 PROCnumeric(B$(2)):IF NOT NUM TH. PROCfail("Not valid inc/dec    :",B$(2),26)
7760 PROCword(B$(2)):IF I%<0 TH.PROCfail("-ve argument not allowed    :",B$(0),59)
7770 PROCoutval:PROCwrite
7790 ENDPROC
```

```
7830 DEFPROCselect
7850 parray(0)=0
7860 IF B$(1)="MAX" TH. parray(0)=36
7870 IF B$(1)="MID" TH. parray(0)=37
7880 IF B$(1)="MIN" TH. parray(0)=38
7890 IF parray(0)<36 TH. PROCfail("Incorrect FSD :",B$(1),29)
7900 i=2
7910 REPEAT
7920 IF B$(i)="" THen PROCfail("Missing argument :",B$(0),30)
7930 PROCisdev(B$(i))
7940 IF dev<0 TH. PROCfail("Not a valid channel :",B$(i),31)
7950 IF dcode(dev)<56 TH. PROCfail("Not a valid channel
  :",B$(i),31)
7960 I%=dcode(dev):PROCoutpar
7970 i=i+1
7980 UNTIL i>9 OR B$(i)=""
7800IF i>9AND B$(i)<>""TH.PROCfail("Too many arguments
:",B$(0),32)
8010 PROCwrite
8030 ENDPROC
8060 DEFPROCif
8080 PROCnumeric(B$(1))
8090 IF NUM
TH.PROCword(B$(1)):PROCoutval:parray(0)=parray(0)+2:
   dev=-1:reg=-1
8100 IF NOT NUM TH.PROCisdev(B$(1)):IF dev<0 THEN
PROCisreg(B$(0)): IFreg<0TH.PROCfail("Incorrect argument
:",(B$(0)+" "+B$(1)),33)
8110 IF dev>=0TH.I%=dcode(dev) ELSE IF reg>=0 TH.
I%=rcode(reg)
8120 IF reg>=0OR dev>=0TH.PROCoutpar
8140 IF B$(2)<>"<"AND B$(2)<>">"TH.PROCfail("Incorrect operator
      :",B$(2),34)
8150 IF B$(2)=">"TH.parray(0)=parray(0)+4
8170 dev=-1:reg=-1:PROCnumeric(B$(3))
8180 IF NUM TH.
PROCword(B$(3)):PROCoutval:parray(0)=parray(0)+1
8190 IF NOT NUM THENPROCisdev(B$(3)):IFdev<0
THENPROCisreg(B$(3)): IFreg<0TH.PROCfail("Incorrect
argument :",(B$(0)+" "+B$(3)),33)
8200 IF dev>=0TH.I%=dcode(dev):PROCoutpar ELSE IF reg>=0
THEN I%=rcode(reg):PROCoutpar
8220 PROCwrite
8240 ENDPROC
8270 DEFPROCset
8290 IF B$(1)="DELAY" TH.I%=T%+27:PROCoutpar
8300 IF B$(1)="TIMER1" TH.I%=27:PROCoutpar
8310 IF B$(1)="TIMER3" TH.I%=26:PROCoutpar
8320 PROCisbbc(B$(1)):IF bbc>=0TH.PROCsetbbc:ENDPROC
8330 PROCisdev(B$(1)):IFdev>=0TH.PROCsetdev:IFi<16
THENENDPROC
```

```
8340 PROCisreg(B$(1)):IF reg>=0TH.I%=rcode(reg):PROCoutpar
8360 PROCnumeric(B$(2)):IF NUM THEN
parray(0)+16:PROCword(B$(2)): PROCoutval
8370 IF NOT NUM TH.PROCisreg(B$(2)):IF reg<0 TH.
PROCisdev(B$(2))
8380 IF NOT NUM AND reg<0 AND dev<0 TH. PROCfail("Invalid
argument :",B$(2),36)
8390 IF NOT NUM AND reg>=0 TH. I%=rcode(reg):PROCoutpar
ELSE IF NOT NUM THEN I%=dcode(dev):PROCoutpar
8410 IF B$(3)=""THENPROCwrite:ENDPROC
 8420 C$=LEFT$(B$(3),1):PROCsign(C$):PROCnumeric(C$)
8430 IF NOT SIGN AND NOT NUM TH. PROCfail("Invalid operator :",
   B$(3),38)
8440 parray(0)=parray(0)+8:IF C$="+"OR NOT SIGN THEN
   parray(0)=parray(0)+4
8460 IF SIGN AND LEN(B$(3))>1TH.B$(4)=MID$(B$(3),2)
8470 IF NOT SIGN THENB$(4)=B$(3)
8480 PROCnumeric(B$(4)):IF NUM THENparray(0)=parray(0)+2:
      PROCword(B$(4)):PROCoutval:PROCwrite:ENDPROC
8490 PROCisreg(B$(4)):IF reg<0 TH. PROCisdev(B$(4))
8500 IF reg<0 AND dev<0 TH. PROCfail("Invalid argument
:",B$(4),36)
8510 IF reg>=0 TH. I%=rcode(reg):PROCoutpar ELSE
I%=dcode(dev):
   PROCoutpar
8530 PROCwrite
8550 ENDPROC
8590 DEFPROCtask
8610 T%=INSTR("1234",B$(1))
8620 IF T%=0 TH. PROCfail("Unrecognised task number",B$(1),44)

8630 PROCwrite: REM put out ABORT
8640 I%=PTR#filout:REM save current ptr
 8650 PTR#filout=2*T%:J%=BGET#filout+BGET#filout*256
8660IF(T%=1 AND J%>2) OR (T%>1 AND J%>0) TH.
PROCfail("Task already defined :",STR$(T%),45)
8670 parray(0)=0:parray(1)=0
8680 PTR#filout=2*T%
8690 BPUT#filout,(prog MOD 256):BPUT#filout,(prog DIV 256)
8700IFprog=4ANDT%>1TH.PTR#filout=2:BPUT#filout,0:
BPUT#filout,0
8710 PTR#filout=I%
8730 ENDPROC
8760 DEFPROCsetbbc
8780 PROClohi(B$(2)):parray(0)=parray(0)+64+bcode(bbc):IF
hi=TRUE THENparray(0)=parray(0)+32
8790 PROCwrite
8810 ENDPROC
8840 DEFPROCsetdev
```

```
8860 i=dcode(dev):IF i>11 AND i<16 THEN parray(0)=parray(0)+64+i: PROClohi(B$(2)):IF hi=TRUE TH. parray(0)=parray(0)+32
8870 IF i>11AND i<16THenPROCwrite:ENDPROC
8880 IF i>55TH.PROCfail("Set Device - Dev Code=",STR$(i),42)
8890 I%=i:PROCoutpar
8910 ENDPROC
8940 DEFPROCheader
8960 VDU26:CLS
8970PRINTCHR$(D%);CHR$(60);STRING$(37,CHR$(44)); CHR$(108);
8980 PRINTCHR$(D%);CHR$(53);CHR$(E%);" BBC/PCI DATA LOGGER :";
8990 PRINTTAB(38,1);CHR$(D%);CHR$(106);
9000 PRINTCHR$(D%);CHR$(61);STRING$(37,CHR$(44)); CHR$(110);
9020 ENDPROC
9050 DEFPROCboxing
9070 PRINTTAB(0,3);:FORJ%=1TOI%
9080 PRINTCHR$(D%);CHR$(53);CHR$(E%);TAB(38,2+J%); CHR$(D%);CHR$(106);
9090 NEXTJ%
9100 PRINTCHR$(D%);CHR$(45);STRING$(37,CHR$(44)); CHR$(46);
9120 ENDPROC
9150 DEFPROCinitwin
9170 DIM window(10,4)
9190 FOR I=0 TO 4
9200 FOR J=0 TO 4
9210 READ window(I,J)
9220 NEXT J
9230 NEXT I
9250 PROCwin(0)
9260 DATA 3,16,37,3,0
9270 DATA 3,22,35,3,0
9280 DATA 3,18,10,3,1
9290 DATA 11,18,37,3,0
9300 DATA 0,23,39,20,1
9320 ENDPROC
9350 DEFPROCwin(w)
9370 W%=w
9380 VDU28,window(w,0),window(w,1),window(w,2),window(w,3)
9390 VDU31,0,(window(W%,1)-window(W%,3))
9400 IF window(w,4)=1TH.VDU14 ELSE VDU15
9420 ENDPROC
9450 DEFPROCtexout(A$,w)
9470 IF w<>W% TH.PROCwin(w)
9480 IF LEN(A$)=(window(W%,2)-window(W%,0)+1) THENPRINT A$; ELSE PRINT A$
9500 ENDPROC
```

```
9530 DEFPROCsrctxt(A$)
9540 PROCtexout(A$,2)
9550 ENDPROC
9580 DEFPROCtxtout(A$)
9590 PROCtexout(A$,3)
9600 ENDPROC
9630 DEFPROCfailtxt(A$)
9640 PROCtexout(A$,4)
9650 ENDPROC
```