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Shear Strength Characteristics of Certain Colliery Discards with respect to Coal Rank

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ABSTRACT

Shear Strength Characteristics of Certain Colliery Discards with respect to Coal Rank

This work forms part of the research programme into the properties of colliery discards undertaken in Durham since the Aberfan disaster of 1966.

The discussion relating to residual strength in the paper 'Colliery Spoil Tips - after Aberfan' was summed up by the authors, McKechnie Thomson and Rodin, with the words "The information currently available on residual strength poses a number of questions and further studies are needed to clarify such factors as the effect of normal pressure and magnitude of strain". The current work attempts to clarify some of these problems.

Large strain (1.5 to 2.5 metres total displacement) 12-inch shear-box tests have been undertaken on selected samples from different National Coal Board coalfield areas. A supplementary programme of tests in a 60mm shear-box were used to confirm the results of the large-scale tests. Similarly, additional tests have been conducted at normal stresses which are generally higher than those customarily adopted for normal soils testing.

The results show that at low normal stresses (80 kN/m^2), shear strength reduction in most discards is limited (15 - 25 per cent) for a displacement of one metre. The

exception is extreme low rank material from the West Midlands coalfield, for which a strength reduction of over 40 per cent was obtained.

Tests revealed a marked increase in the rate of shear strength reduction for most discards at a normal stress value between 200 - 300 kN/m^2. Above 500 kN/m^2 increase in the rate of breakdown is limited.

Correlation of shear strength characteristics with the rank code number of the associated coal show generally negative results, the exception being extreme 'low rank' discard from collieries in the West Midlands. Statistical treatment of the results has revealed significant correlations between the shear strength properties and the grading parameters.

In practical terms, vehicular activity is unlikely to cause shear planes to develop in the majority of new or existing tips during emplacement or regrading operations.

ACKNOWLEDGEMENTS

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Considerable assistance has been provided by my supervisor, Dr. R.K. Taylor, especially concerning the treatment of the chemical and mineralogical data. Help in the experimental aspect of the compositional analyses was kindly provided by Mr. R.G. Hardy, Experimental Officer in the Geological Sciences Department.

Acknowledgement should be made of the general assistance by the technical staff of the department, especially from those directly concerned with the Engineering Geology Laboratory.

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CHAPTER 1

INTRODUCTION

1.1 The background of research into colliery discard

The failure of Tip No. 7 at Aberfan in 1966. which caused extensive loss of life, revealed the remarkable lack of knowledge concerning the fundamental properties of colliery discard.

It is not conceivable that in any other aspect of civil engineering would such large earthworks be executed without even simple design methods being utilised. However, colliery tips were commonly constructed by tipping material at its angle of repose. It is therefore surprising that so few of the 2000 tips which have existed in this country have given trouble.

There was an awareness in South Wales for many years of the potential dangers of the tips on the valley sides (Knox, 1927). The Abercynon tip failure and flow-slide preceeded the Aberfan disaster by nearly thirty years, and was potentially as destructive (Bishop et al, 1969). It is surprising that the Abercynon failure did not attract more attention at the time.

The Aberfan disaster stirred public opinion, which resulted in Government action through the Mines and Quarries (Tips) Act (1969). However, it did not remain for this Act to initiate research into colliery discard. Soon after the Aberfan disaster, site investigations were initiated by the National Coal Board on what were thought to be other potentially dangerous tips. Such operations, although they answered the question of the stability of the tips concerned, provided little information on any time-dependent changes in colliery discard. It was the opinion of Bishop <u>et al</u> (1969) that some process of weathering or hydration was necessary to produce the low shear strength of the Aberfan shear plane. Such time-dependent changes could be the cause of instability developing in some tips.

As a result of the Aberfan disaster, and in the light of the results from site investigations, the National Coal Board (1970) drew up a set of basic design rules for all tips.] It had been recognised that there were regional variations in the mechanical properties of colliery discard, but these had not been adequately defined for tip design to operate on a regional basis.

1.2 Aims of this research

Price (1966) demonstrated a possible correlation between the uniaxial strength of some rocks from the South Wales coal field and the probable maximum depth of burial of the rocks. Such a correlation, if proved on a national basis, would vastly simplify the task of classifying colliery discards by their mechanical properties. The depth of burial of coal is usually reflected in the coal classification system known as coal rank. (See section 1.3).

A further indication of the possible relation between the mechanical properties of discard and coal rank was first observed about twenty years ago, when it was noticed that some discards broke down more readily in the washeries than others. Further work established a close correlation between the extent of breakdown and the rank of the associated coal. (Berkovitch et al, 1959; Taylor and Spears, 1970).

The difference between the peak shear strength ($39\frac{1}{2}^{\circ}$) and the residual shear strength (18°) for the Aberfan material indicates an extensive change in shear strength that results from considerable deformation.

Extensive testing has now established the range of peak shear strengths to be expected in the British coal fields. This lies between about 25° and 40°. (McKechnie Thomson and Rodin, 1972). Far less work has been done concerning residual shear strengths, and there is considerable variation in the results which have been obtained. It was hoped that during this research the order of residual shear strength and the magnitude of the displacements involved would be more accurately determined.

One of the possibilities that has been considered in this research programme concerns the re-activation of pre-existing shear surfaces. It is fairly clear that at Littleton tip regrading operations caused such a re-activation.* In the future many tips are likely to be regraded and we must therefore consider the fall-off in shear strength under the likely normal stresses which may be applicable. For this purpose many of the large shear-box tests have been carried out at a normal stress corresponding to about 5 metres of overburden.

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* At Littleton the implication was that a small displacement (0.5 to 1.0 metres) might well reduce the shear strength to a residual state. (Durham Annual Report to National Coal Board, 1972).

1.3 Coal Rank

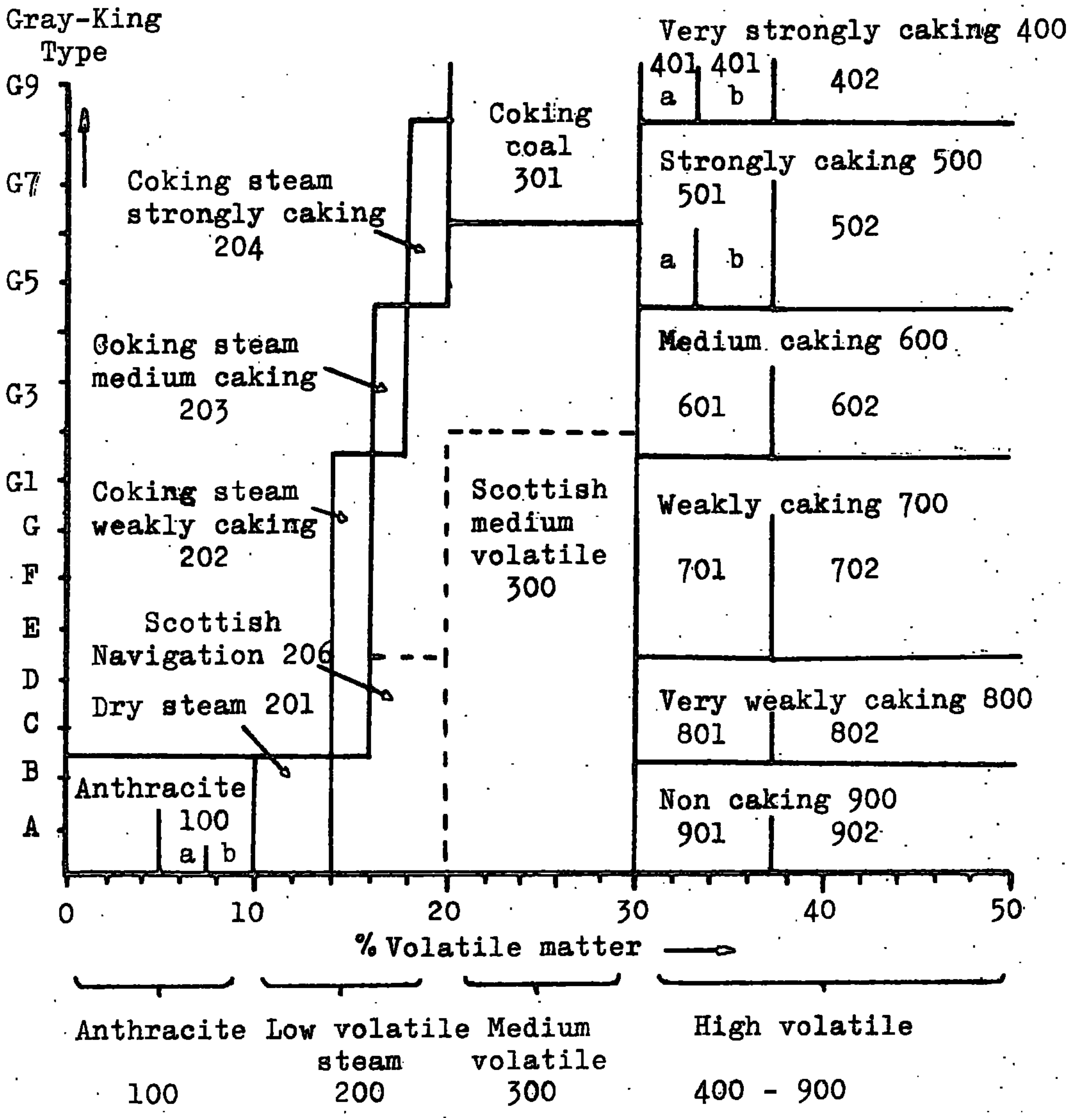
Coal rank is one of the methods of classifying coal. The term is essentially qualitative. The classification is based on the stages of coalification. Lignite, which is a very low level form of coal, which has a very high volatile content, is known as a low rank coal. The bituminous coals are of medium rank, while anthracite, which has a very low volatile content, is the highest rank of coal. The process of coalification requires either pressure and/or temperature, which are usually the result of burial.

It has been shown (Teichmuller and Teichmuller,1968), that there is an almost linear decrease in the volatile content of coal as the depth of burial increases. The same authors have also shown that the density of the associated shales increase with depth of burial.

Unfortunately, a classification of coal based only on the content of volatiles is of little commercial importance. In Britain, the coal rank classification system used is based both on the volatile content and the caking properties, the latter being determined by the Gray-King Assay.

The table in Figure 1.1 shows the arrangement of the British coal rank classification system. This shows that although the rank code numbers do increase overall with the increase in volatiles, there are groups in the rank coding where the volatile content remains constant and the coking properties vary. It should be noted that the rank coding is inverse in as much as anthracite, which is a high rank coal, has the lowest rank code number.

Such a rank coding system hinders attempts to correlate directly between the rank codes and the mechanical



The arrangement of the British Coal Rank Classification System

Figure 1.1

properties, as the rank coding is not directly dependent on the volatile content.

1.4 Shear Strength Characteristics

Most work in soil mechanics concerning peak and residual shear strengths has been carried out on the finer materials such as clay and sand. The standard testing procedures for these mechanical properties have consequently been based on the experience with such materials.

It has been recognised that colliery discard cannot be completely satisfactorily tested in accordance with British Standard No. 1377 (1967), and the National Coal Board (1969) has produced a technical memorandum which adapts some of the standard tests for use with colliery discard.

With respect to colliery discard little consideration, however, seems to have been given to the relevance and significance of the standard mechanical tests.

Drained peak shear strength is one parameter which is relevant. In clays and fine aggregates of sand sizes it is usually well defined in shear-box tests, but with colliery discards it may be necessary to provide a much larger strain before peak shear strength is attained. When reached, this condition may well be marked by no further increase in shear strength, rather than a significant decrease.

It is with residual shear strength that care needs to be taken when testing colliery discard. With clay the drop in shear strength from peak to residual is commonly very rapid, and rarely requires strains in excess of a few tens of percent. In most of the post-Aberfan tip investigations, for which some residual tests were performed, the strains involved rarely exceeded one hundred percent.* This resulted in some unusual results. Many of those tests determined that there was a limited drop in shear strength after such a displacement, but to call the final value the "residual shear strength" would now be questionable.

It is the writer's opinion that the use of residual shear strength should be reserved for a fully developed single shear plane, for this will be the condition of lowest shear strength. In fine grained materials such as clays the fully-developed shear plane requires only a small strain to ensure its full development, for all that is required is a slight remoulding of the components of the existing material.

It is a well-established fact that shear planes can develop in colliery discard, for specimens have been removed from failed tips. Such shear planes, when tested in the laboratory, have angles of internal shearing resistance in the order of 18°-20°. (Bishop et al, 1969; Taylor, 1973). Yet most laboratory tests on tip material have given "residual" values well above this.

The probability is that in few of these tests have the displacements been sufficient for a shear plane to develop, and the "residual" shear strength quoted was the value at which the shear strength apparently stabilised.

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*e.g. National Coal Board internal reports: Wimpey Central Laboratories site investigation reports:- Sherwood Colliery; Elsecar Colliery (2); Mynydd Brithwaunydd Colliery; Western Colliery, Nant-y-Moel.

1.5 Breakdown Mechanisms

For a shear plane to become established, there needs to be a zone of fine (e.g. < 200B.S.) material in which two relatively smooth, discrete surfaces can develop. Colliery discard is generally a well-graded material with the largest particles being up to about 100 mm across, and often less than ten percent of the material passes the 75 micron (B.S.No. 200) sieve. Further breakdown towards fundamental particle size will need to take place before a shear plane can develop.

When shearing materials such as colliery discard, the writer feels that the concept of a shear "zone" would be more suitable than the conventional shear plane principle.* This concept requires that for much of the shearing process there is no discrete shear plane. Instead, movement will take place along the weakest path in a zone around the line of enforced shearing action. Further displacement may affect the material in this zone so that the shear movement may take place along a more direct path.

It has been recognised that the reduction of shear strength in colliery discards is the result of a comminution process. (Taylor, 1973). This process probably has two separate constituents:

(i) Inter-particle attrition due to movement;

(ii) Particle breakdown under stress.

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* For the Littleton tip failure in 1970 it was observed that particles had been rounded in response to the movement for a distance of up to 4.5 mm either side of the shear plane. (Taylor, 1973)

Process (i) will be basically a function of displacement, the rate of attrition perhaps increasing as the normal stress across the shear zone increases. Process (ii) will be very dependent on the stress levels around the shear zone. For a shear-box test this depends on the vertical loading, whilst in a tip the height will be the governing factor.

The final development of a complete shear plane may be preceeded by the establishment of separate local shear planes in parts of the shear zone where sufficient fine material has been generated. If these develop, then much greater shear stresses will be concentrated on the intervening regions, which can result in rapid breakdown (especially by process (ii)), leading to the establishment of a single complete shear plane.

Most shear-box tests are carried out in the normal stress range below that required for significant breakdown as a consequence of normal stress alone to take place. Thus the attrition process alone will be available for the generation of fine material(i.e. fragments moving towards fundamental particle sizes). With the conventional reversing shear-box the fine material tends to escape from the shear zone through the gap separating the two halves of the shear-box. This can result in the condition being reached when the fine material is lost as rapidly as it is formed, this equilibrium condition giving rise to an apparent "residual" shear strength condition.

1.6 Selection of Samples

The requirement was for a representative selection of samples throughout the range of coal rank. The matter of from which region each sample was to be obtained was decided by the National Coal Board.

The samples were as follows:

Rank 101: Cynheidre washery (West Wales area) material from the Big Vein seam. Coal floors and mudstone roof;

Rank 301: Morrison Busty washery (North Durham area) material from the Harvey Seam (N). 10% roof, 60% band, 30% floor;

Rank 502: Bersham colliery (North Western area) material from the Prince and Queen Seams. 75 mm band of mudstone and 75mm of fireclay floor;

Rank 600: Easton colliery (Scottish South area) material from Wilsontown Main Coal Seam. 200 mm of dirt from roof and bands in seam;

Rank 700: Askern colliery (Doncaster area) material from the Warren House (Barnsley) Seam. Proportions of roof and floor not estimated;

Rank 802: Ollerton colliery (North Nottinghamshire area) material from the Top Hard Seam. 15% mudstone seatearth, 20% dirt bands;

Rank 902: Birch Coppice colliery (South Midlands area) material from the Bench and Top Bench Seams. 60% floor, 40% roof.

In addition, during the period of the research, material from Tip No.3 at Orgreave colliery (South Yorkshire area, Rank 502) was tested in connection with engineering works taking place there. Results from the tests on this material are included as they provide a comparison between ex-washery and tip material.

CHAPTER 2

EXPERIMENTAL TECHNIQUES

2.1 Geochemistry and mineralogy

All samples were subjected to chemical and mineralogical analysis. The purpose of this was to identify any constituents which could affect the shear strength properties. In addition, the samples could be compared with previous work on colliery discards. A small portion of each sample was dried and ground to a fine powder in a tungsten carbide disc mill.

The chemical analyses were performed using a Philips PW 1212 Automatic Sequential Analyser X-Ray Fluorescence (XRF) machine. Part of each ground sample was formed into a small pellet suitable for testing by the machine. The sample is irradiated with a monochromatic X-ray beam. The constituent elements in the sample fluoresce at characteristic frequencies, and the intensity of this fluorescence permits the elemental concentration to be calculated by comparison with selected standards. These standards have been previously analysed by wet chemical methods. The output from the analyser is in the form of radiation intensities at certain frequencies. A computer program has been developed which reduces this data to elemental concentrations, and also corrects for absorption. (Holland and Brindle,1966). The results, except for sulphur, are expressed in the combined oxide state.

Samples for mineralogical analysis were prepared by mixing 0.45 grams of the ground material with 0.045 grams of boehmite, which was used as an internal standard. A fine layer of this mixture was then spread onto a small glass plate to produce a smear amount. For this, acetone was used as a dispersing agent, for its high volatility inhibited particle re-orientation.

The samples were then examined in a Philips PW 1130 2kW X-ray diffractometer (XRD) machine, using iron-filtered cobalt radiation. The results appeared as a diffraction chart of counts per second against diffraction angle. In order to determine expandable mixed-layer clay minerals the samples were treated with ethylene glycol for 24 hours and then re-examined. The basis of this method is that the ethylene glycol is absorbed into the basal lattice of the expandable clays, thus altering their diffraction properties.

The diffraction traces were interpreted by measuring the peak areas of diagnostic reflections (d-spacings), using a polar planimeter. Using curves previously prepared at Durham, quantitive assessments were made of mineral by comparing the peak areas with the area of the peak due to the boehmite 6.11Å reflection.

Carbon was determined using the absorption method (Groves, 1951). This method involves the decomposition of any carbonates by orthophosphoric acid and the absorption of the purified CO_2 on self-indicating sofnolite. The organic carbon is then oxidised to CO_2 by orthophosphoric and chromic acids, and the gas is again absorbed on sofnolite.

2.2 12-inch shear-box tests

2.2.1 Box modifications

Large strain shear tests were conducted on samples passing a 37.5mm sieve. A modified Farnell type 305 12 inch

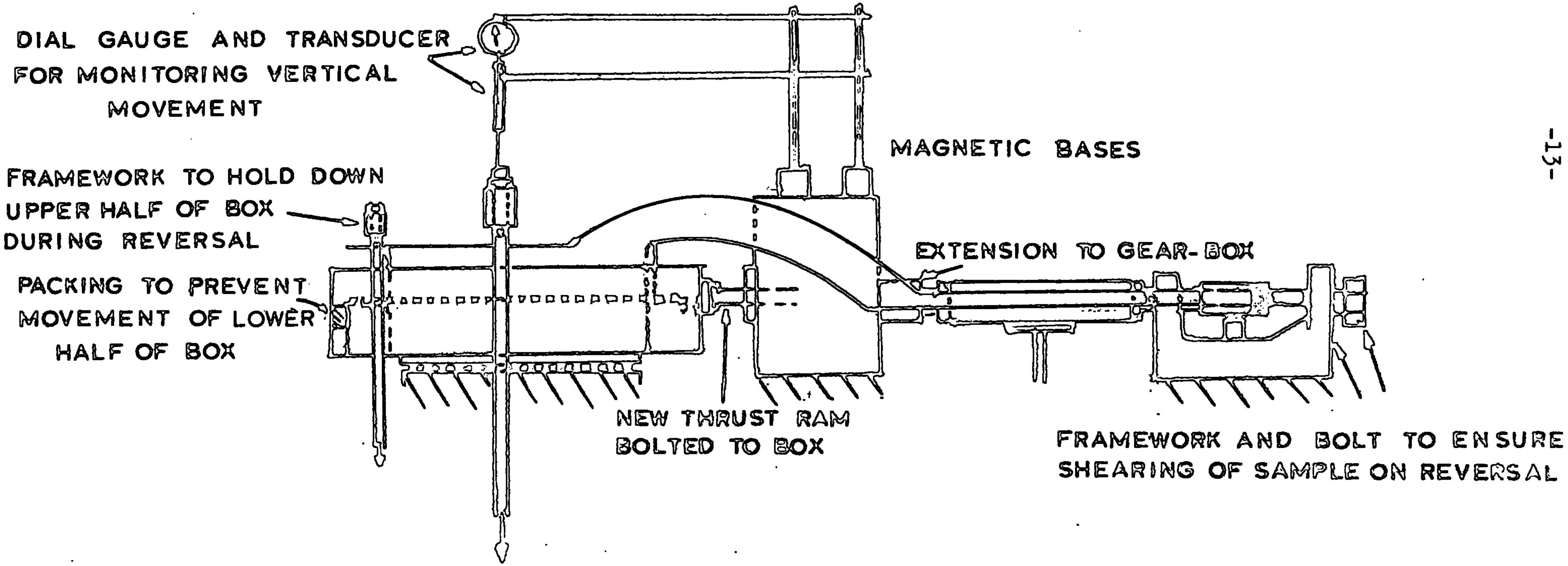

DIAGRAM SHOWING MODIFICATIONS TO 12-INCH SHEAR-BOX

SIDE VIEW

Not to scale

Figure 2.1

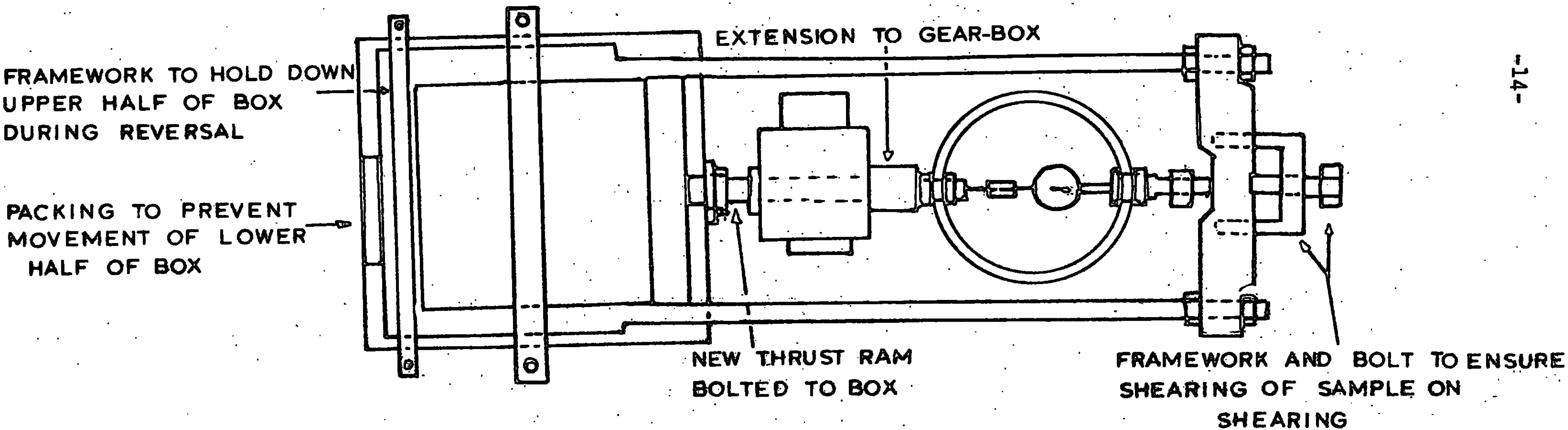

DIAGRAM SHOWING MODIFICATIONS TO 12-INCH SHEAR-BOX

TOP VIEW

not to scale

Figure 2.2

shear-box was used. This shear-box had been designed for the evaluation of peak strength of aggregates, and had to be extensively modified before it was suitable for large-strain shear tests. These modifications are briefly described, and are illustrated in Figures 2.1 and 2.2.

As delivered, the drive motor of the shear-box was reversible, but the thrust ram was not rigidly attached to the lower half of the box. Consequently, the box was not drawn back when the motor was reversed. A new thrust ram was manufactured with a flange at the end adjacent to the box. This was firmly attached to the box with high tensile steel bolts. The new ram was also designed in order to provide a longer travel (40mm instead of 25mm). There were two reasons for this:

(i) To investigate further the rising shear force observed towards the end of runs in previous tests.*

(ii) To increase the overall displacement obtained in a test series. Half of this will be forward travel, which is monitored.

The gear-box housing the thrust ram had to be extended to accomodate the longer ram. This was achieved by placing a tubular collar on the side of the gear-box away from the thrust ram. The thrust bearing for the proving ring was then mounted on this collar.

In order to obtain shearing of the sample upon reversal of the box it is necessary to restrain movement of the upper half of the box. To achieve this, a bracket was mounted on the structural framework of the apparatus adjacent to the centre of the loading yoke crosshead. A large steel bolt was screwed through this bracket to bear against the

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*Durham Annual Report to N.C.B., 1972

crosshead. This bolt provides a means of setting the proving ring to zero before the start of each run.

Also necessary to ensure shearing of the sample when the box was reversed was some packing between the lower half of the shear-box and the side of the water reservoir away from the thrust ram.

A problem resulting from large strain reversing shear tests is the escape of material through the separation between the two halves of the box. Material is initially trapped on the flanges at each end of the box due to the reversing action. This increases the separation of the two parts of the box, through which a significant part of the sample may escape during the course of many runs.

An attempt has been made to minimise this problem by the fabrication of a yoke which can be tightened down on the end of the upper half of the shear-box away from the thrust ram. This was done during the reversal of the box, when no readings were taken. This eliminated further loss of material during reversal, and also forcibly reduced the separation between the two halves of the box. The yoke was released before the start of the forward runs.

Linear variable differential transformers (LVDT's) were attached to the dial gauges which measured the proving ring compression and the vertical movement of the sample. These movements were thus recorded on a Rikadenki B261 two channel pen recorder. This enabled the apparatus to be run without constant supervision.

2.2.2 Experimental procedure

In order to reduce the amount of sample required, two 25mm thick steel bars were placed below the lower plate of the shear-box. This still left 50mm of material below the potential shear plane, which was considerably greater than the thickness of any possible shear zone. Penman (1971) states that the maximum particle size to be tested is between 1/4D and 1/6D, depending on grading, where D is the smallest dimension of the test specimen. Using this criterion, the testing of material up to 37.5mm in size cannot be justified. The sieving analyses (Figure 3.2) show that the well-graded nature of the material tested resulted in no more than 40 per cent of any sample being retained on a 10mm sieve. Such a particle size distribution reduces the possibility of a concentration of large material in the test specimen, which could result in an enhanced shear strength.

of th [illegible] The slightly reduced sample thickness decreased the settlement due to consolidation, thus reducing the downwards movement of the shear zone during the first few runs.

It was found impossible to satisfactorily compact some of the samples to their optimum density without causing extensive breakdown. McKechnie Thomson and Rodin (1972) have shown that the effect of initial density on peak shear strength is very limited. Figure 2.3 relates the increasing density to the shear strength for a series of tests on one of the samples.

On occasions, sample consolidation during the first few runs of a test series was such that further material had

The relationship between density and shear strength

(sample from Bersham colliery
12-inch shear-box test at 347·1 kN/m^2)

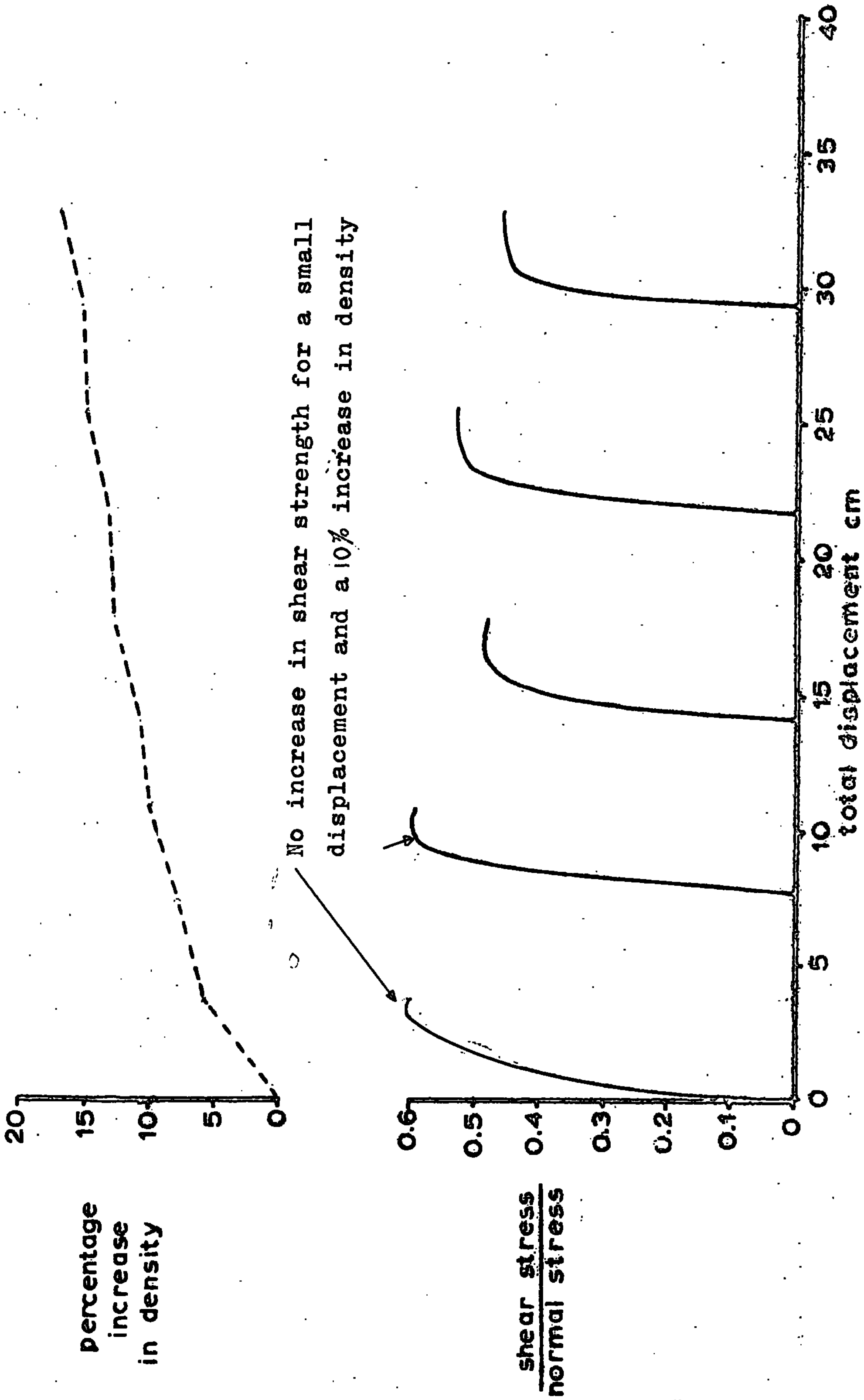

Figure 2·3

to be added in order to retain a satisfactory sample thickness.

A pre-loading technique was used for the shear-box tests. This involved testing one sample at different normal stresses, rather than the testing of separate samples. With the time available and the displacements involved, the latter method would have been impracticable. The method used provides only one point for the estimation of peak strength, but a failure envelope can be produced for a known displacement by performing successive runs at differing normal stresses.

It is apparent from the results (e.g. Figure 3.28) that the material is capable of gaining maximum shear strength during the run immediately following an increase in normal stress. It was the practice to alter the normal stress before the box was reversed following the forward run. Similarly, it has been found that test specimens recovered from a reduction in normal stress in a similar period. An example of this is drawn from the 60mm shear-box test results. For one sample (Bersham) the normal stress was reduced from 160 to 63.4 kN/m^2. Four successive runs then gave shear stress values of 39.5, 40.0, 42.6 and 37.2 kN/m^2.

McWilliam (personal communication; also Durham Annual Report to National Coal Board, 1972), compared 12-inch shear-box and 4-inch triaxial results for material from Isabella spoil heap in Northumberland. It was found that for low confining pressures (less than 200 kN/m^2), the results were compatible. Triaxial tests were performed on the two extreme rank samples of the present series of tests. Linear regression results gave:

Cynheidre: $\phi'=36^{\circ}$ for $c'=0$;

Birch Coppice: $\phi'=34.3^{\circ}$ for $c'=0$.

Corresponding shear-box results for the initial peaks were 37.3° and 35.3°, using the 12-inch shear box.

Once developed, the testing cycle became: 14 runs (about 1.1 metres total displacement) at a normal stress of 80.3 kN/m^2; then 7 runs at each of 160.3 and 240.3 kN/m^2. For some samples one run was made at a further increased normal stress before the unloading cycle commenced. This involved one run only at each increment of unloading. Some tests were discontinued before the full cycle had been completed because of the loss of material between the two halves of the box. Those samples with which this happened are mentioned in the results.

When the sample was removed from the shear-box, a portion less than 10 centimetres thick was removed from the centre of the sample for the particle size distribution test. This material was selected so that it would include the region where material breakdown as a result of the shearing should be present. This sample was also inspected for any evidence of shear plane or shear zone development.

Since a permanent record of the results was produced by the pen recorder, complete runs could be made without supervision. One feature of the shear-box as supplied by the manufacturer was a micro-switch mounted adjacent to the thrust ram. This micro-switch stopped the drive motor when the thrust ram reached the end of its travel in either direction. This facility allowed overnight runs to be made without fear of damage to the shear-box. By the rapid reversal of the shear-box after the forward runs, it was possible to make two complete testing cycles in a 24-hour period. During the day a forward run was made at a strain rate of 0.1mm/minute. This was followed by rapid reversal of the box at the highest possible speed (2mm/min). Another forward run was then made overnight at a strain rate of 0.05mm/minute.

During some of the tests a pore-pressure monitoring system was arranged. This consisted of a pressure transducer which was connected to a pressure sensor which was placed in the sample close to the anticipated shear zone at the time of loading the shear box. The arrangement is shown diagramatically in Figure 2.4(a). The pressure transducer was calibrated with a standard pressure gauge. The calibration curve is illustrated in Figure 2.4(b). It can be seen that the response of the pressure transducer is linear. The maximum resolution of the digital voltmeter used was 0.1 millivolts, which meant that pressure variations of greater than 2kN/m^2 could be detected. This was less than 5 per cent of the lowest normal stress most frequently used for testing, and was thus capable of indicating any moderate pore-pressure buildup.

Tests showed that long-term drift was a greater problem than any short-term changes in pore-pressure. It was found that even at the high strain rates present during the reversal of the box the pore-pressure buildup was very limited.* It was concluded that at the strain rates used during the forward runs the effect of any limited pore-pressure development on the shear strength would be negligible. The practice of using two distinctly different strain rates for the forward runs provided an overall method of monitoring the pore pressure. During no test series was any variation in shear strength corresponding to the

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*Less than the drift

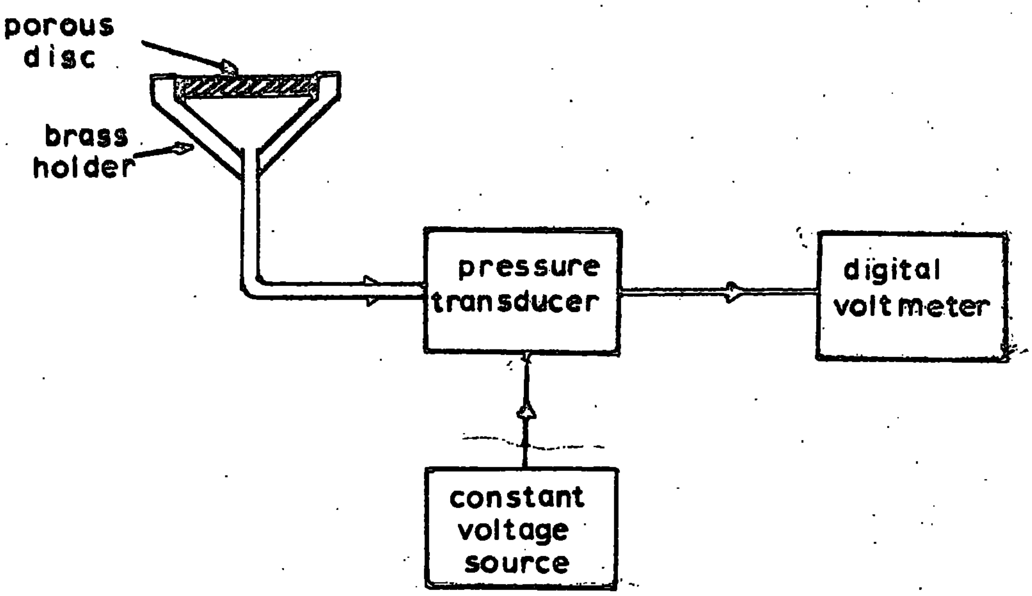
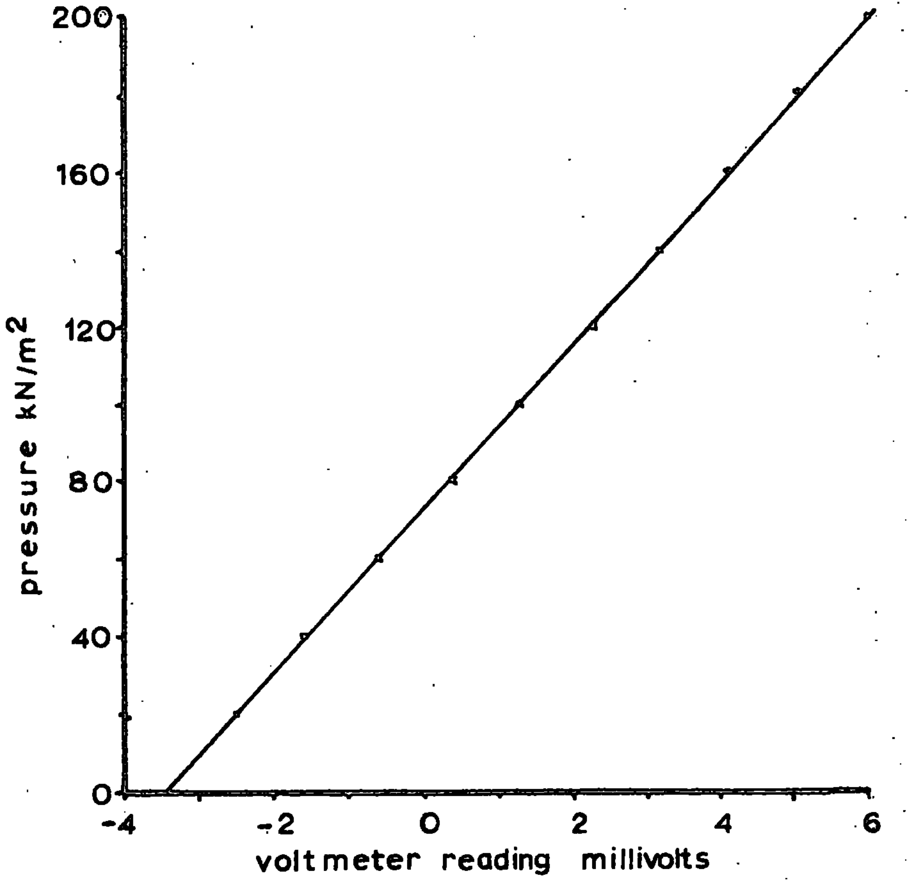


Diagram of pore pressure monitoring arrangement

(a)



Calibration curve for pressure transducer

(b)

Figure 2.4

different strain rates observed.

The chart output from the pen recorder was used to provide data input for a specially-developed computer program which plotted stress-displacement curves for a complete series of tests. The ratio (shear stress/normal stress) is plotted instead of shear stress so that runs at different normal stresses can be plotted on the same graph for comparison.

The program (Appendix 1) is provided with the coordinates of points at regular intervals along the stress line plotted by the pen recorder, and also with conversion factors relating the coordinate system to the shear force and the displacement. Sets of data for each run are used to provide a complete set of results. In order to make the resulting plot as compact as possible, the gaps in the stress-displacement curve due to the reversals are left out (i.e. forward travels only are plotted).

No correction has been made in the calculations for changes in area. The ratio shear stress/ normal stress is independent of area changes as these would be applied to both quantities. However, Petley(1966) has shown that for even a one-third reduction in area, only a 5 per cent correction to the shear strength would be in order.

It is felt that the other unknowns in shear-box tests, especially the interaction of the trailing edge of the box with the sample, outweigh any benefits derived from an area correction. It is incidental that the above effect seems to provide an apparent increase in strength, which is balanced by the decreasing area of sample being sheared.

2.2.3 Use of a load cell for shear force measurement.

Flexure of the proving ring means that the stress record plotted by the pen recorder is not a true stress - strain curve. The difference is only pronounced at the start of each run when most of the applied displacement is taken up by compression of the proving ring as the shear stress builds up.

If compression of the proving ring could be eliminated, then the pen recorder would produce a true stress-strain curve. Such a condition cannot be easily fulfilled. However, a load cell of a suitable range would only require a compression of about an order of magnitude lower than the equivalent proving ring.

Such a load cell was obtained (Transducers (CEL) Ltd type CM48 LR). This was substituted for the proving ring after modifications to the mountings. An immediate result was an apparent increase in the shear strength of the material being tested. Tests using the load cell and then a proving ring on successive runs established that the load cell was producing results about 50 per cent too high (Figure 3.12).

Tests in a Denison compression machine proved the load cell to be very accurate in the vertical position. It was concluded that the design of the load cell resulted in incorrect readings in the horizontal mode. The device was returned to the manufacturers, who agreed to modify it.

After return from the manufacturers, the load cell was again fitted to the shear-box. The results are shown in Figure 3.8. It was apparent that not only was the load cell still providing over-estimations of shear strength, but also that the magnitude of the error varied with the stress level involved. The load cell was therefore removed pending further consultations with the manufacturers, who are still attempting to account for the phenomenon.

2.3 60mm shear-box tests

These tests were performed in a standard 60mm reversing shear-box.

The strain rate used was 0.06mm/minute, which was compatible with the lower strain rate used for the large shear-box tests. No automatic recording was fitted to the small shear-box, but few manual readings were taken, however, as the main point of interest was the shear strength at the end of each run.

The material used for these tests was sieved from the main sample such that only material passing a 1200 micron (No. 14 BS), but retained on a 600 micron (No. 25 BS) sieve was used. This made the breakdown of material more noticeable. For all samples at least 30 runs (giving a total displacement of about 0.5 metres) were performed at a normal stress of 133.7 kN/m^2. Further runs then took place at increased normal stress, and finally an unloading cycle took place in a similar manner to that described for the 12-inch shear-box.

A portion of the sample was retained for the sieving analyses. The entire thickness of the sample was used for this test. At the same time the sample was inspected for shear plane and shear zone development.

When the basic series of tests had been performed on all the samples, further experiments were conducted on selected samples to investigate the effect of normal stress on the rate of reduction of shear strength. The material used for these tests was of the same narrow size range as for the earlier tests.

Also performed were some tests to establish the shear strength of intact pieces of shale. For these tests selected small pieces of shale were cleaned. A special mould 60mm square and 25mm deep was manufactured. Also a block 60mm square and 12.5mm thick was obtained. The block was placed in the bottom of the mould, and then half of the piece of shale was cast into a 12.5mm thick layer of dental plaster placed over the block. When this had set, the block was removed and the upper surface of the plaster was coated with grease. A further layer of plaster was then cast over this. This method successfully held the shale sample between the two pieces of plaster, while leaving a distinct shear plane in the plaster.

These samples were shear tested at a strain of 0.5mm/minute. This permitted a large number of tests to be performed in a short time. Samples were sheared beyond failure so that an indication of the order of the residual shear strength could be established.

2.4 Classification and fundamental properties

The following tests were performed in accordance with British Standard 1377:1967, amended where necessary by the National Coal Board Technical Memorandum (1969).

(i) Moisture content

(ii) Specific gravity

(iii) Atterberg limits

2.5 Other tests

2.5.1 Weathering test

A portion of each of the seven main samples was placed in a specially-made wooden box, which was then placed on the roof of the Engineering Geology laboratory. The contents of the box were photographed at intervals (Plates 3.1 and 3.2).

This simple weathering experiment indicated the styles of weathering which the various 'ranked' samples have undergone, and also provided an indication of the specific rock types which are susceptible to atmospheric (climatic) degradation.

CHAPTER 3

DISCUSSION OF RESULTS

3.1 Chemistry and mineralogy

The results of the mineralogical analyses are listed in Table 3.1. These results, however, should only be regarded as semi-quantitative, for variations in crystallinity can significantly affect X-ray diffraction analyses. The chemistry of the samples is controlled by the mineralogical components, and embody a much higher degree of accuracy. For this reason, these results (Table 3.2) will be considered first.

The alumina can be almost entirely attributed to the clay minerals, together with K, Na, and part of the Fe, Mg and Ca. For this reason, it is useful to express the chemical analyses as oxide/alumina ratios (Table 3.3).

Table 3.1 has been normalised to 100 per cent, and from this it can be seen that the 'as received' discard from Birch Coppice contains about 25 per cent organic carbon (mainly coal). In contrast, the sample from Ollerton contains only 5 per cent organic carbon. Previous work (Taylor and Spears,1970) has implied that a high percentage of the mineral pyrite (FeS_2) originates from coal, and also that carbonates are commonly found on the faces of the coal cleats. The trace pyrite and ankerite (Table 3.1) are frequently from this source. The high sulphur content of the Birch Coppice sample undoubtably reflects the high coal content.

The total SiO_2 figure in Table 3.2 comprises both free silica (quartz) and that combined largely in the clay minerals. The combined silica/alumina ratio provides a guide

Sample	Illite	Kaolinite	Quartz	Pyrite	Chlorite	Siderite	Carbon	Total
Cynheidre	62.5	3.0	23.5	trace		trace	11.0	100.0
Morrison Busty	42.0	31.5	11.5			trace	15.0	100.0
Bersham	51.0	16.5	17.5	trace	2.0	trace	13.5	100.0
Orgreave	58.0	8.0	15.5	trace	4.0	trace	15.0	100.0
Easton	30.0	36.0	15.5			trace	18.5	100.0
Askern	65.5	9.0	15.5	trace	2.0	trace	8.0	100.0
Ollerton	61.0	13.5	19.5		2.0		5.0	100.0
Birch Coppice	42.0	24.0	9.0	trace	trace	trace	25.0	100.0

Mineralogical Composition and Carbon content

total normalised to 100 per cent

Table 3.1

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	S	P_2O_5	Total	C	Total
Cynheidre	51.17	21.01	2.06	0.91	0.36	0.82	3.92	0.86	1.58	0.06	82.81	11.	93.81
Morrison Busty	42.15	26.04	3.07	0.76	0.85	0.39	2.29	1.13	1.03	0.06	77.37	15.	92.37
Bersham	51.50	26.92	4.24	1.36	0.26	0.56	3.50	1.07	0.08	0.07	89.76	13.5	103.26
Orgreave	43.04	19.84	5.40	1.44	0.65	0.48	4.03	0.83	1.88	0.08	77.67	15.	92.67
Easton	38.66	22.20	4.27	1.04	0.41	0.66	1.17	2.86	1.43	0.06	72.76	18.5	91.26
Askern	50.89	24.71	4.14	1.42	0.42	0.68	4.24	0.90	1.02	0.08	88.50	8.	96.50
Ollerton	53.30	26.12	3.71	1.44	0.52	0.64	4.24	1.02	0.06	0.09	91.16	5.	96.16
Birch Coppice	37.32	17.94	3.54	0.82	0.65	0.44	1.80	0.98	3.69	0.14	67.38	25.	92.67

<u>Percentage composition of major chemical components</u>

Table 3.2

Sample	$\frac{SiO_2}{Al_2O_3}$	$\frac{Fe_2O_3}{Al_2O_3}$	$\frac{MgO}{Al_2O_3}$	$\frac{CaO}{Al_2O_3}$	$\frac{Na_2O}{Al_2O_3}$	$\frac{K_2O}{Al_2O_3}$	Combined $\frac{SiO_2}{Al_2O_3}$	Illite Shape Factor
Cynheidre	2.44	.098	.033	.047	.039	.187	1.32	7.25
Morrison Busty	1.62	.118	.031	.02	.015	.088	1.18	3.0
Bersham	1.92	.158	.048	.01	.02	.13	1.27	5.0
Orgreave	2.17	.272	.073	.033	.024	.203	1.39	8.77
Easton	1.74	.163	.046	.018	.030	.053	1.03	1.0
Askern	2.06	.168	.060	.017	.028	.17	1.43	11.9
Ollerton	2.04	.142	.055	.020	.025	.16	1.29	.72
Birch Coppice	2.08	.197	.046	.015	.020	.10	1.22	4.17

Oxide / Alumina ratios

Table 3.3

to clay mineral type.*

The combined silica/alumina ratios reveal that the samples from Easton, Morrison Busty and Birch Coppice should be Kaolinite-rich. The Bersham and Ollerton samples also have a moderate kaolinite content. The slightly higher ratios for the Cynheidre, Askern and Orgreave samples suggest a dominance of the illitic minerals. The ratio for the Cynheidre sample is not as high as the mineralogy would suggest, but this could be a result of the semi-quantitative determination for the quartz.

A better indication of the micaceous (illitic) minerals is the wholly chemical K_2O/alumina ratio, for potassium is an important interlayer cation in these minerals. This ratio reveals that the Cynheidre, Askern and Orgreave samples are rich in illite, while the very low ratios for the Morrison Busty, Easton and Birch Coppice samples infer a dominance of the other main clay mineral, kaolinite.

By plotting the peak area ratios (Figure 3.1) it is possible to compare the current X-ray data with the known clay mineral variations already found for the British coalfields (Taylor and Spears, 1970). These results, which do not include any correction for crystallinity, substantiate the conclusions drawn from the chemical data. The clay mineral contents show a generally higher proportion of mixed-layer clay compared with previous work. This is most likely the result of a slightly differing experimental technique, in

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*Kaolinite has a theoretical combined silica/alumina ratio of 1.2, while illites like the reference Fithian illite (which includes mixed-layer clay) have ratios of around 1.98.

which the sample is deposited onto a porous disc instead of the current smear mount technique. The former method enhances preferred orientation, which reduces the effect of the expandable clay minerals when the sample is glycolated. In other words, the smaller clay platelets such as mixed-layer clay are sucked into the pores. With the smear mounts some sedimentation must take place, so that the smaller platelets are preferentially scanned.

The presence of a high kaolinite content is believed to preclude immediate slaking (Taylor and Spears,1970). It has also been shown that a high mixed-layer clay content promotes slaking in water. All the samples, with the exception of Easton (4 per cent), have mixed-layer clay contents between 18 and 22 per cent. The figures for Morrison Busty and Birch Coppice are slightly higher than the others. Previous work Taylor and Spears, 1970) has revealed mixed-layer clay contents of 21 and 23 per cent for the Park floor and the Brooch seatearth respectively, so the 22 per cent content of the Birch Coppice sample (which contains 61 per cent floor material) is not altogether unexpected. The Morrison Busty washery handles material from the Harvey seam. Pearson and Wade (1967) have previously reported that at Fishburn colliery the Harvey seam floor contains at least 30 per cent mixed-layer mica-montmorillonite. Thus the high mixed-layer clay content of the washery discard is not surprising.

The high kaolinite content of the Birch Coppice sample was surprising. To investigate this further, a piece of roof material was selected, and this was subjected to a separate qualitative XRD examination. This material contained a dominance of illitic minerals. The high kaolinite content of the bulk sample therefore reflects on a kaolinite-rich floor material.

The mineralogical analyses of Table 3.1 and Figure 3.1 reveal the distinct regional variations in mineralogy. Care should be taken, however, in the consideration of the subsidiary clay minerals, because of possible variations in the distribution among the material.

Shear-box tests on the Scottish discard revealed a small quantity of exceptionally resistant material. This was subjected to a separate qualitative XRD analysis. The results indicated that the material was a clay-ironstone (siderite, $FeCO_3$), which was concentrated into gravel-sized fragments. In no other samples were such concentrations observed, yet the chemical analyses (Table 3.2) show that the overall iron content of this sample was not exceptionally high.

The iron content of the sample from the tip at Orgreave was noticeably higher than for any of the ex-washery samples. This high iron content had no significant effect on the mechanical properties. It is possible that this iron was mainly in the form of limonite, a less durable form of iron oxide, as a result of weathering.

The K_2O/alumina ratio is high for Orgreave, and the shape factors (Table 3.3) imply that it may be marginally more crystalline than other samples. This would in fact suggest that leaching out of K^+ and other readily extractible ions is not significant in the Orgreave material.

3.2 Weathering tests

The photographs in Plates 3.1 and 3.2 reveal the condition of the samples after certain periods of exposure to the weather.* The first photograph in the sequence was taken three weeks after the samples had been put out. This was after rainfall had cleaned the samples, removing fines from the larger fragments, but before significant breakdown had taken place. The samples were initially exposed in mid-autumn (27th October). The photographs were taken on 17th November, 19th December, 3rd May and 14th August. After the final photograph in the sequence, the samples were carefully examined in order that material prominent in the photographs could be accurately identified. The observations are recorded below.

Sample 1 (Cynheidre)

Little identifiable breakdown took place between the first and second photographs. After the winter, however, some breakdown was becoming widespread, and this became very extensive during the last few months of the test. Inspection revealed that coal and some ironstone nodules had been little affected. Pieces of carbonaceous shale were starting to disintegrate along the laminations. The seatearth material had extensively broken down.

Sample 2 (Morrison Busty)

In this sample initial breakdown was limited, but by the time of the third photograph the floor material had extensively disintegrated. The inspection revealed that some siltstone material was also starting to break down along

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* Boxes left on the roof of Engineering Geology Laboratories, Durham.

17.11.72

19.12.72

3.5.73

14.8.73

Plate 3.1

17.11.72

19.12.72

3.5.73

14.8.73

Plate 3.2

laminations, while pieces of coal, coaly shale and sandstone remained unaffected.

Sample 3 (Bersham)

Again, little detectable breakdown took place between the first and second photographs, but by the time of the third photograph, however, extensive disintegration of some materials had occurred. This had increased further by the time the final photograph was taken. Identified as resistant material were small pieces of sandstone and some coaly shale, although the latter was beginning to split in places. The seatearth material had extensively disintegrated.

Sample 4 (Easton)

This sample proved the most resistant of those tested. In the process of disintegration at the end of the test were pieces of roof material and silty mudstone. Apparently unaffected by the weather, however, were pieces of sandstone, coal, coaly shale and clay-ironstone.

Sample 5 (Askern)

Breakdown was observed with this material during the first few weeks of exposure. By the end of the winter a considerable amount of material had extensively disintegrated. Further weathering left a small number of pieces of resistant material among a large amount of fines. There was little sandstone in the sample, and the resistant material was a coaly shale, which was starting to breakdown by the end of the test.

Sample 6 (Ollerton)

Weathering had rapid effect on this sample, which resulted in an early reduction of general particle size.

By the end of the test period a considerable amount of the material had extensively disintegrated. Intact at the end of the test were small pieces of coaly shale, ironstone and fine sandstone.

Sample 7 (Birch Coppice)

It took a considerable time for the weather to remove the fines and the separate the pieces. For this reason any early breakdown has been difficult to detect. By the time of the final photograph much of the sample had broken down into fine material. A surprising amount of large material still remained. This was identified as being mainly coal (the sample contained about 25 per cent organic carbon). There was also some ironstone. Pieces of dark shale were splitting along the laminations, while the seatearth material had extensively disintegrated.

3.2.1 Summary of visual observations

The visual observations agree well with the behaviour predictable from the mineralogical analyses. The sample which had by far the lowest mixed-layer clay content, Easton, showed less breakdown than any other sample. The other samples, containing about the same proportions of mixed-layer clay, generally showed similar breakdown patterns. It is not possible to identify a delayed breakdown in the kaolinite-rich samples. It will be recalled that in the case of the Birch Coppice sample the latter material is concentrated in the floor debris which in any case is subject to breakdown along slickensides.

The extent of the resistant material generally correlated well with the carbon contents of the samples. This is especially meaningful when comparing the Ollerton and Birch Coppice samples. The former, with a very low carbon content, contained few pieces of larger material at the end of the weathering test. In the latter sample, much of the surviving large material could be attributed to the high carbon content.

This simple sequence of exposure to the elements clearly shows that coal and highly carbonaceous shales are particularly resistant to weathering. These materials and ironstone were also found to be highly resistant in the Yorkshire Main investigation (Spears et al, 1971).

3.3 Shear-box tests

3.3.1 12-inch shear-box results

For the 12-inch shear-box tests at a normal stress of 80.3 kN/m^2, variations in peak shear stress were from a minimum of 56.8 kN/m^2 (Birch Coppice) to a maximum of 72.7 kN/m^2 (Morrison Busty). These peak values are shown in Figure 3.3(a). No distinct correlation with rank is apparent. More interesting is the shear strength reduction during one metre of displacement (Figure 3.3(b)). The Birch Coppice sample shows a much greater drop in strength (42 per cent) than any of the other samples, which range from 13.5 to 23 per cent reduction from peak strength.

Figure 3.4 shows the failure envelopes at the end of the 12-inch shear-box tests on the different samples. The values used for the production of the envelopes are contained in Appendix 2. It is difficult to compare these results because of the different displacements involved. Material loss caused the premature termination of the three shortest runs. However, it seems reasonable to observe that the material from Easton proved most durable, and that from Birch Coppice the least durable. The latter sample was the only one which appeared to reach residual shear strength during the test series (re-orientation peaks* were detected on the stress-displacement curves of the last few runs).

Inspection of samples after testing revealed that a well-developed shear plane had formed in the Birch Coppice sample, and also that small parts of the Askern and Ollerton samples were slickensided, but no continuous shear planes had developed. With the higher rank materials shearing had caused the development of a zone of broken-down material through the sample, but no evidence of any slickensides could be detected.

3.3.2 60mm shear-box results

The initial period of testing was performed at a normal stress of 133.7 kN/m^2. The peak shear stresses (Figure 3.5(a)) show a much greater degree of uniformity than the large shear-box results. The peak stress of the Birch Coppice material (85.7 kN/m^2) was noticeably lower than the others, which ranged between 93 and 104.6 kN/m^2. This uniformity of peak stress suggests a dependence of peak strength on grading. For the 12-inch shear-box tests the material was

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* Previous work suggested that such a peak could imply the formation of a discrete shear plane (Durham Annual Report to National Coal Board, 1972). The current work confirms this view.

tested with the grading 'as delivered', whereas the small shear-box tests were performed on material of a particular size range (between 0.6 and 1.2mm).

The reduction in shear stress during the small shear-box tests was generally larger than for the large shear-box. There are two possible reasons for this:

(i) The tests were performed at a higher normal stress.

(ii) The smaller size of the material tested.

It will be shown later (Section 3.9) that the normal stress is a dominant factor in the rate of reduction of shear strength. Statistical correlations (Section 3.7) reveal a dependency of shear strength on particle size and its distribution.

The sample from Easton showed very little shear stress reduction (7.6 per cent), whilst the same displacement was sufficient to reduce the Birch Coppice material to the residual shear strength condition. Also showing an extensive reduction in shear strength at this normal stress was the Orgreave tip material (39.5 per cent).

Apart from the samples already mentioned, the others were reasonably consistent in the extent of breakdown in the two different shear-box tests.

3.4 Results of sieving analyses

The range of particle size distributions for all samples as delivered is shown in Figure 3.2. Figure 3.6 shows the range of the size distributions after the 12-inch shear-box tests. It can be seen that some reduction in particle size has taken place with all samples.

Table 3.4 lists the median diameter, Trask sorting coefficient ($\sqrt{(P_{75}/P_{25})}$) and the fraction smaller than 75

Sample	12-inch shear-box results						60mm shear-box results		
	median diameter mm		Trask coeff.		lt. 75 microns %		median diameter mm	Trask coeff.	lt. 75 microns %
	b	a	b	a	b	a	after test		
Cynheidre	12	6	1.2	3.2	1.8	8.0	.75	1.8	15.3
Morrison Busty	9	8	3.6	3.6	1.7	7.0	.95	1.3	6.2
Bersham	11	4.2	2.3	4.3	2.5	10.0	.85	1.7	15.1
Orgreave	8.5	1.1	5.0	8.7	3.3	24.2	.75	3.3	19.5
Easton	11	9.0	1.7	2.3	0.8	4.8	.90	1.2	1.7
Askern	9	3.2	1.8	5.8	2.1	19.0	.60	2.6	18.9
Ollerton	8	1.8	1.9	4.7	4.9	28.0	.70	2.6	19.2
Birch Coppice	10	4.0	1.8	15.5	10.5	26.0	.50	3.4	24.4

b = before test

a = after test

Summary of particle size distribution results

Table 3.4

microns for before and after the 12-inch shear box tests, and for after the 60mm shear-box tests. The standard Uniformity Coefficient was not used since it was not feasible to determine the 10 per cent passing size for certain samples (Figures 3.2,3.6 and 3.7). The Table demonstrates that the three different parameters used for describing particle size distribution do not all vary similarly. It seems possible that the percentage of material passing the B.S. No 200 sieve (75 microns) may have a greater effect on the shear strength properties than either of the other two parameters listed. (Section 3.7 discusses the correlations). All samples exhibited a decrease in the median diameter and an increase in the Trask sorting coefficient and the percentage passing the No. 200 sieve. No systematic change in these parameters was recorded.

The range of particle size distributions at the end of the 60mm shear-box tests is shown in Figure 3.7. These results can be easily compared since all tests started with the same particle size distribution. The sample which showed very little reduction in shear strength, Easton (Figure 3.25), also shows very little material breakdown. Similarly, the Birch Coppice sample, which revealed the greatest reduction in shear strength, also shows the greatest breakdown of material.

An observation concerning the 12-inch shear-box results shows that those samples which contained the greatest fraction smaller than 75 microns after the shear test (Figure 3.6) all showed well defined peaks during the first run.

3.5 Summary of properties for each sample.

The results of the various standard tests performed but not already discussed are contained in Table 3.5. Also included in the table is a summary of the shear strength characteristics for each sample. The moisture content figures are for the ex-washery samples as received. These figures can be regarded more as a measure of the effectiveness of the sealing of the samples, rather than as an accurate indication of the ex-washery moisture content. The two lowest ranking samples, however, contained a surprising amount of moisture, despite a dry appearance.

Diagrams showing the stress-displacement curves for the large and small shear-box tests for each sample, also the failure envelopes at the end of the tests and the corresponding sieving results, are contained in figures 3.7 - 3.39.

In order to compress the stress-displacement curves to a reasonable length, without losing detail from the individual runs, only the forward runs have been plotted. The equal displacements corresponding to the reverse runs have been omitted. For a complete set of runs (forward and reverse) however, total displacement will therefore be equivalent to twice the forward displacement. For the 60mm shear-box results, only the final point for each run has been plotted. It is apparent from these results that several runs may be required for the material to reach peak strength. This is a result of the uniform grading of the material being tested, which has a high void ratio at the start of the test. As the test progresses, breakdown will fill many of the voids, thus

sample	12-inch shear-box peak ϕ'	 "res." ϕ'	60mm shear-box "res." ϕ'	moisture content	S.G.	plasticity index
Cynheidre	37°	28°	28.5°	10.3%	2.13	7.25
Morrison Busty	42°	31°	36°	11.6%	2.28	7.48
Bersham	40°	29.5°	32°	8.8%	2.31	7.10
Orgreave	39°	24°	17°	10.7%	2.13	10.84
Easton	39°	35°	35°	12.2%	2.15	4.63
Askern	35°	22°	17.5°	9.1%	2.09	9.47
Ollerton	37°	26°	20° *	13.8%	2.23	13.02
Birch Coppice	35°	15.5°	15°	14.7%	2.04	11.89

note: All shear strength results are for c'=0, except where otherwise indicated.

* For c'= 30 kN/m^2

Table 3.5

increasing the density and the shear strength. Although it has been shown earlier that for the 12-inch shear-box the initial density had little effect on shear strength, for the small shear-box tests the increase in density was such that an increase in shear strength did result. Many of the small shear-box tests started to show an increase in shear strength after about 0.5 metres total displacement. This is thought to be an effect due to the mechanics of the reversing shear-box, which has already been discussed in Section 1.5.(Material loss).

3.5.1 Cynheidre discard

Figure 3.8 shows the stress-displacement curve for the large shear-box test on this material. The result included is for the third test on this material. The first two tests were performed using the load cell for the shear force measurement, and are therefore unreliable. In Figure 3.8, the four runs showing enhanced values were performed using the load cell. These show the degree of over-estimation of shear strength by the load cell. The diagram shows a poorly defined peak and a slow, gradual reduction in shear strength with increasing displacement. The 60mm shear-box test shows a more rapid reduction in shear strength once the peak strength had been achieved (Figure 3.9). However, after about 0.6 metres total displacement, no further drop in shear strength was observed.

Figure 3.10 shows the failure envelopes at the end of the two separate tests. The results are reasonably similar in view of the differences in testing techniques and displacements. Figure 3.11 demonstrates that for this material the greatest particle size reduction has taken place in the medium size range (i.e. generally less than medium gravel sizes).

3.5.2 Morrison Busty discard

The 12-inch shear-box stress-displacement curve for this sample (Figure 3.12) is difficult to interpret because it contains a mixture of results using either the proving ring or the load cell for shear force measurement. The difference in the results obtained by these two different methods is very distinct. The proving ring results do show a small, gradual reduction in shear strength. The small shear-box results (Figure 3.13) show a similar trend, but the results of this test series were variable. The grading of the material after this test (Figure 3.7) shows that very little breakdown had taken place. Figure 3.15 confirms a similar behaviour for the large sample.

The overall failure envelopes (Figure 3.14) show that the two different shear-box tests give compatible results. Some degree of curvature is evident, but this should be treated with caution, for the points used for defining the envelopes were obtained at significantly different displacements. These points were the final result at each load increment. Material loss prevented the usual unloading sequence being adopted at the end of the tests.

3.5.3 Bersham discard

The 12-inch shear-box stress-displacement curve (Figure 3.16) shows a steady reduction in shear strength with increased displacement. A similar result occurred with the 60mm shear-box (Figure 3.17), although this result contains the puzzling phenomenon of a distinct sudden increase in shear strength after about 0.5 metres total displacement. This is most likely caused by the shear-box, rather than being a true property of the material.

When the failure envelopes for the two tests are compared (Figure 3.18), they show general agreement. The large shear-box test, which was carried to the reasonably high normal stress of 347.1 kN/m^2, shows slight curvature. The small shear-box tests gives slightly lower strength values, which is probably a result of the material size, but could possibly reflect the different mineralogical composition of the material tested.

Figure 3.19 shows that there was an overall reduction in material size during the 12-inch shear-box test. There was a similar reduction in the material size during the small shear-box test (Figure 3.7).

3.5.4 Orgreave discard

This ex-tip material showed a much better defined peak in the large shear-box test (Figure 3.20) than for any of the materials so far discussed. After the initial rapid drop from peak strength, further reduction in shear strength was gradual. Increases in normal stress, however, did cause further reduction in shear strength. The small shear-box stress-displacement curve (Figure 3.21) shows a similar behaviour in this respect.

The failure envelopes (Figure 3.22) show greater curvature for the small test sample. At very low normal stresses (less than 100 kN/m^2), the results are compatible. The sieving analyses (Figures 3.23 and 3.7) show an overall reduction in particle size as a result of the shear tests.

3.4.5 Easton discard

Figure 3.24 shows that in the large shear-box test the shear strength of this material falls off very little from the peak strength, even at increased normal stress levels. A similar deduction can be made from the small shear-box results (Figure 3.25).

The two tests provide very close results for the shear strength properties. In addition, the extent of material breakdown for the two tests was very limited (Figures 3.27 and 3.7). This would suggest that material breakdown is a prime factor in shear strength reduction.

3.4.6 Askern discard

The large shear-box test on this material shows a steady reduction of shear strength with increased displacement. (Figure 3.28). The small shear-box results (Figure 3.29) indicate a similar trend. This figure, however, reveals that, although the shear strength had virtually stabilised at the initial normal stress value, an increase in normal stress caused a further rapid decrease in shear strength.

It was probably this period of testing at higher-than-normal stresses in the small box which reduced the shear strength of the small sample to the near-residual value for ϕ' of 18° (Figure 3.30), which is much lower than the result for the large sample.

Material breakdown was considerable with both test specimens (Figures 3.31 and 3.7). Both specimens contained nearly 20 per cent material smaller than 75 microns in size after the tests were completed.

3.5.7 Ollerton discard

A very well defined peak was reached on the first run of the 12-inch shear-box test (Figure 3.32) After the initial drop from peak strength, further reduction in shear strength took place at a very low rate. The increases in normal stress had very little effect. The peak of the small shear-box test (Figure 3.33) is very poorly defined, for there seems to be a double peak before the main reduction in shear strength took place. This main reduction was rather more consistent than occurred with many of the samples.

The final failure envelopes (Figure 3.34) are of interest. For the large shear-box result, some curving of the envelope is necessary at low stress levels if it is to pass through the origin. For the small shear-box, the failure envelope shown was obtained by successive small decreases in normal stress. The results give an almost linear envelope with a very definite cohesion. The shearing angle of the envelope is only 20°. This result will be considered more fully in Section 4.2.2.

The particle size distribution test results (Figures 3.35 and 3.7), show that for the 12-inch specimen most breakdown took place among the smaller material. The small shear-box test gave a more general size reduction.

3.5.8 Birch Coppice discard

A well-defined peak followed by a steady reduction in shear strength summarises the 12-inch shear-box test on this material (Figure 3.36). As mentioned earlier, this sample appeared to reach residual strength by the end of the test. The main evidence for this was the appearance of re-orientation peaks. It has been mentioned earlier (Section 3.3.1) that earlier work has associated the appearance of these peaks with the development of a shear plane. The present work has confirmed this.

In the small shear-box test (Figure 3.37) a total displacement of about 0.6 metres was required to reduce this sample to the residual condition. Of considerable interest in this result is the sudden drop in shear strength after a displacement of 0.35 metres. This may be the result of shear plane development, and is further discussed in Section 4.2.2.

Figure 3.38 brings out a point of special note. This is the closeness of the failure envelopes for the two shear-box tests. This suggests that the residual strength parameter is a property of the mineralogical composition, rather than of the grading of the material. Also of significance is the linearity of the failure envelopes.

The grading curves (Figures 3.39 and 3.7) show that for the residual condition, about 25 per cent of the material is less than 75 microns in size. It should be remembered that the samples used for these sieving analyses were about 50 to 100 mm thick (12-inch shear-box) and about 20 mm thick (60mm shear-box). It can be expected that the concentration of fine material close to the shear plane will be much greater. The small shear-box test specimen showed more breakdown than for any other material tested.

3.6 Comparison of results with existing information

A summary of the major part of recent research into the mechanical properties of colliery discard has been produced by Wimpey Laboratories (National Coal Board, 1972). Among the materials mentioned in this report were samples from Askern, Birch Coppice and Orgreave.

Much of the work was conducted on peak strengths, determined by triaxial tests, mainly using fresh washery discard. For the lower normal stress range, ϕ' was found to vary between about 34 and 38° for the Askern material, depending on the initial density. For the Birch Coppice material, ϕ' was found to be about 30°, and virtually independent of density. The Orgreave material (ex-tip) gave a ϕ' of about 32° close to the origin.

The Askern figures agree well with the initial 12-inch shear-box peak (34°). The shear-box work of the current tests gave significantly higher results for Orgreave (38°) and Birch Coppice (35°). For the latter material subsequent triaxial tests showed a ϕ' of 34.3°. These differences could possibly reflect variations in the materials tested.

Of special note is the Wimpey "residual" test on material from Askern. This was performed in a small shear-box using material which passed a B.S. No. 14 sieve (1.2 mm). The "residual" failure envelope, obtained from four separate tests, up to a normal stress of 1000 kN/m^2, is distinctly curved. At the highest normal stress, ϕ' is down to only 9°. This contrasts with the failure envelope at the end of the corresponding test in the present series (Figure 3.30), which is virtually linear over the stress range tested.

3.7 Correlation of results

The results were compared by a correlation matrix program. Table 3.6 contains the correlation matrix only for those properties for which some correlation was detected. Originally, 23 different variables were compared. No correlation was observed between any of the properties and the coal rank code number. Also, no dependence could be detected between the shear strength properties tested and the mineralogical composition. Results which showed significant correlations are discussed below.

Outstanding is the extent of the correlations between the shear strength properties and the grading parameters. Some confusion may result from the correlations between the results from the large shear-box tests and the grading parameters for the small shear-box tests. These correlations suggest that the behaviour of small material is similar to the behaviour of the large material, and consequently material breakdown is an important factor in the shear strength properties. Two main dependencies appear.

A close correlation was found between the peak strength achieved in the large shear-box test and the median diameter of the material after testing in the small shear-box. All the small shear-box tests started with the same median diameter, so this correlation suggests a relationship between shear strength and material breakdown.

The extent of shear strength reduction in the 12-inch shear-box test correlated closely with the percentage of material less than 75 microns in size before the test. The suggestion behind this is that the extent of fine material

LPK	L%	LF	S%	SF	P1L	M2L	T2L	P2L	M2S	T2S	P2S	PI	
		99		95				-95	99.9	-95	-99		LPK=large box peak
		-95	95		99.9		99						L% =large box % red.
			-95	99	-99		-99		99.9	-95	-95		LF =large box final
				-95	99		99.9			95	95		S% = small box % red.
							-99		99	-95	-95		SF =small box final
							99	95	-95		95	-95	P1L=1t. 75μm into large box
								-95		-95	-99	-95	M2L=Med dia from large box
									-95	95	95	95	T2L=Trask coeff. from large box
									-95	99	-99	99.9	P2L=1t. 75μm from large box
										-95	95	-95	M2S=med dia from small box
											95	99	T2S=Trask coeff. from small box
												99	P2S=1t. 75μm from small box
													PI =Plasticity index

for 8 samples

r ≥ .9249 = 99.9% = highly sig.

r ≥ .8343 = 99 % = significant

r ≥ .7067 = 95 % = probably sig.

CORRELATION MATRIX

Table 3.6

controls the development of shear planes. A similar conclusion can be drawn from the correlation between the extent of shear strength reduction during the small shear-box test and the Trask sorting coefficient for the corresponding sample after the large shear-box test. This possibly indicates that particle distribution can affect shear plane development.

The Plasticity Index provided several significant correlations, all with the grading parameters. The most significant of these was the correlation between the Plasticity Index and the percentage of material smaller than 75 microns after the large shear-box test. The Plasticity Index reflects the clay content of the material, and it is such material which will break down to the finer sizes during the shear tests.

Two additional correlation matrices were formed. One of these neglected the results for the ex-tip material (Orgreave). The other did not include the results for the Birch Coppice material. The purpose of these additional matrices was to reveal any further correlations which may have been concealed by different characteristics of either of the two materials mentioned.

3.8 The shale tests

Forty different specimens from two different samples, Cynheidre and Ollerton, were tested. The shear and normal stresses on each specimen were calculated by using the area of the specimen at the place of failure, measured after the test.

The results are shown in Figure 3.40. There is considerable scatter, but it appears that the Cynheidre material has the slightly higher shear strength. This is to be expected, both from the results of the normal shear tests on aggregate material, and also from any possible rank dependency. For the two materials tested, the rank contrast should have been adequate to bring out any relationship between rank and strength.

It appears that the fundamental difference between the two samples is that the higher ranking material, Cynheidre, shows a higher cohesion. The shearing angle for the two types appear to be about the same.

Residual values down to about 25 per cent of peak strength were observed after displacements of less than 10 mm. It should be noted, however, that at this displacement, much of the contact was between the shale and plaster, and no correction has been made for this.

3.9 Shear tests at increased normal stress

To study further the process of shear strength reduction, it was decided to perform additional 60 mm shear-box tests at higher-than-usual normal stresses.

During the time available it was possible to perform a series of tests at normal stress values of up to 1500 kN/m^2 on material from Ollerton washery. In addition, tests at 350 and 550 kN/m^2 only were performed on certain other samples. The material tested was of the same size range as for the previous 60 mm shear-box tests. This enabled material breakdown to be easily monitored.

An additional 12-inch shear-box test was performed in order that the rate of shear strength reduction in the two different shear-boxes could be compared.

3.9.1 Tests at different normal stresses

Stress-displacement curves for the tests at different normal stresses are shown in Figure 3.41. The material used for these tests was crushed from the main sample in order to obtain sufficient material of suitable size. It is possible, therefore, that the material for the individual tests was not consistent in composition.

The general trend of results is very evident from Figure 3.41. As the normal stress is increased, the peak and final stress values are lower. Pressure of time meant that tests had to be discontinued as soon as the reduction in shear strength ceased to be rapid. The appearance that residual strength tends to drop with normal stress should be partially accredited to the shear-box, as discussed in Section 1.5.

It is reasonable to assume that if the displacement could be extensive, without material loss taking place, all the stress-displacement curves would converge onto the same, fundamental residual value, which would be a property of the material composition.

Most notable about these results is the vast difference between the stress-displacement curve at a normal stress of 133.7 kN/m^2 and that at 350 kN/m^2. With reference to the breakdown mechanisms discussed in Section 1.5, then it would be reasonable to suppose that breakdown of particles under stress is taking place at the latter stress level, but not at the former. The increase in the normal stress beyond the latter value results in comparatively little change in the rate of breakdown.

Figure 3.42 illustrates the peak and the final strength failure envelopes for the series of tests on the Ollerton material. The peak envelope shows slight curvature. At low normal stresses ϕ' is about 37°, but by a normal stress of 300 kN/m^2, ϕ' has dropped to 31°. The peak envelope is virtually linear thereafter, ϕ' still being only reduced to 30° for the sample tested at the highest normal stress.

The "residual" envelope also shows curvature, but to a much greater extent. This reveals a similar trend to the Askern material tested in the Wimpey laboratories (National Coal Board, 1972).

The sample tested at 500 kN/m^2 was unloaded in two stages so that a failure envelope for the shear plane developed in this particular test could be determined. This envelope is illustrated in Figure 3.43. This shows the same linear characteristic found in the case of Birch Coppice. Also shown on this diagram is the result for an additional test on Bersham material. This was reduced to a "residual" value at a normal stress of 1150 kN/m^2 and then unloaded in three stages. This result shows slight curvature.

The results of the sieving analyses on the various sheared samples of Ollerton material are shown in Figure 3.44. This demonstrates the general increase in the overall breakdown as the normal stress is increased. The rate of breakdown is much diminshed at the very high values of normal stress.

3.9.2 Tests on different materials

Figure 3.45 shows the stress-displacement curves for tests on different discards. The results are rather confusing. As has already been observed for the Ollerton material, the "residual" strength is reduced as the normal stress is increased.

The most surprising feature is the extremely low residual values obtained. The accuracy of the shear-box must be questioned. However, the proving ring has been checked and found correct. It is possible that at high normal stresses an area correction should be applied. It should be noted that the tests on the Cynheidre, Morrison Busty and Orgreave discards were performed using one shear-box, whilst another box was used for the remainder of the tests of this series, and also for the previous series of tests at lower normal stresses. Thus, some results are comparable among themselves, and these illustrate that the Morrison Busty material has slightly more durable properties than the Cynheidre material.

3.9.3 Comparison between the large and small shear-box results

The stress-displacement curve for the 12-inch shear-box test on Bersham discard at a normal stress of 347.1 kN/m^2 is shown in Figure 3.46. This should be compared with the corresponding small shear-box result (Figure 3.45). It is apparent that a displacement of only 0.3 metres was required in the small shear-box test for the "residual" state to be reached. The equivalent value in the large shear-box was about 1.8 metres total displacement.

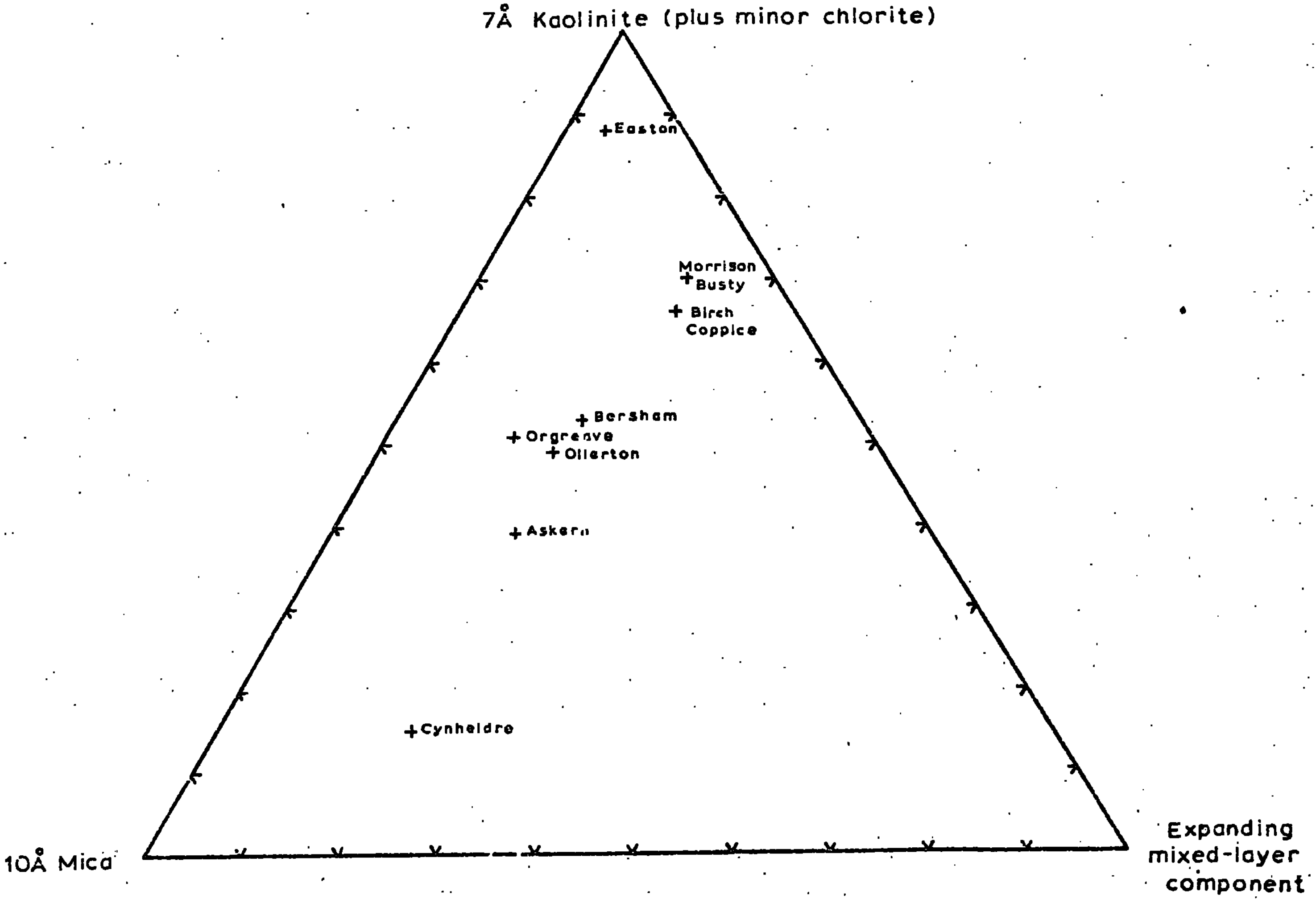


DIAGRAM SHOWING CLAY MINERAL COMPOSITION FOR ALL SAMPLES

Figure 3.1

Particle size distribution
all main samples as received

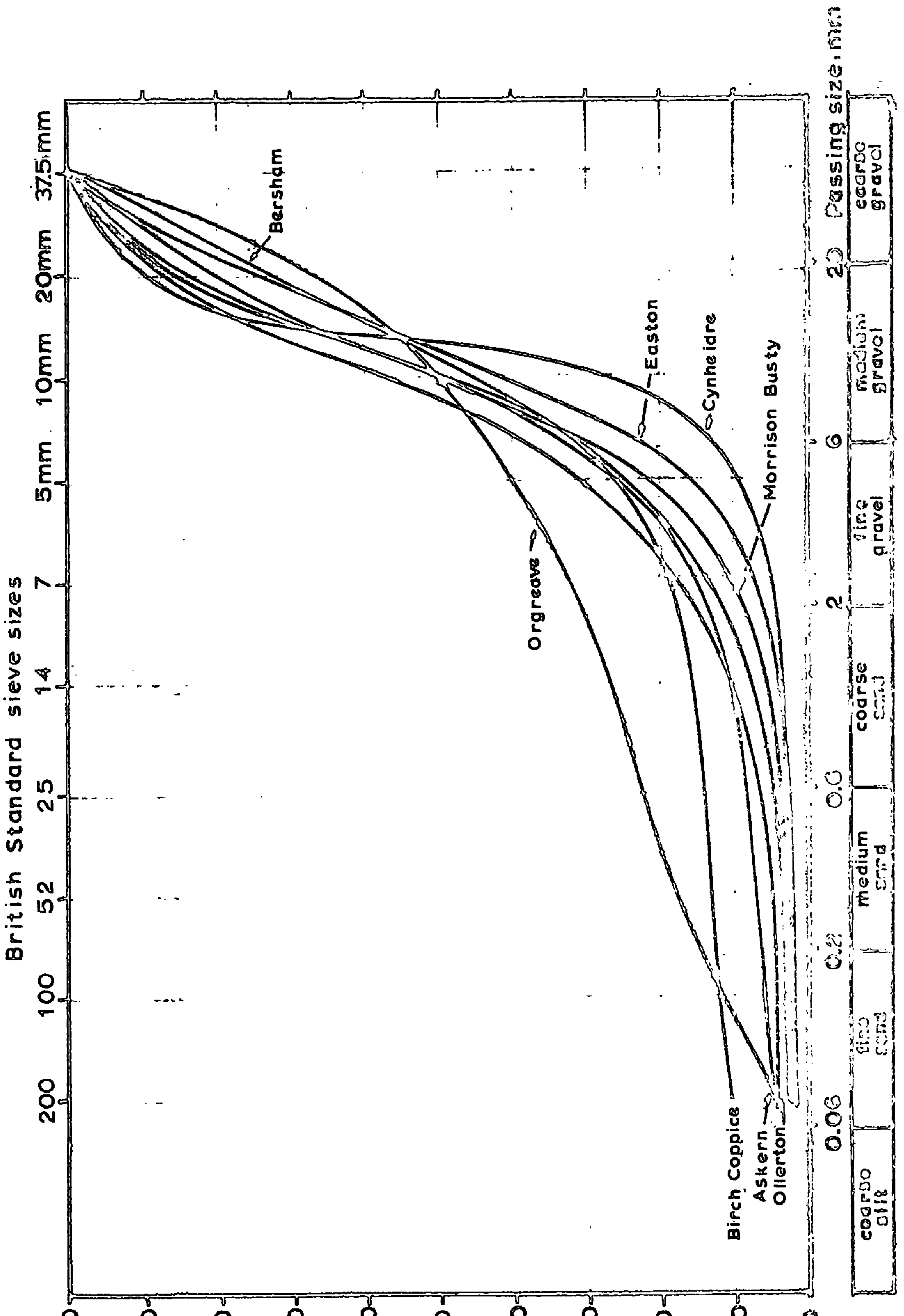
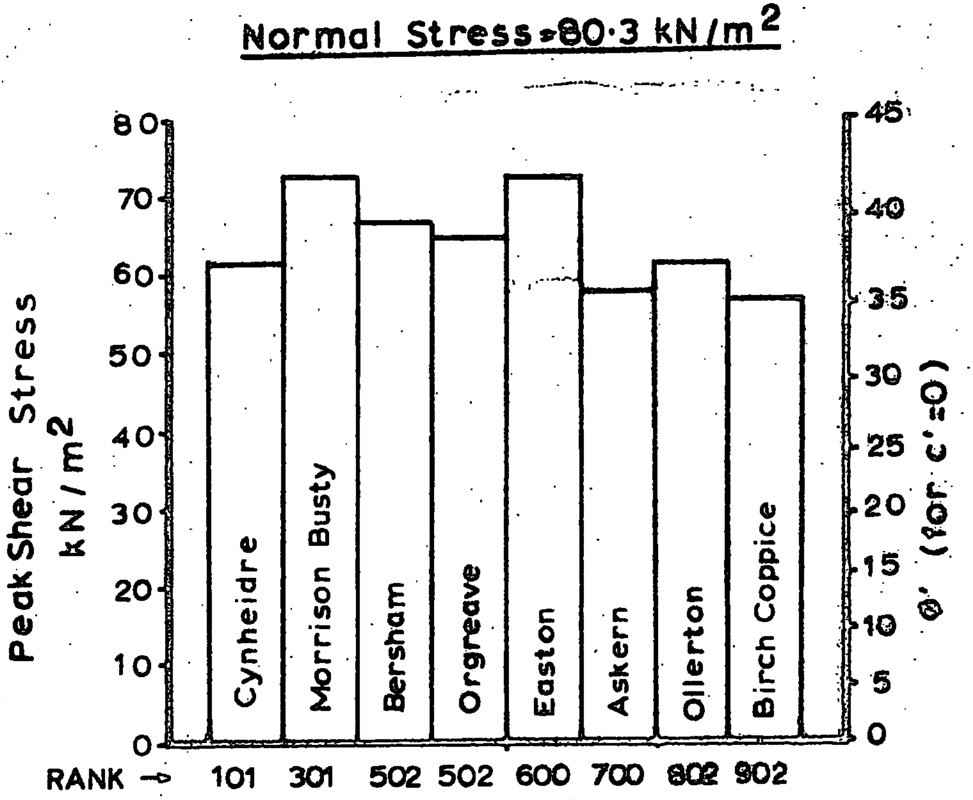
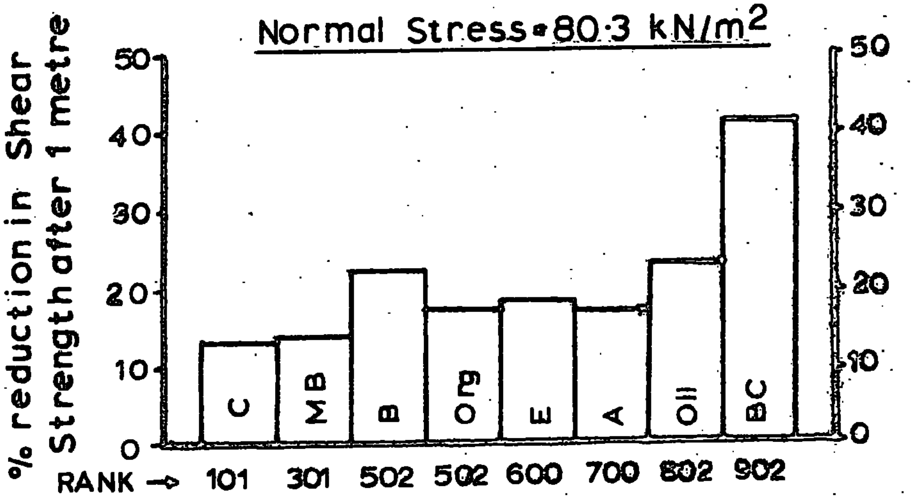


Figure 3.2

12-inch shear-box results

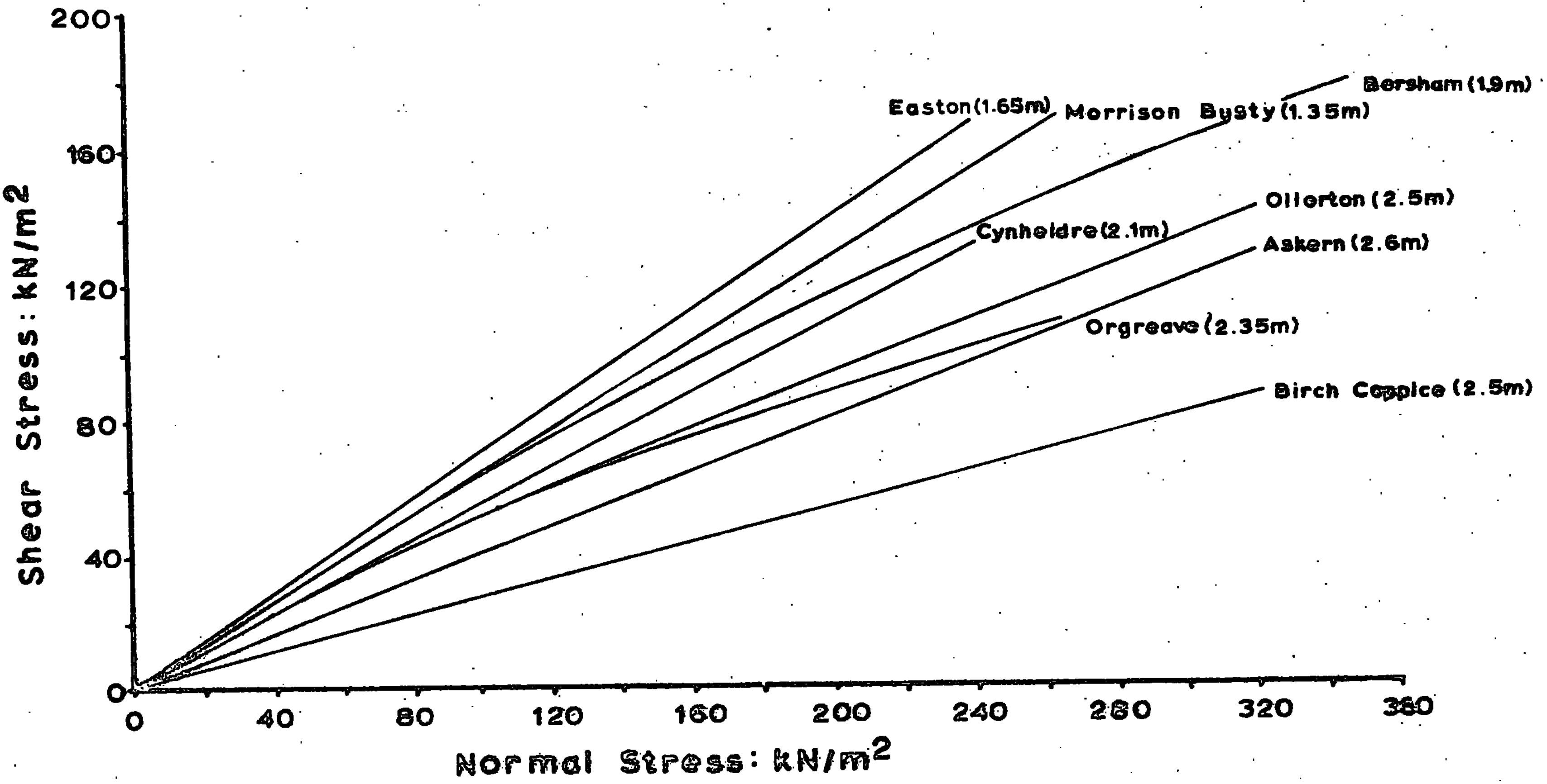


(a) PEAK SHEAR STRENGTH v. COAL RANK



(b) PERCENTAGE REDUCTION IN SHEAR STRENGTH AFTER 1 METRE DISPLACEMENT v COAL RANK

Figure 3·3

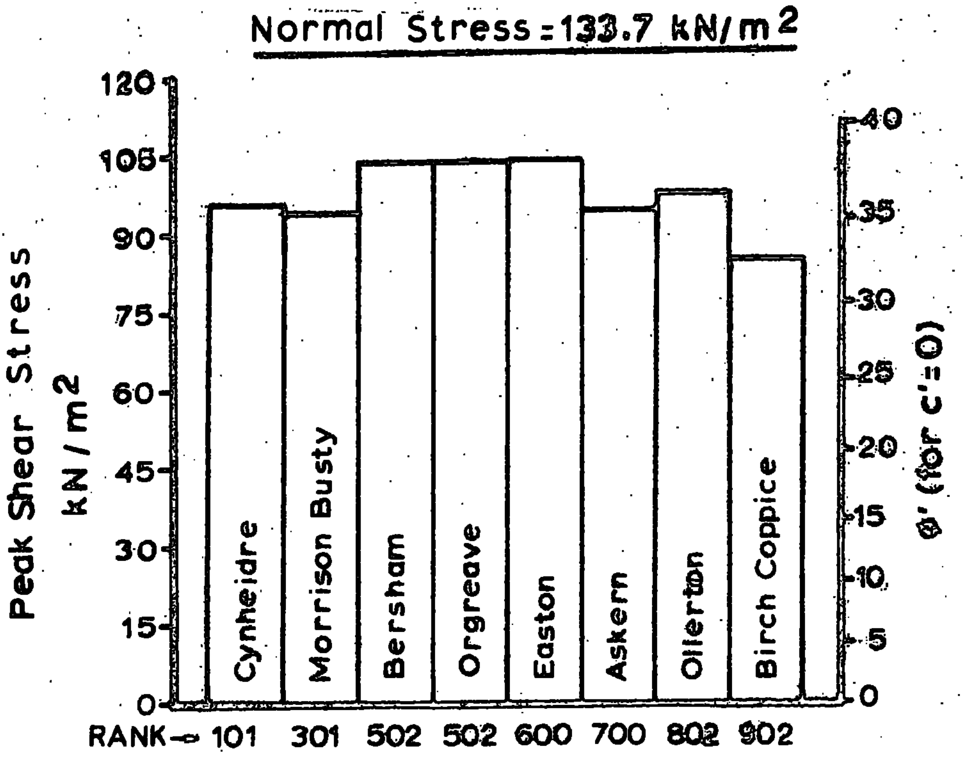


12 INCH SHEAR BOX TESTS

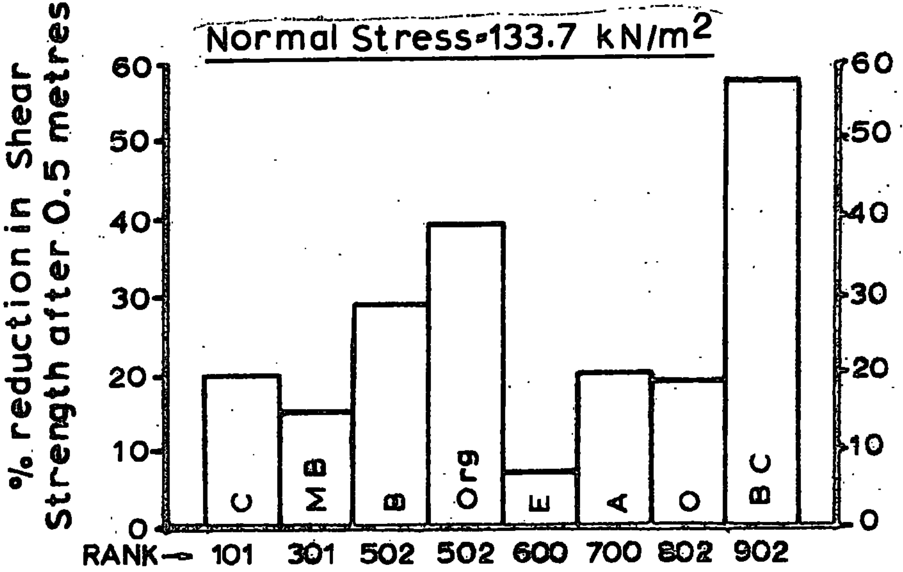
FAILURE ENVELOPES AT END OF TESTS

Figure 3.4

60mm shear-box results



(a) PEAK SHEAR STRENGTH v. COAL RANK



(b) PERCENTAGE REDUCTION IN SHEAR STRENGTH AFTER 0.5 METRES DISPLACEMENT v. COAL RANK

Figure 3.5

Particle size distributions after 12-inch shear-box tests

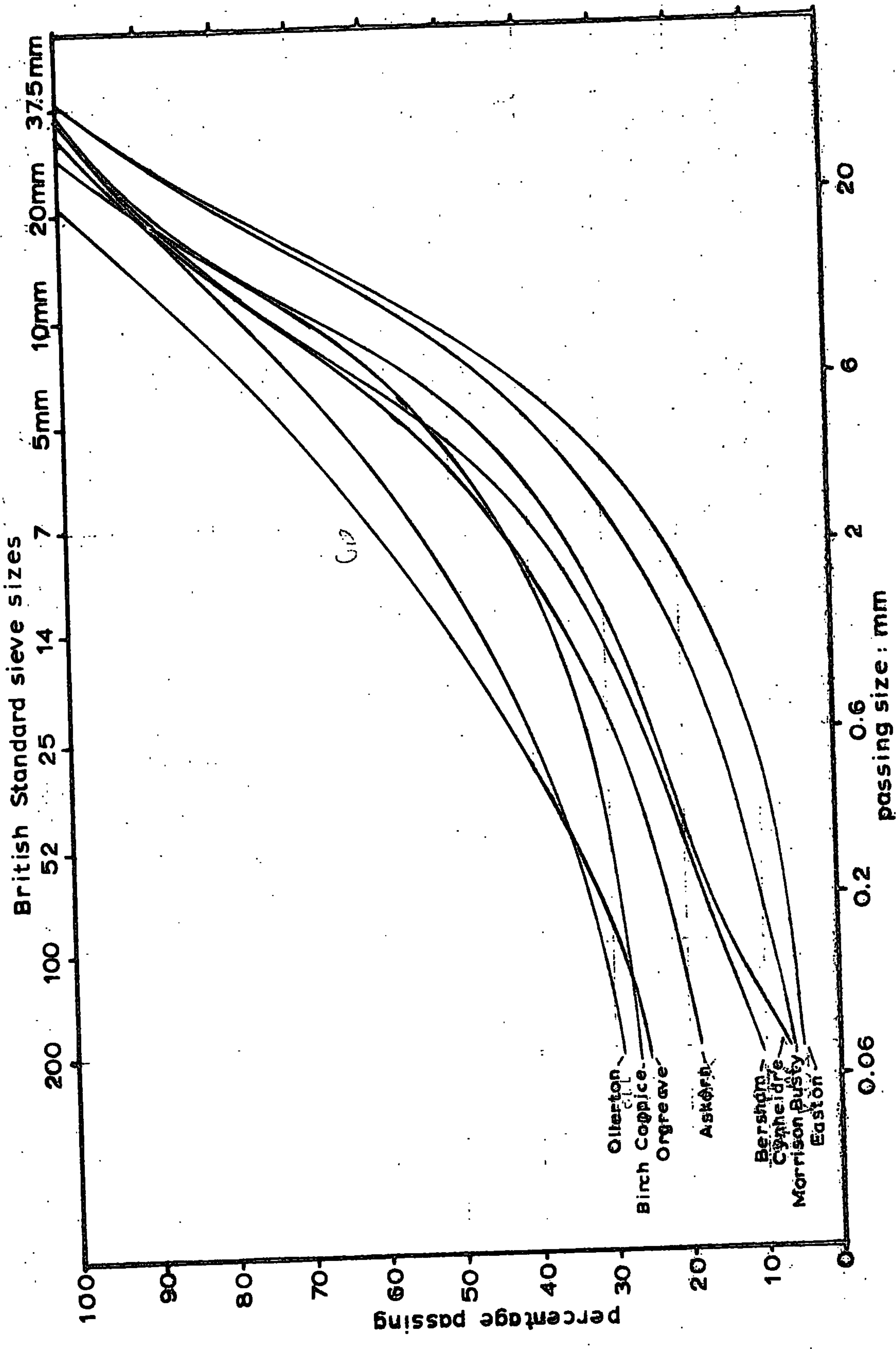


Figure 3·6

PARTICLE SIZE DISTRIBUTION AFTER 60mm SHEAR-BOX TESTS

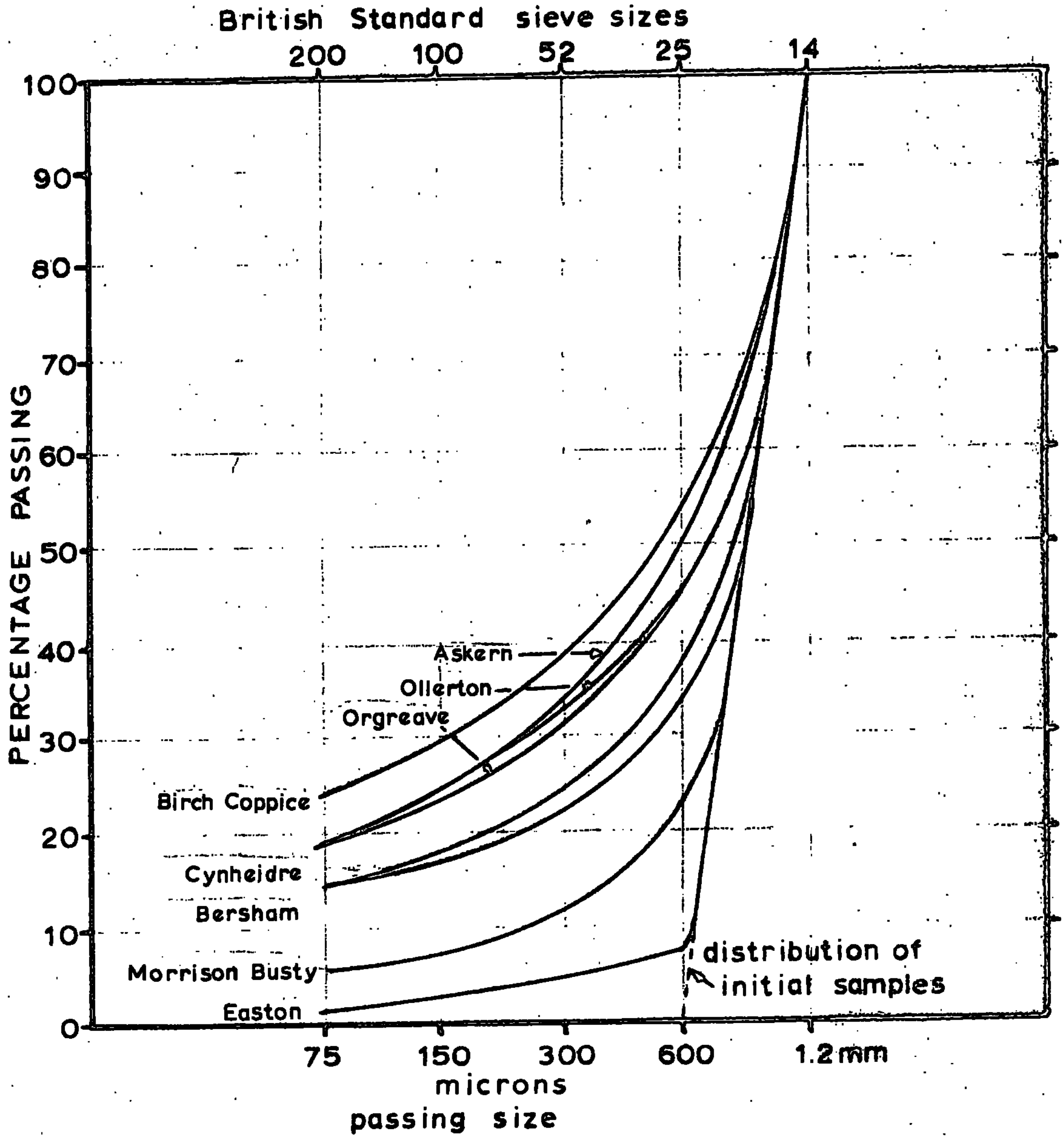


Figure 3.7

12 INCH SHEAR BOX TEST

CYNHEIDRE WASHERY DISCARD (RANK 100) THIRD TEST

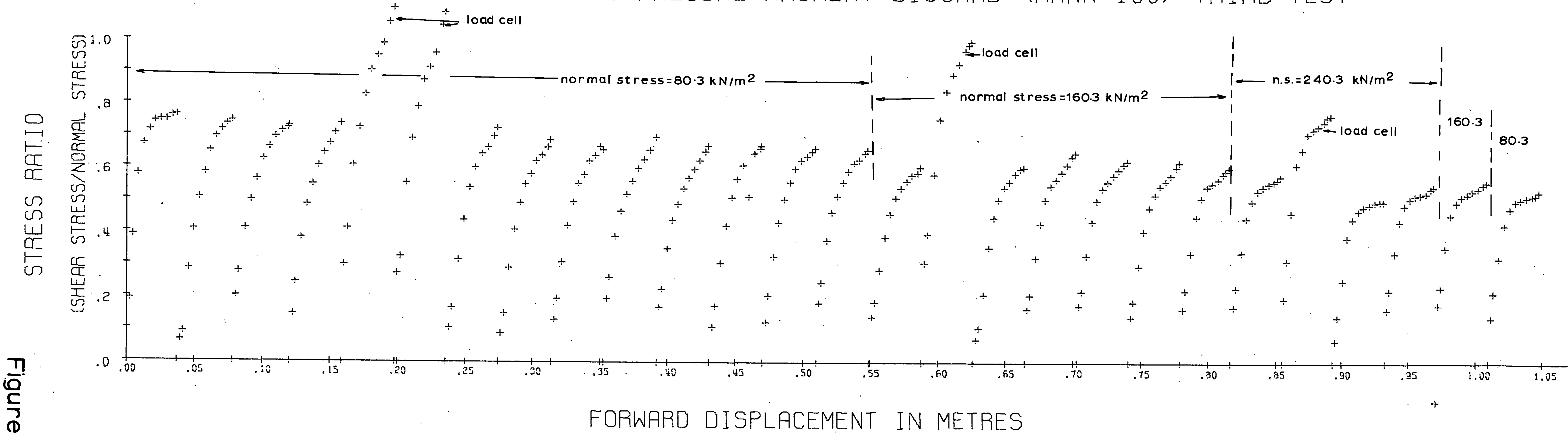


Figure 38

Cynheidre discard

60mm shear-box test stress-displacement curve

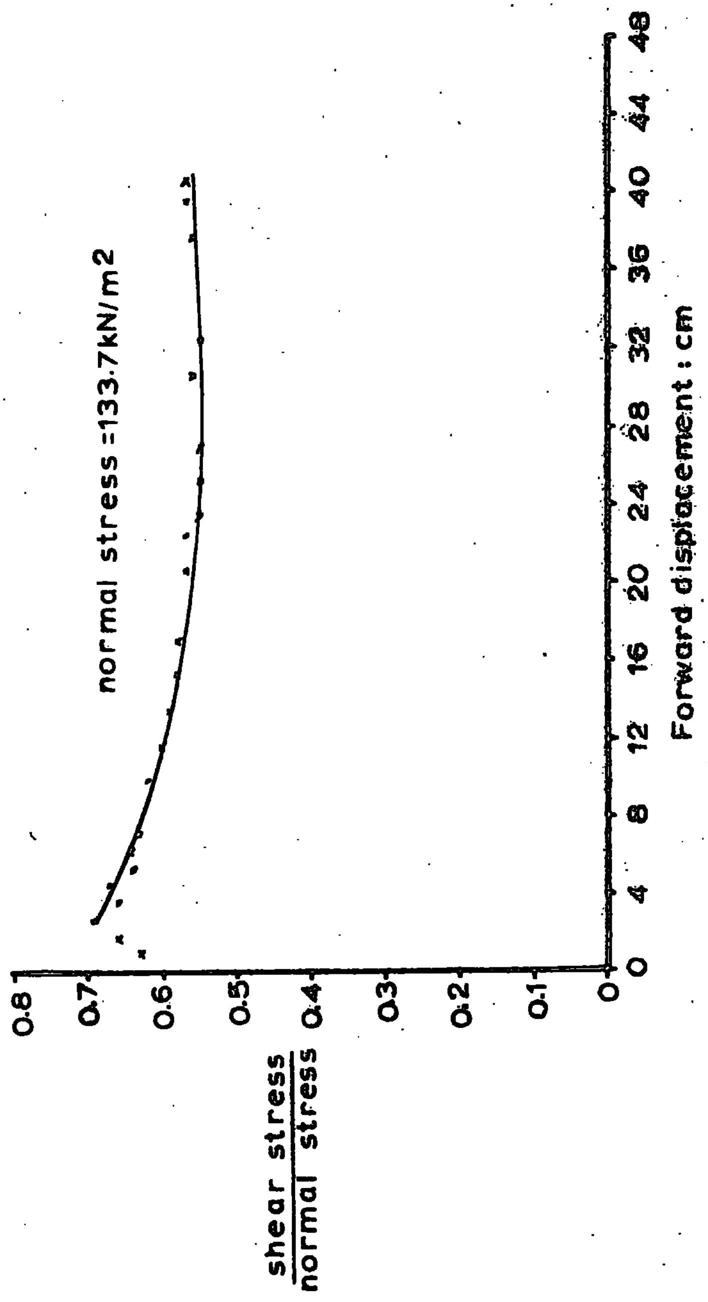


Figure 3·9

Cynheidre discard failure envelopes

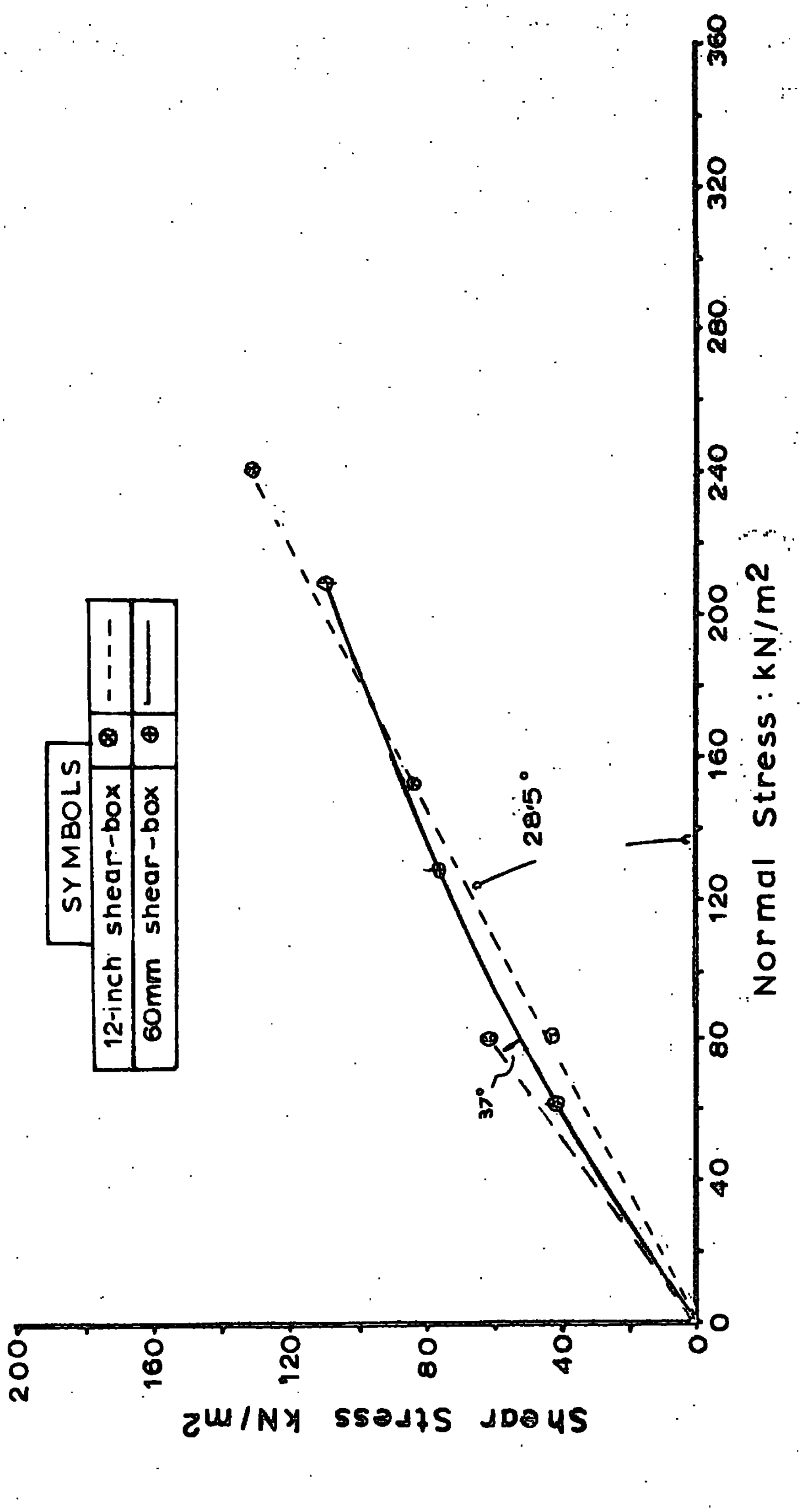


Figure 3.10

Particle size distributions
Cynheidre discard

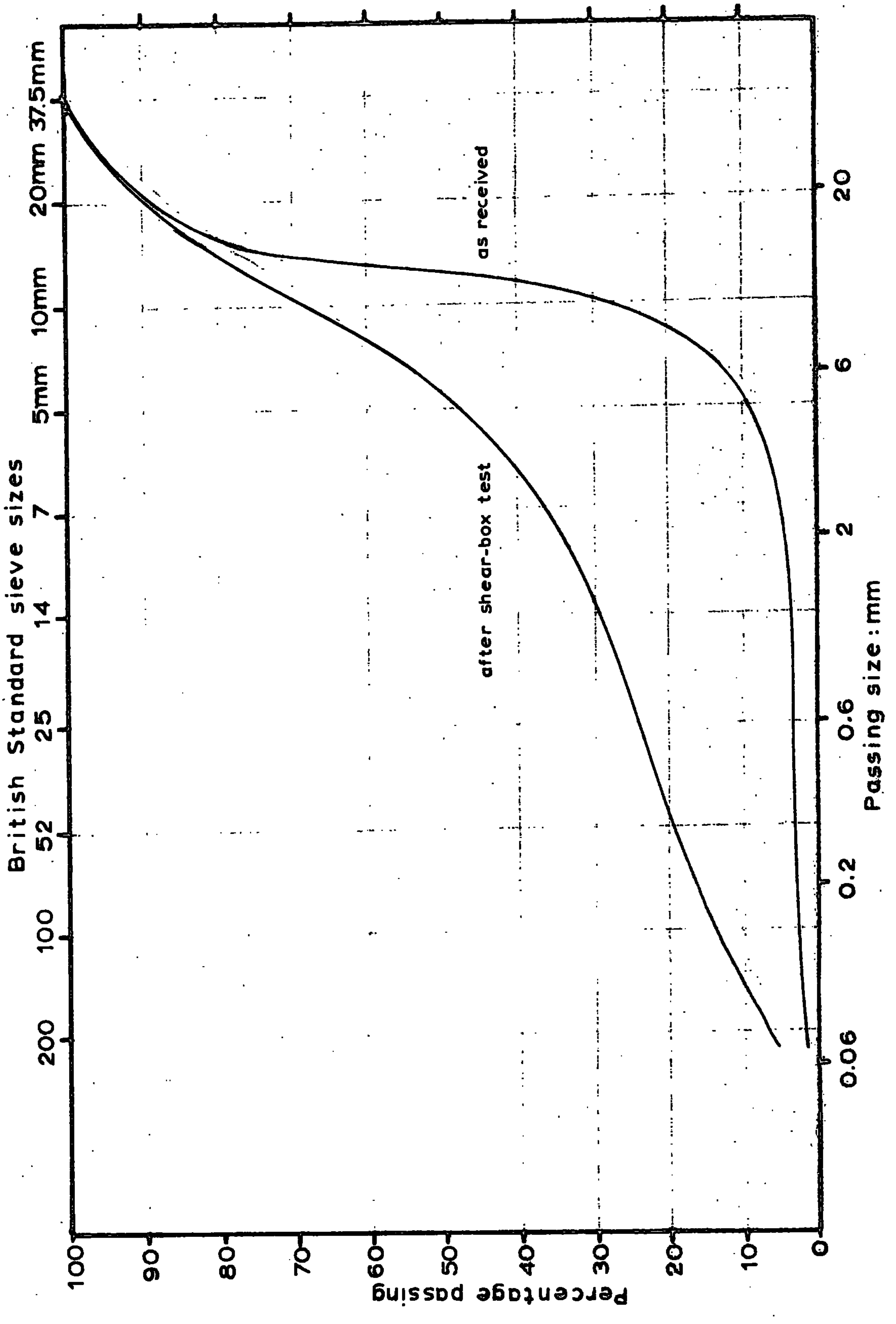


Figure 3·11

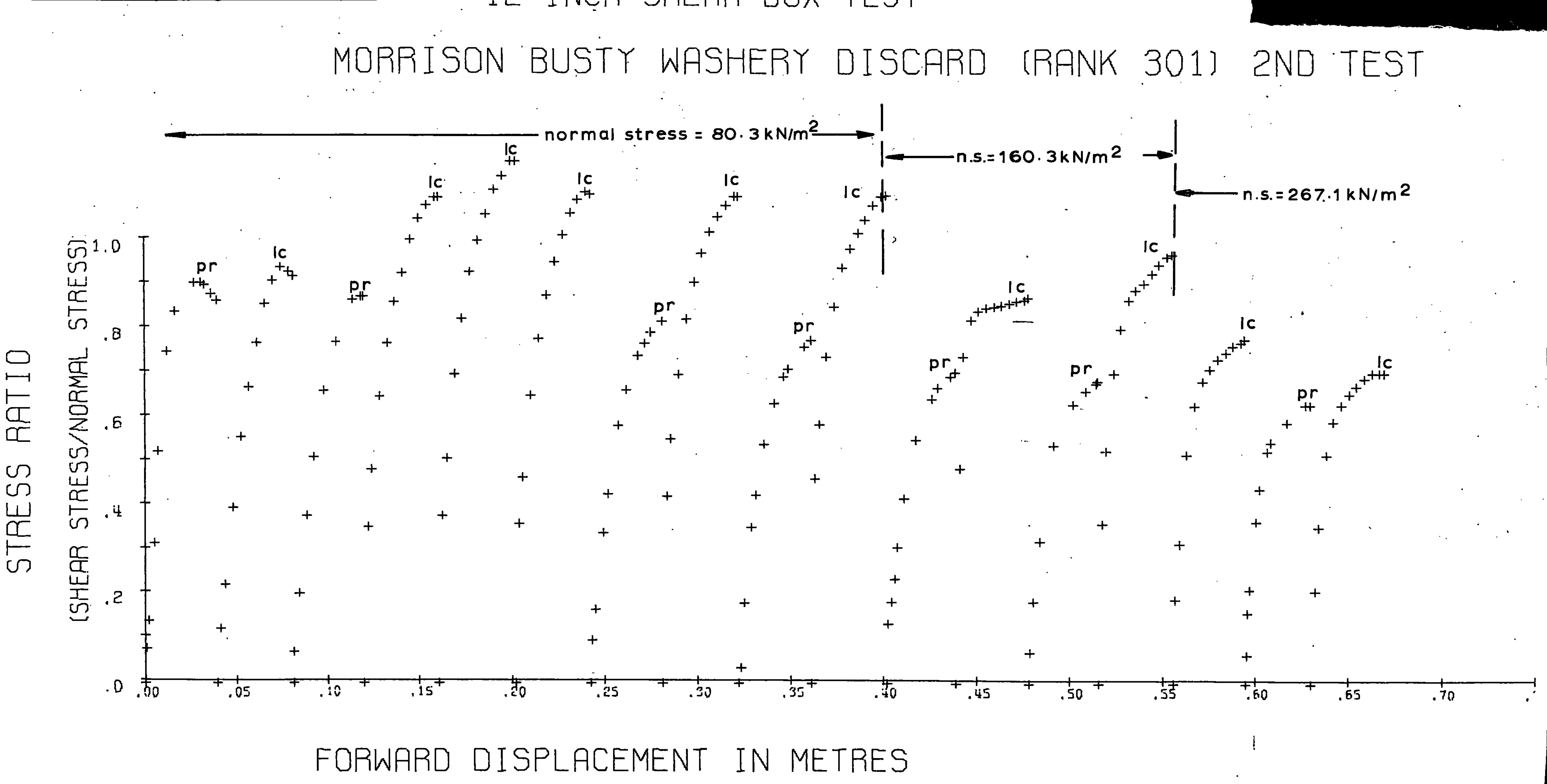

12 INCH SHEAR BOX TEST
MORRISON BUSTY WASHERY DISCARD (RANK 301) 2ND TEST
normal stress = 80·3 kN/m²
n.s.=160·3 kN/m²
n.s.=267·1 kN/m²
pr
lc
STRESS RATIO
(SHEAR STRESS/NORMAL STRESS)
1.0
.8
.6
.4
.2
.0
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
FORWARD DISPLACEMENT IN METRES

Figure 3.12

Morrison Busty discard
60mm shear-box test
stress-displacement curve

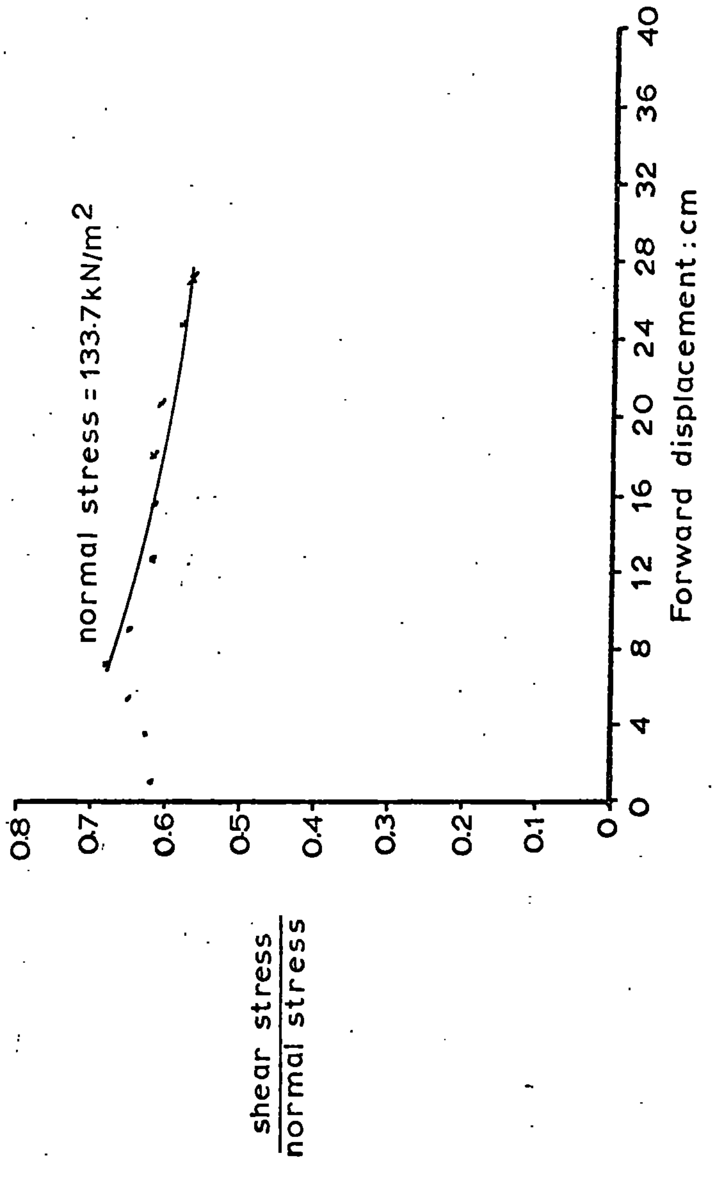


Figure 3·13

Morrison Busty discard failure envelopes

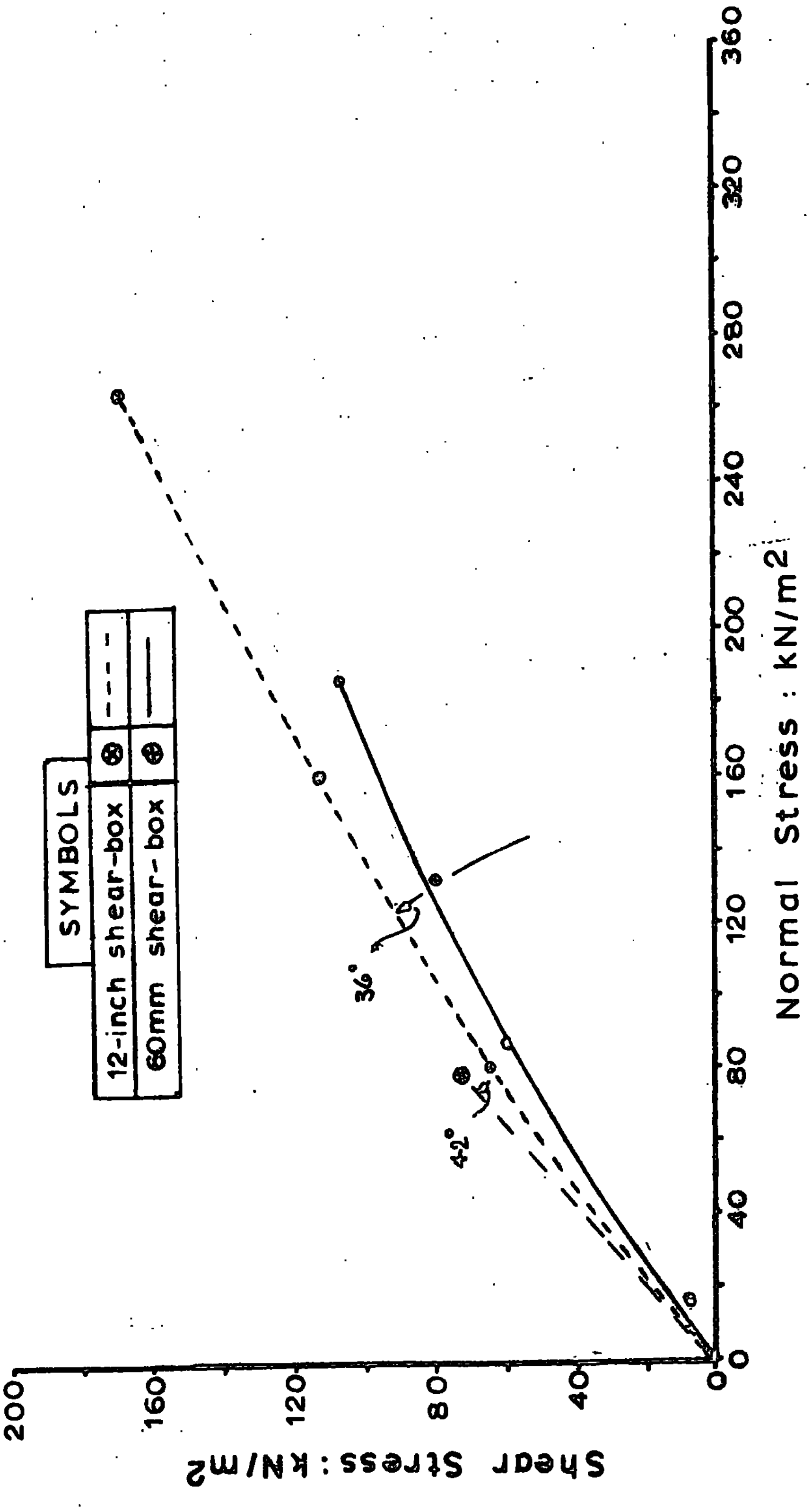


Figure 3.14

Particle size distributions

Morrison Busty discard

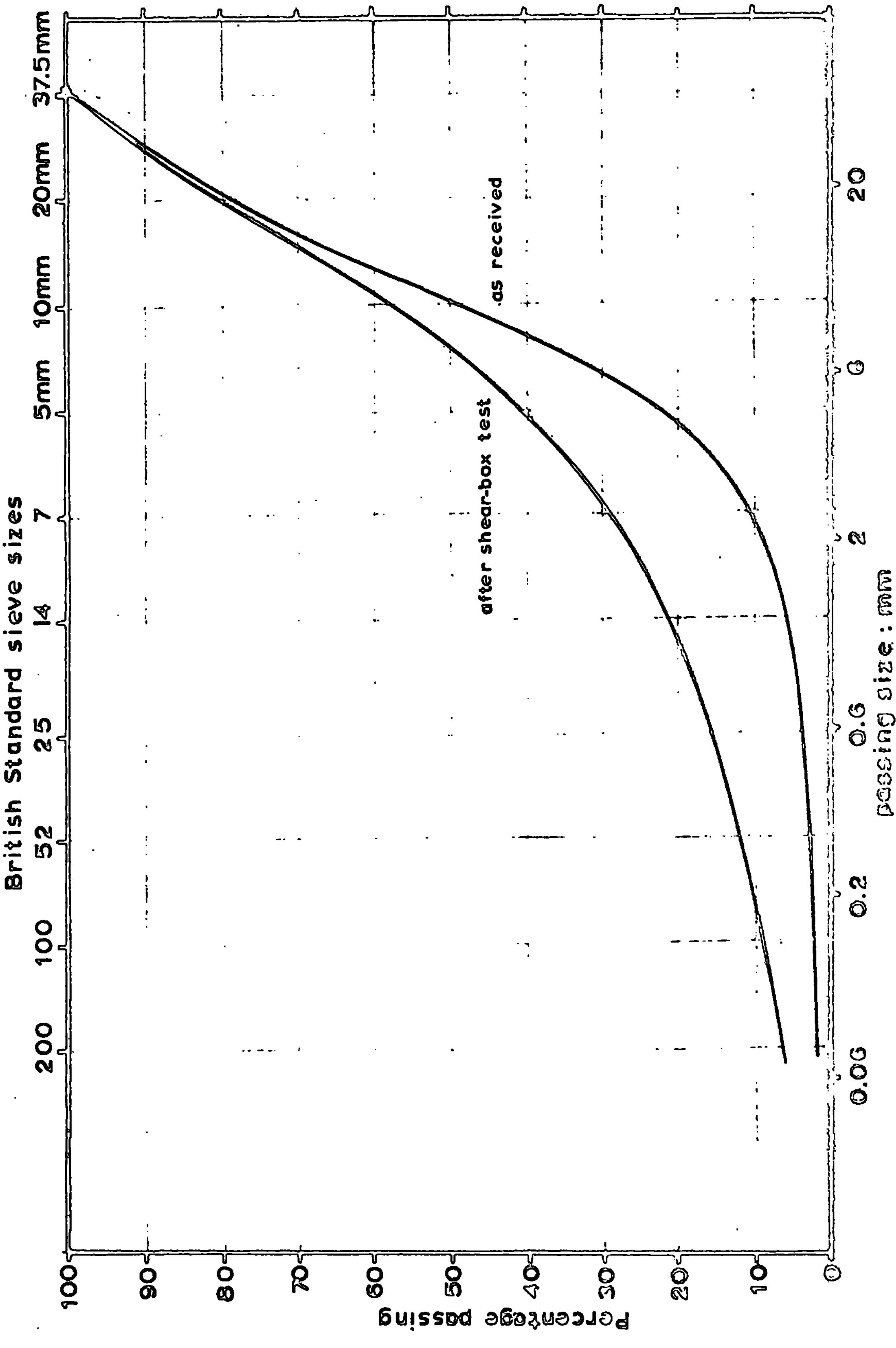


Figure 3.15

12 INCH SHEAR BOX TEST

DISCARD FROM BERSHAM COLLIERY, N. WALES (RANK 500)

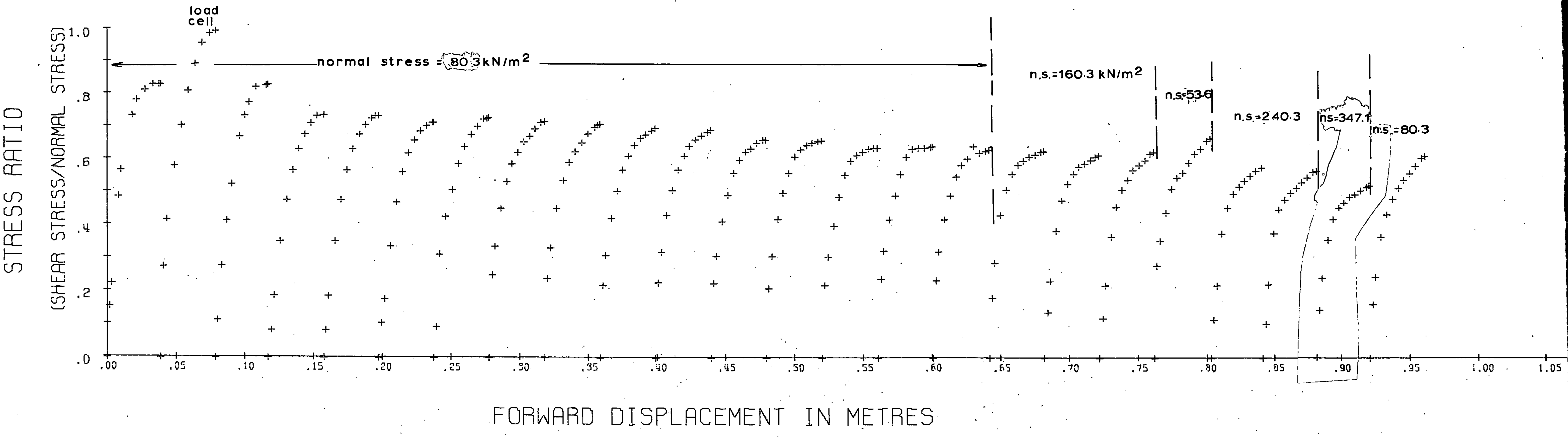


Figure 3-16

Bersham discard
60mm shear-box test
stress-displacement curve

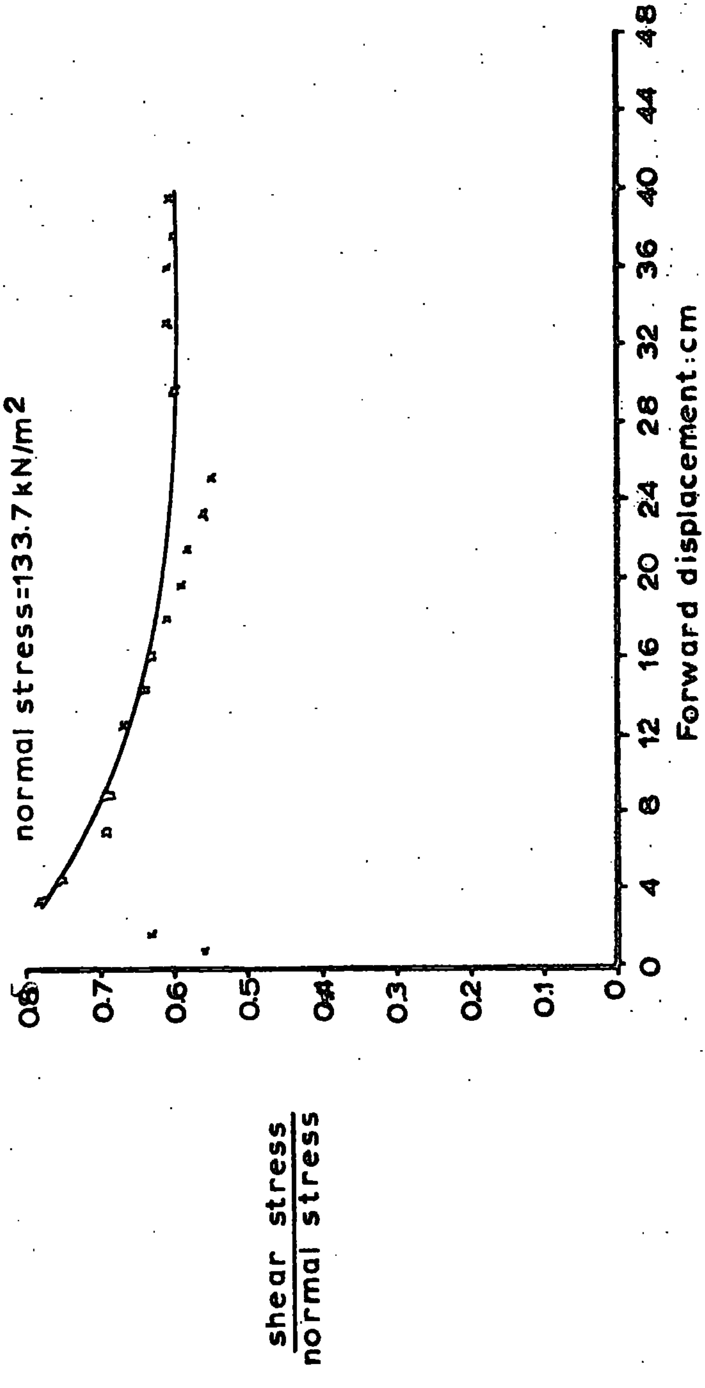


Figure 3.17

Bersham discard failure envelopes

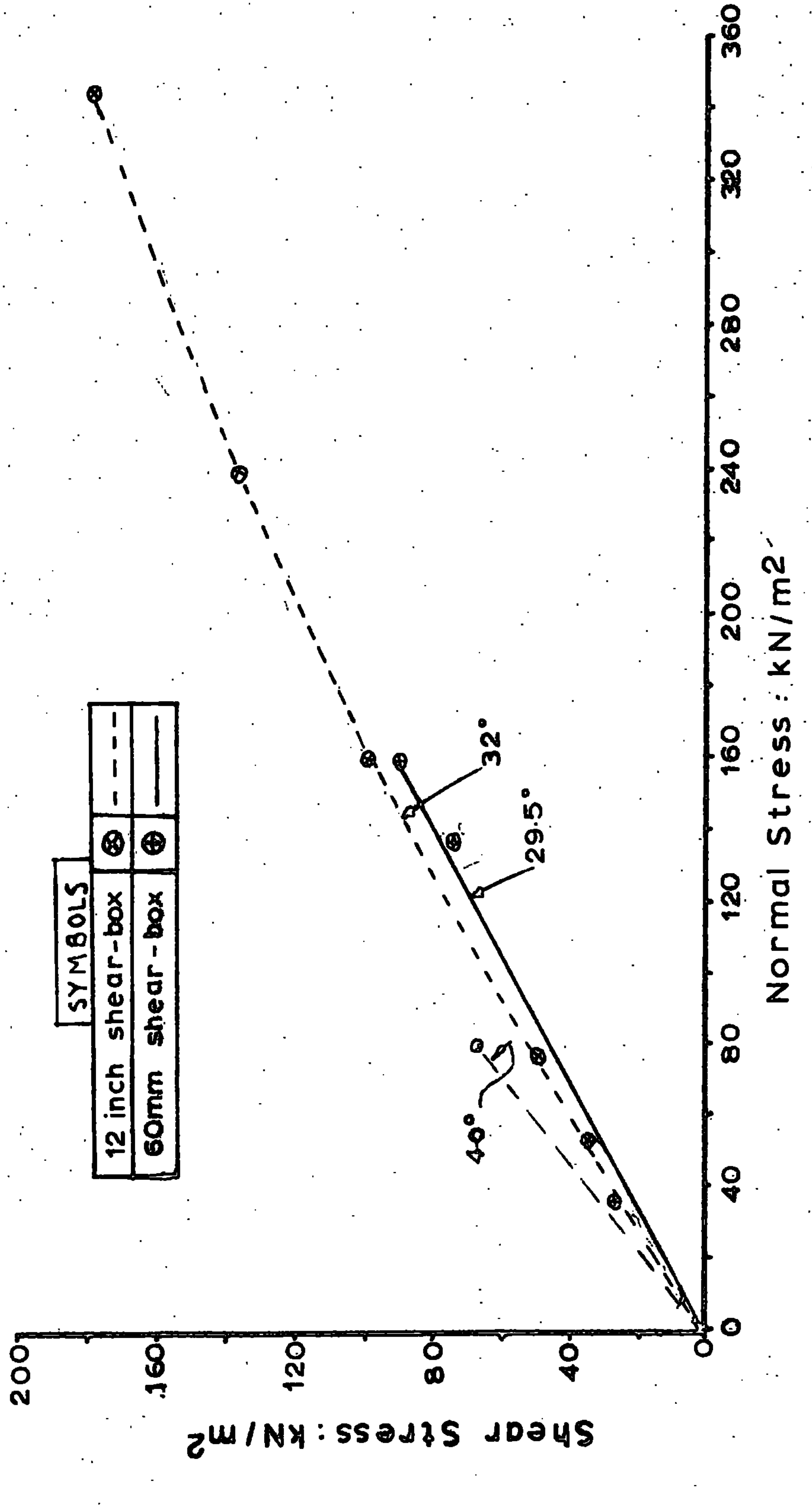


Figure 3.18

Particle size distributions

Bersham discard

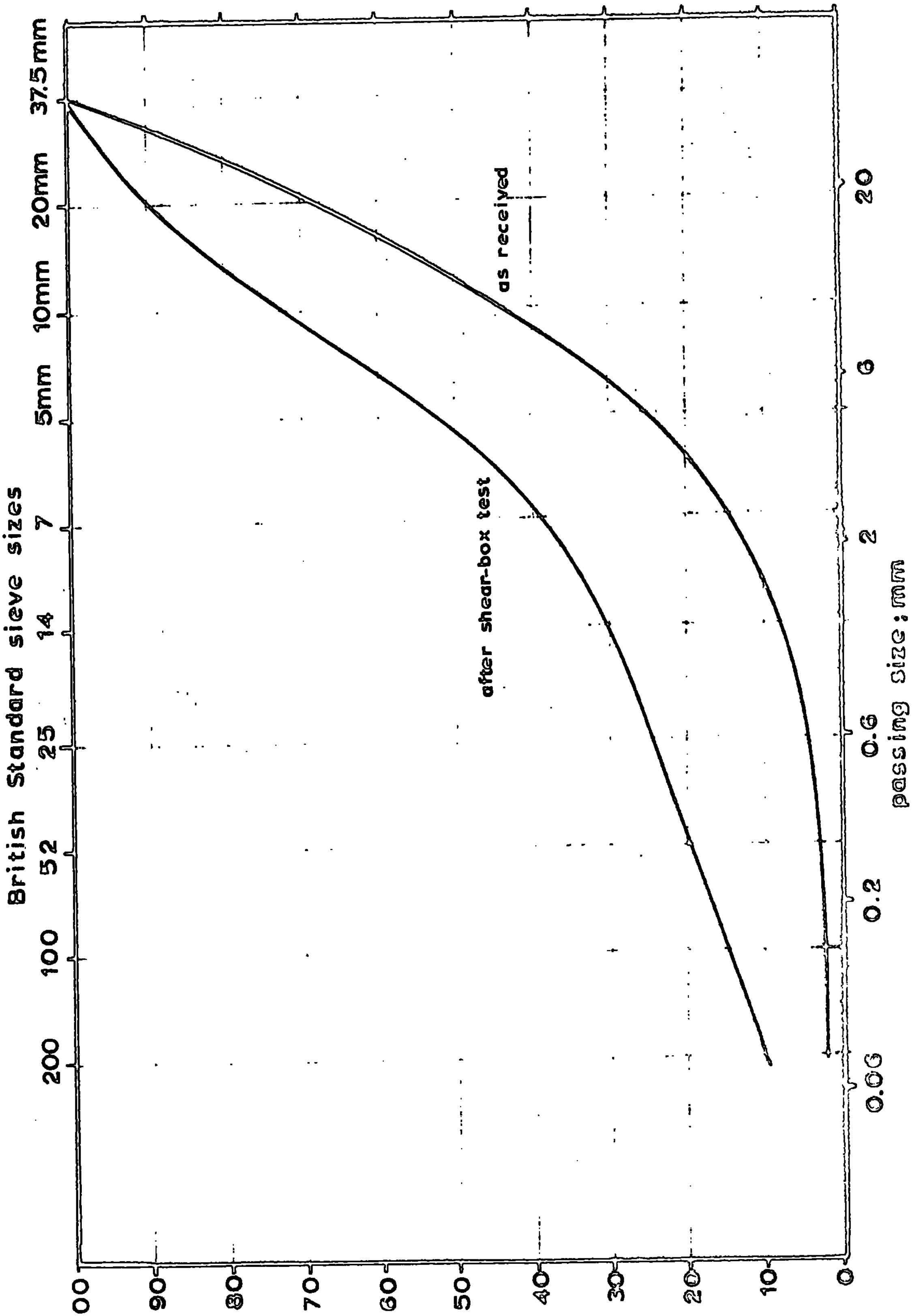


Figure 3.19

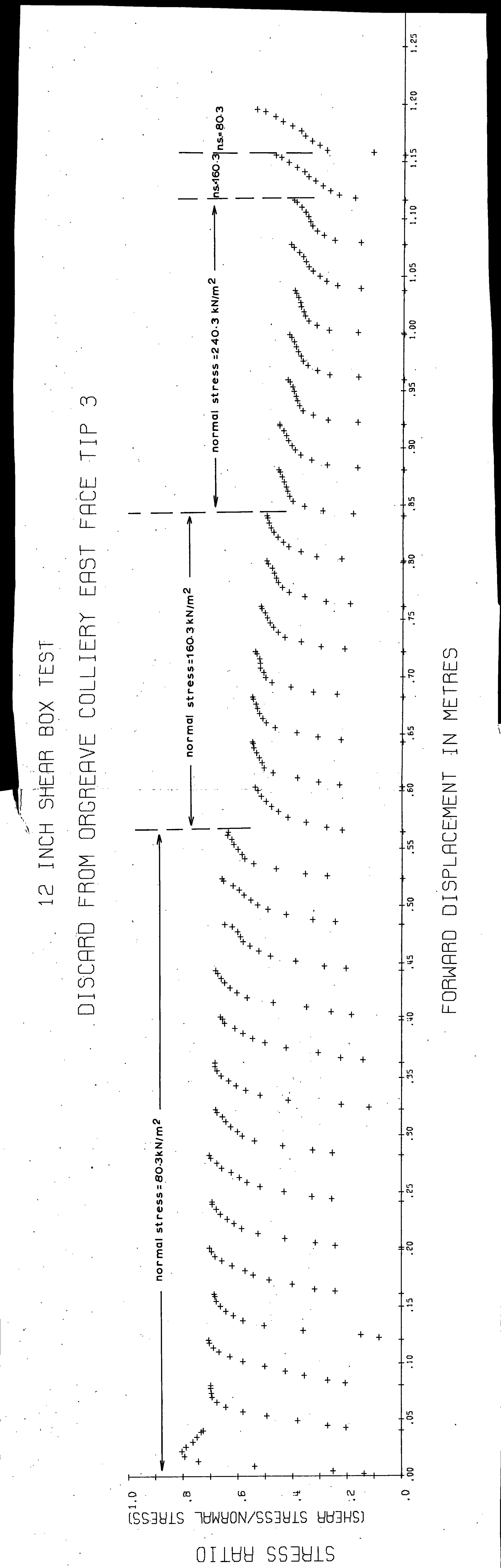

12 INCH SHEAR BOX TEST
DISCARD FROM ORGREAVE COLLIERY EAST FACE TIP 3
normal stress = 80.3 kN/m^2
normal stress = 160.3 kN/m^2
normal stress = 240.3 kN/m^2
ns = 160.3
ns = 80.3
STRESS RATIO
(SHEAR STRESS/NORMAL STRESS)
1.0
.8
.6
.4
.2
.0
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
.75
.80
.85
.90
.95
1.00
1.05
1.10
1.15
1.20
1.25
FORWARD DISPLACEMENT IN METRES

Figure 3.20

Orgreave discard
60mm shear-box test
stress-displacement curve

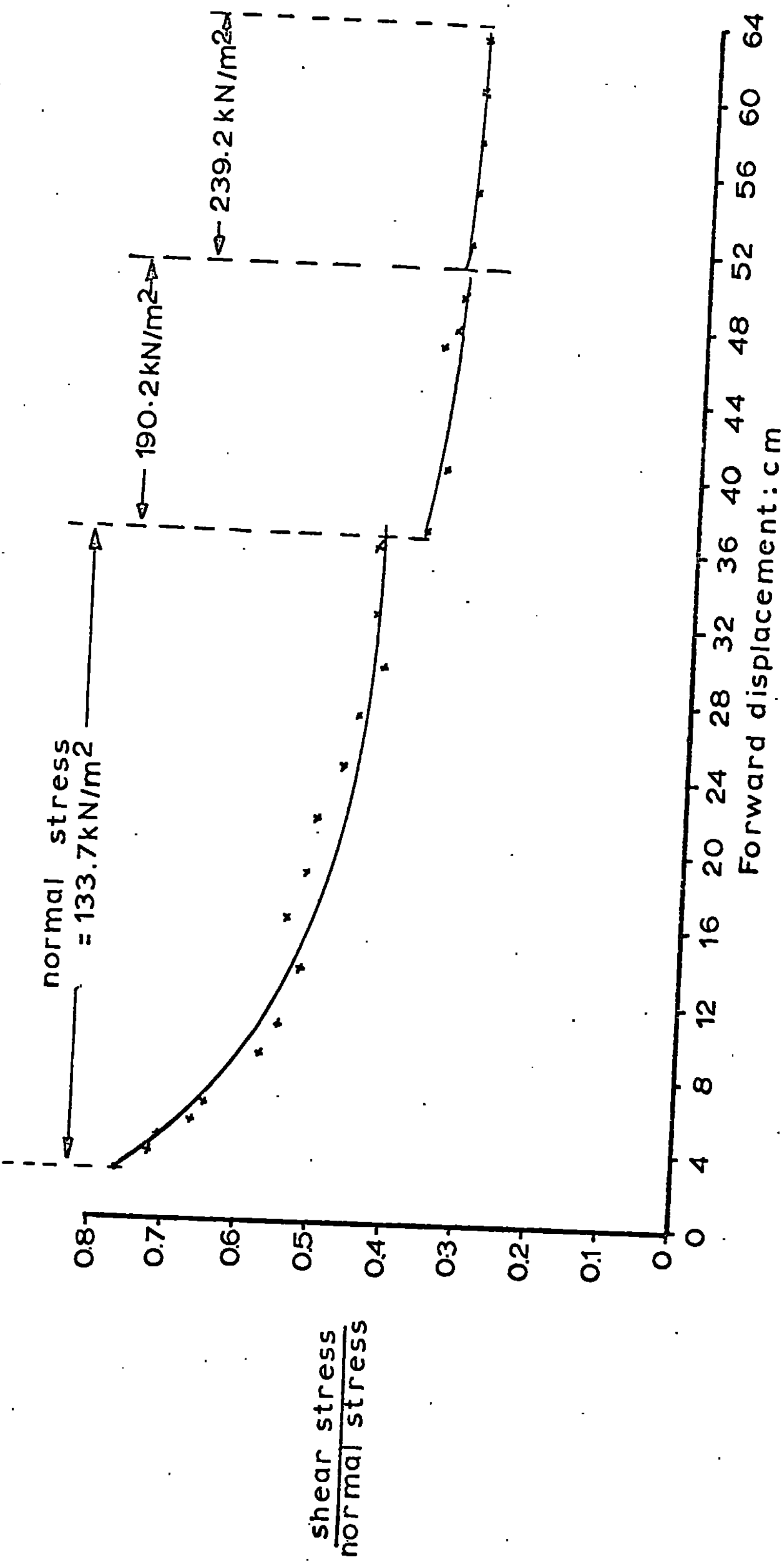


Figure 3.21

Orgreave discard failure envelopes

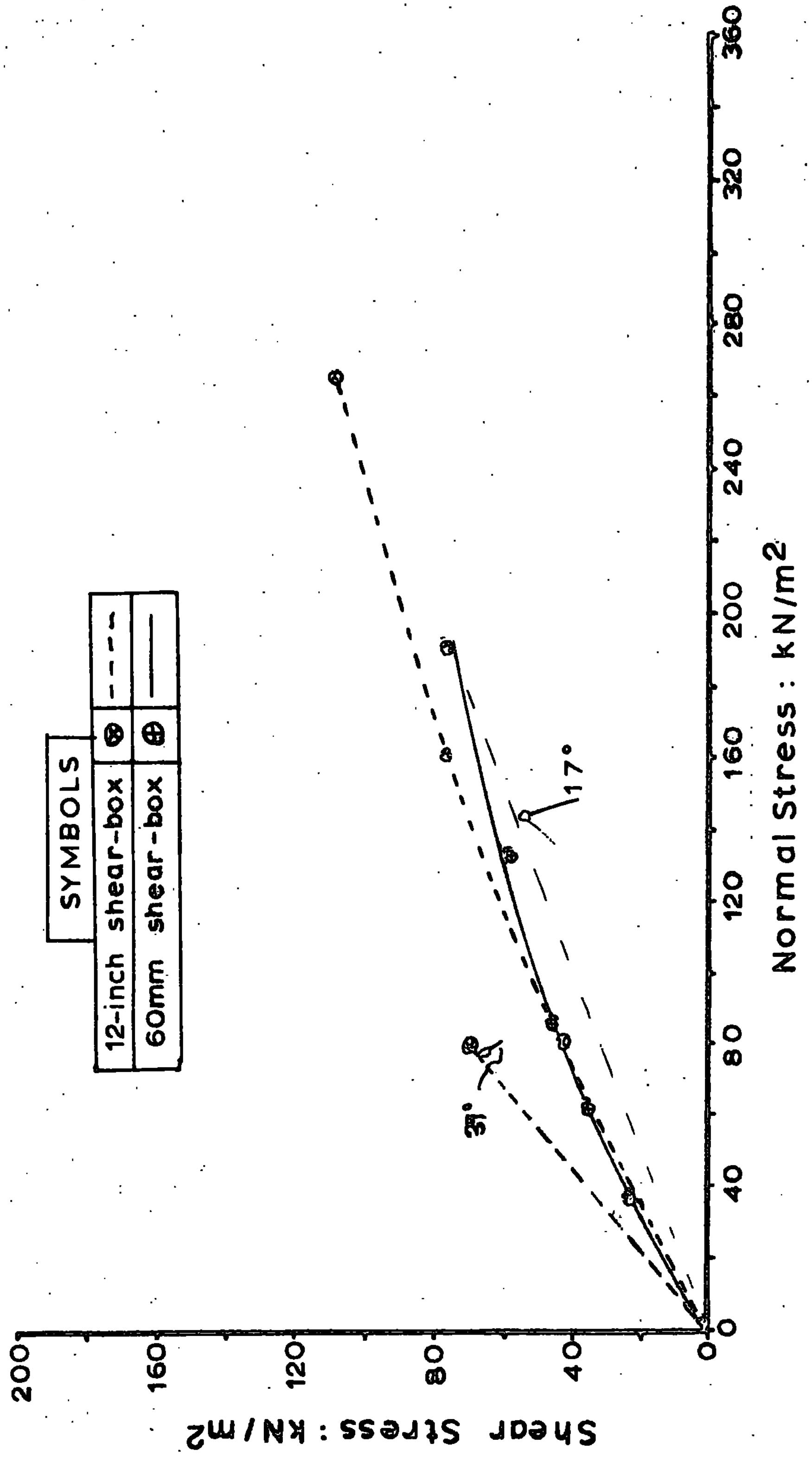


Figure 3.22

Particle size distributions

Orgreave discard

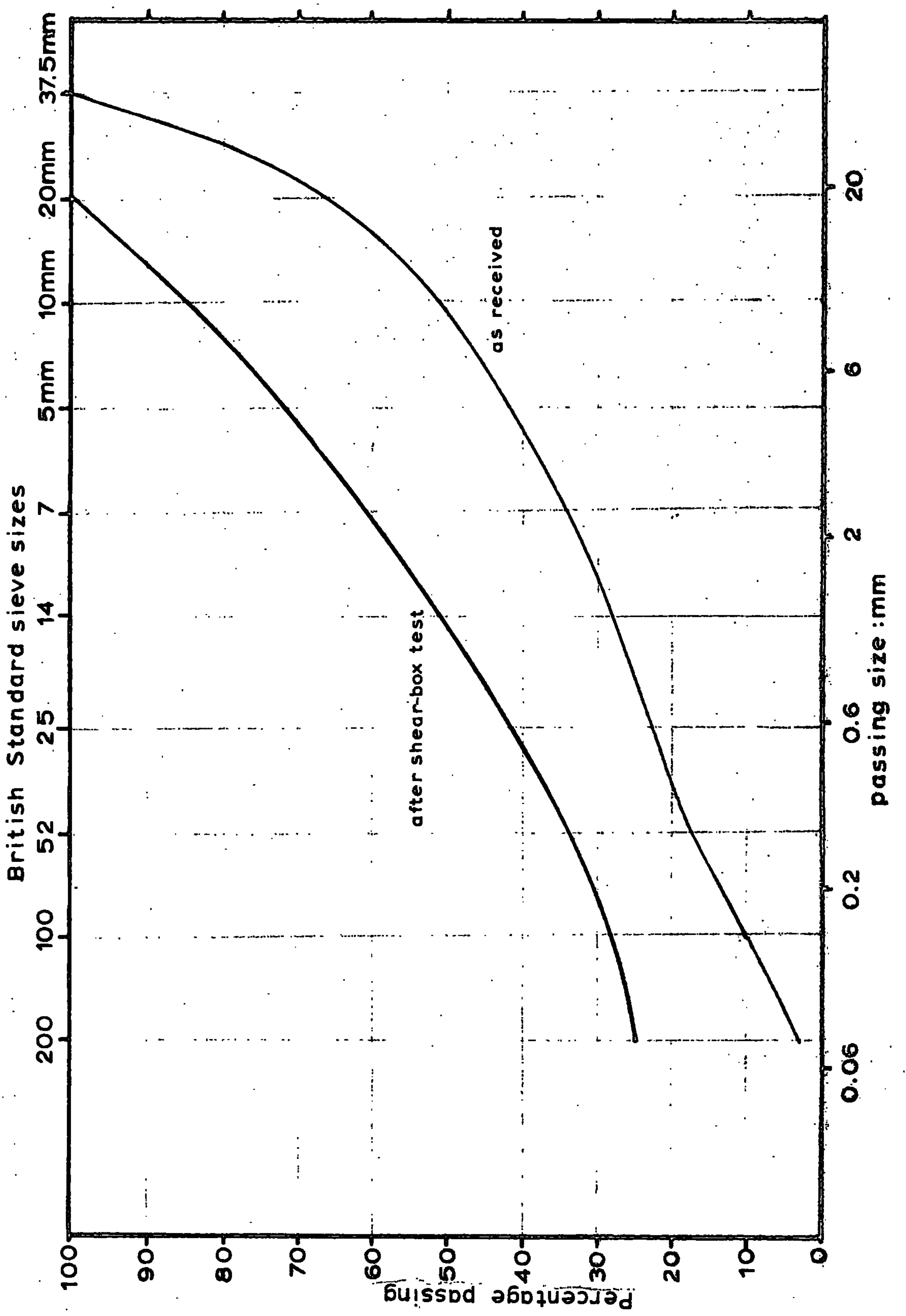


Figure 3.23

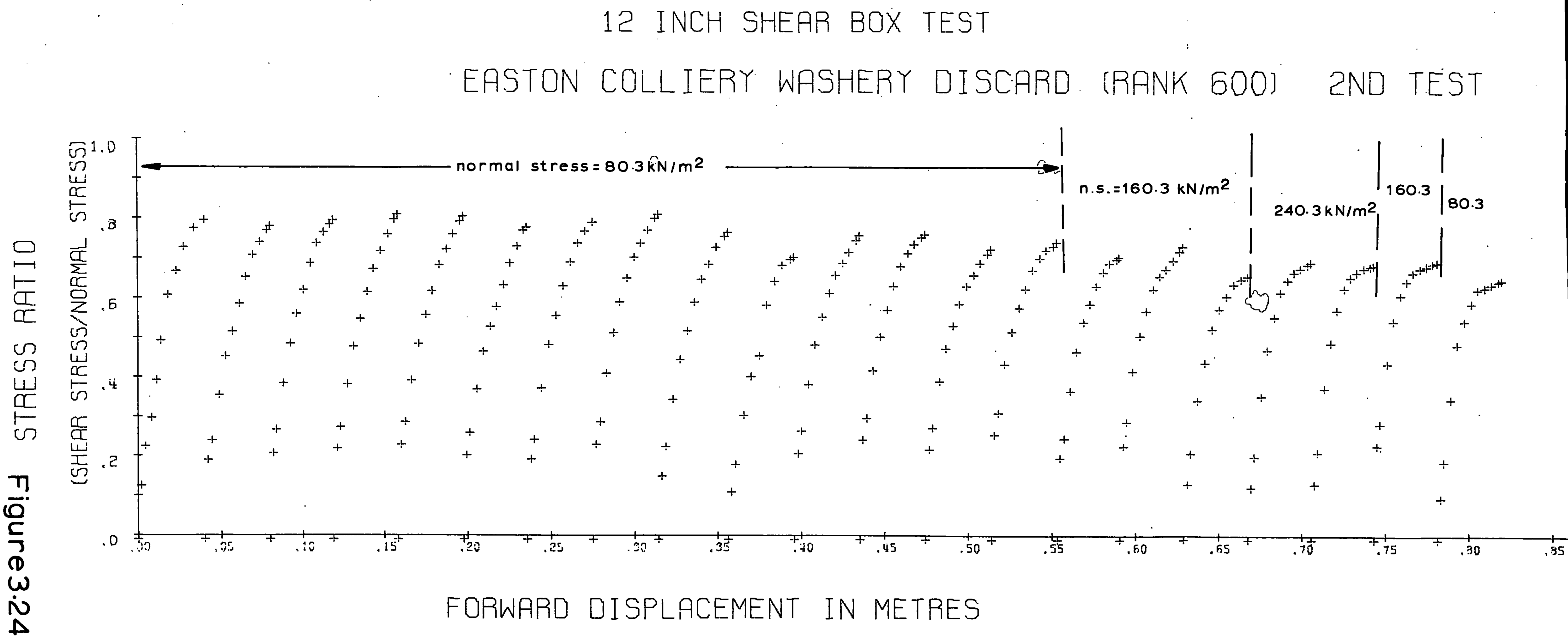

12 INCH SHEAR BOX TEST
EASTON COLLIERY WASHERY DISCARD (RANK 600) 2ND TEST
normal stress = 80.3 kN/m²
n.s. = 160.3 kN/m²
240.3 kN/m²
160.3
80.3
STRESS RATIO
(SHEAR STRESS/NORMAL STRESS)
1.0
.8
.6
.4
.2
.0
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
.75
.80
.85
FORWARD DISPLACEMENT IN METRES

Figure 3.24

Easton discard

60mm shear-box test

stress-displacement curve

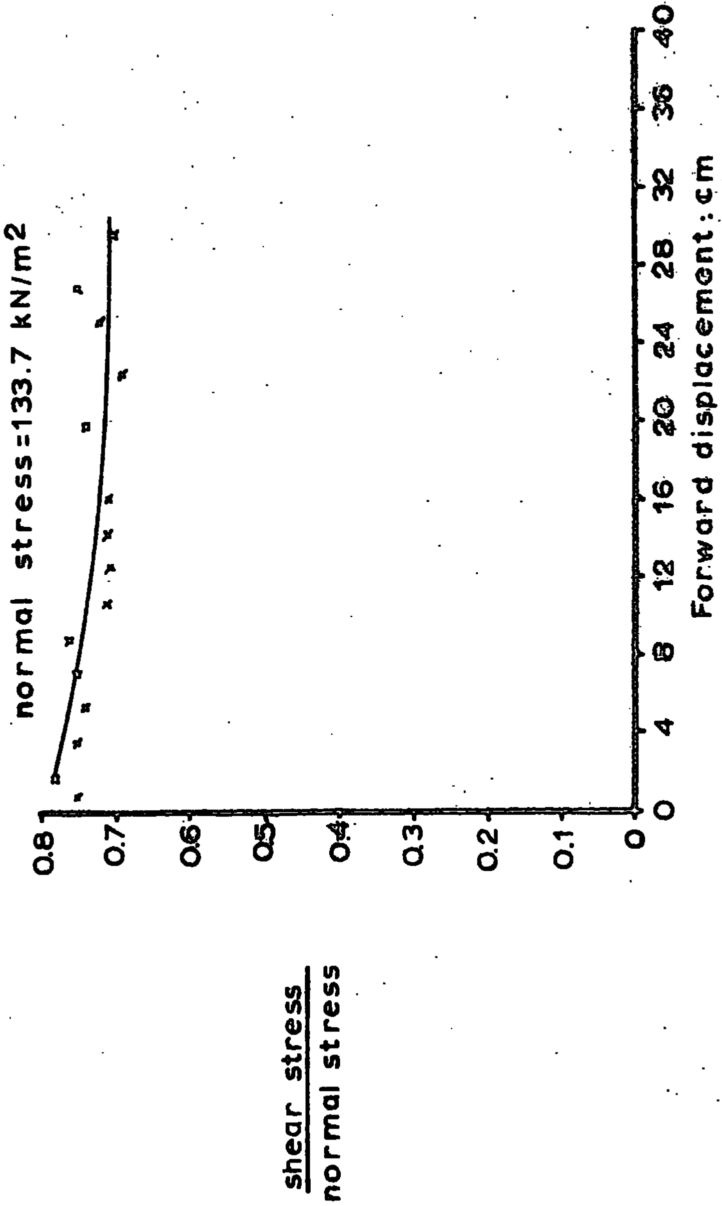


Figure 3.25

Easton discard failure envelopes

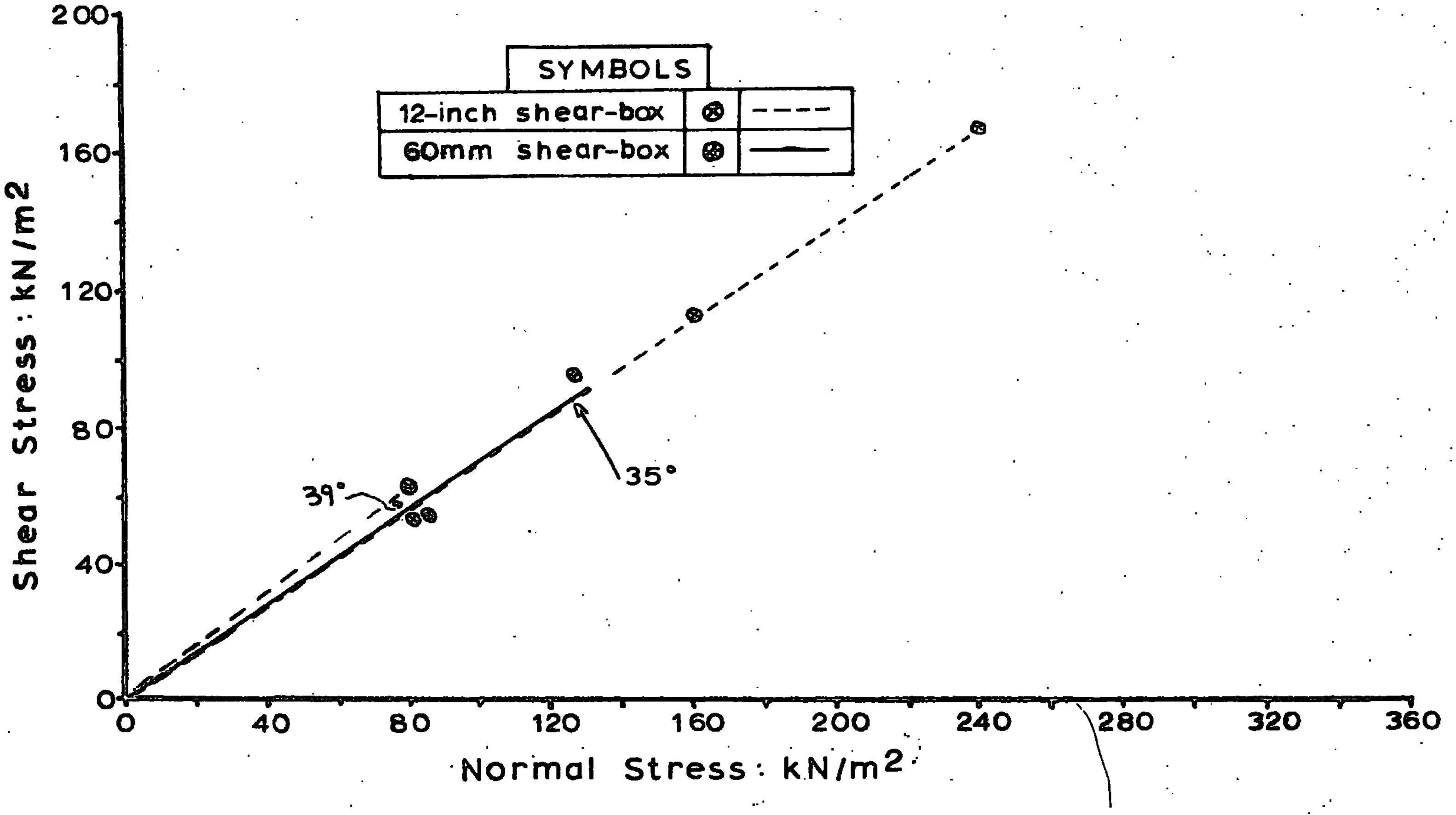


Figure 3·26

Particle size distributions
Easton discard

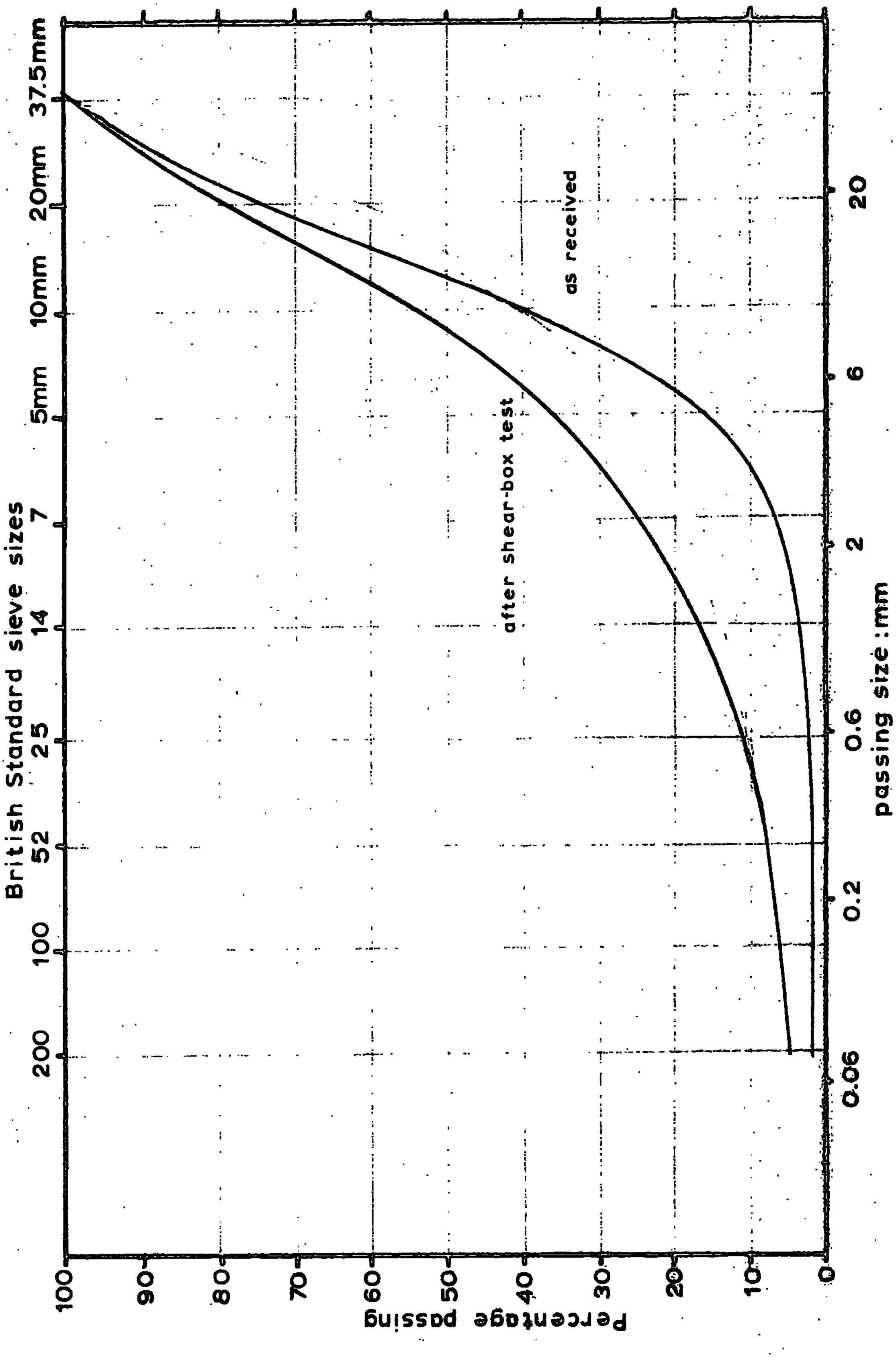


Figure 3.27

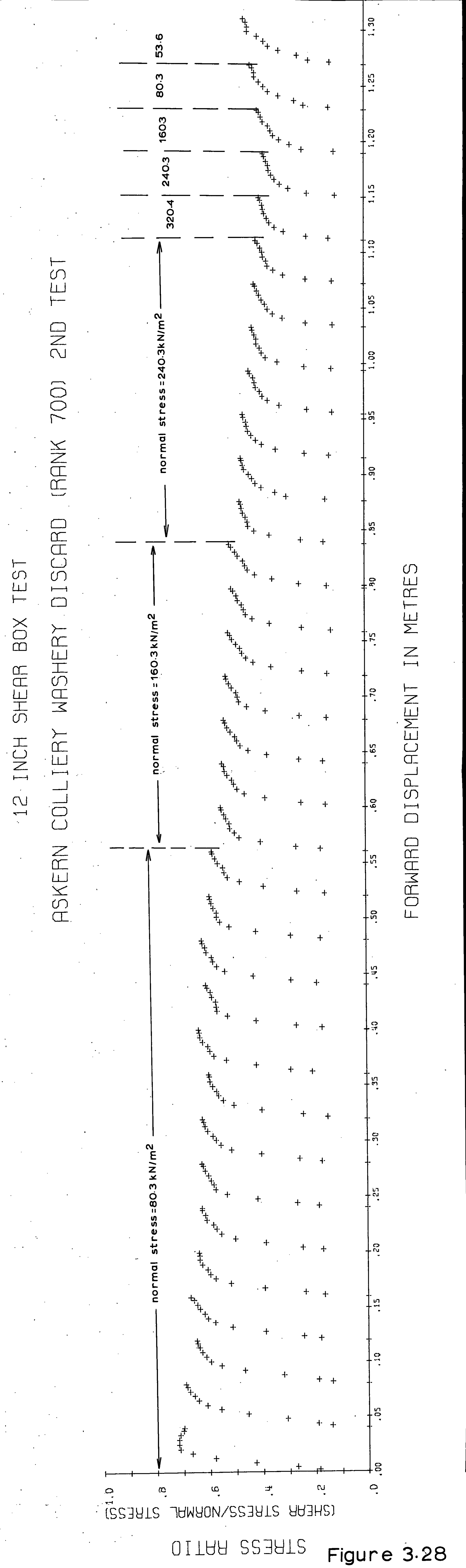

12 INCH SHEAR BOX TEST
ASKERN COLLIERY WASHERY DISCARD (RANK 700) 2ND TEST
normal stress = 80.3 kN/m²
normal stress = 160.3 kN/m²
normal stress = 240.3 kN/m²
320.4
240.3
160.3
80.3
53.6
STRESS RATIO
(SHEAR STRESS/NORMAL STRESS)
1.0
.8
.6
.4
.2
.0
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
.75
.80
.85
.90
.95
1.00
1.05
1.10
1.15
1.20
1.25
1.30
FORWARD DISPLACEMENT IN METRES

Figure 3.28

Askern discard
60mm shear-box test
stress-displacement curve

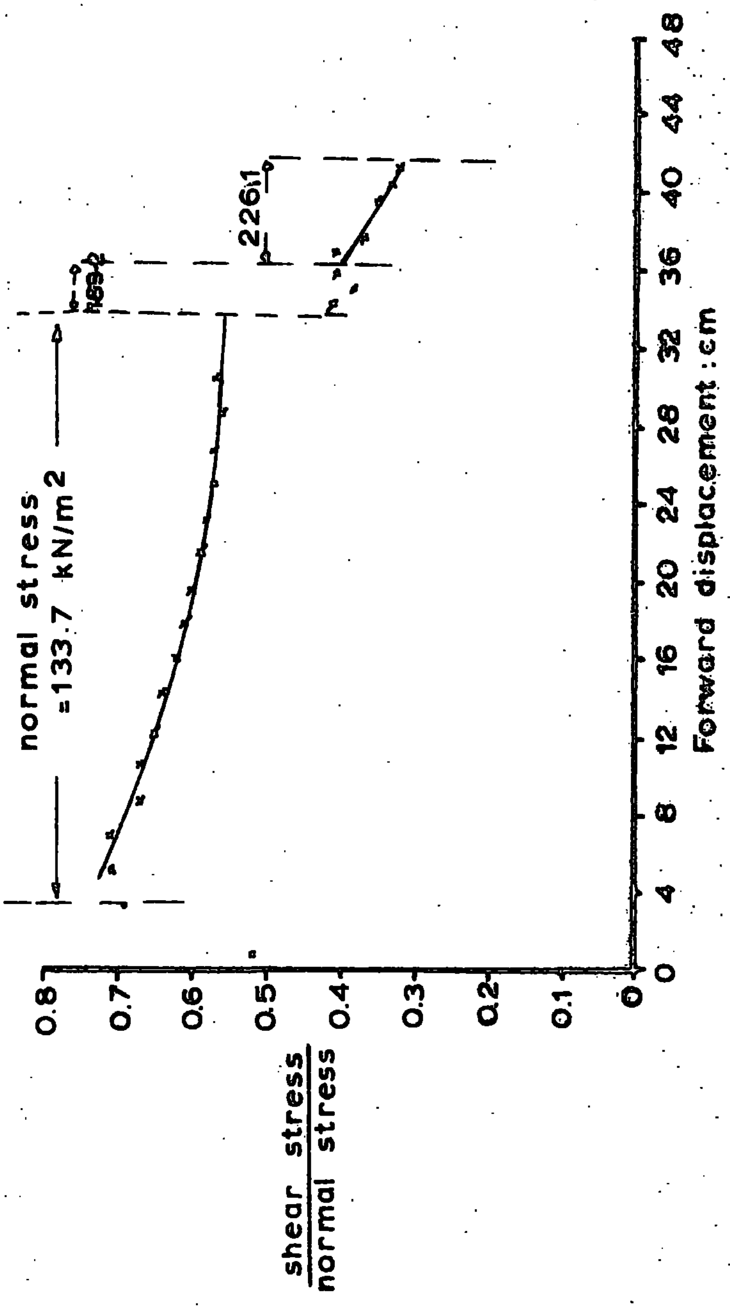


Figure 3·29

Askern discard failure envelopes

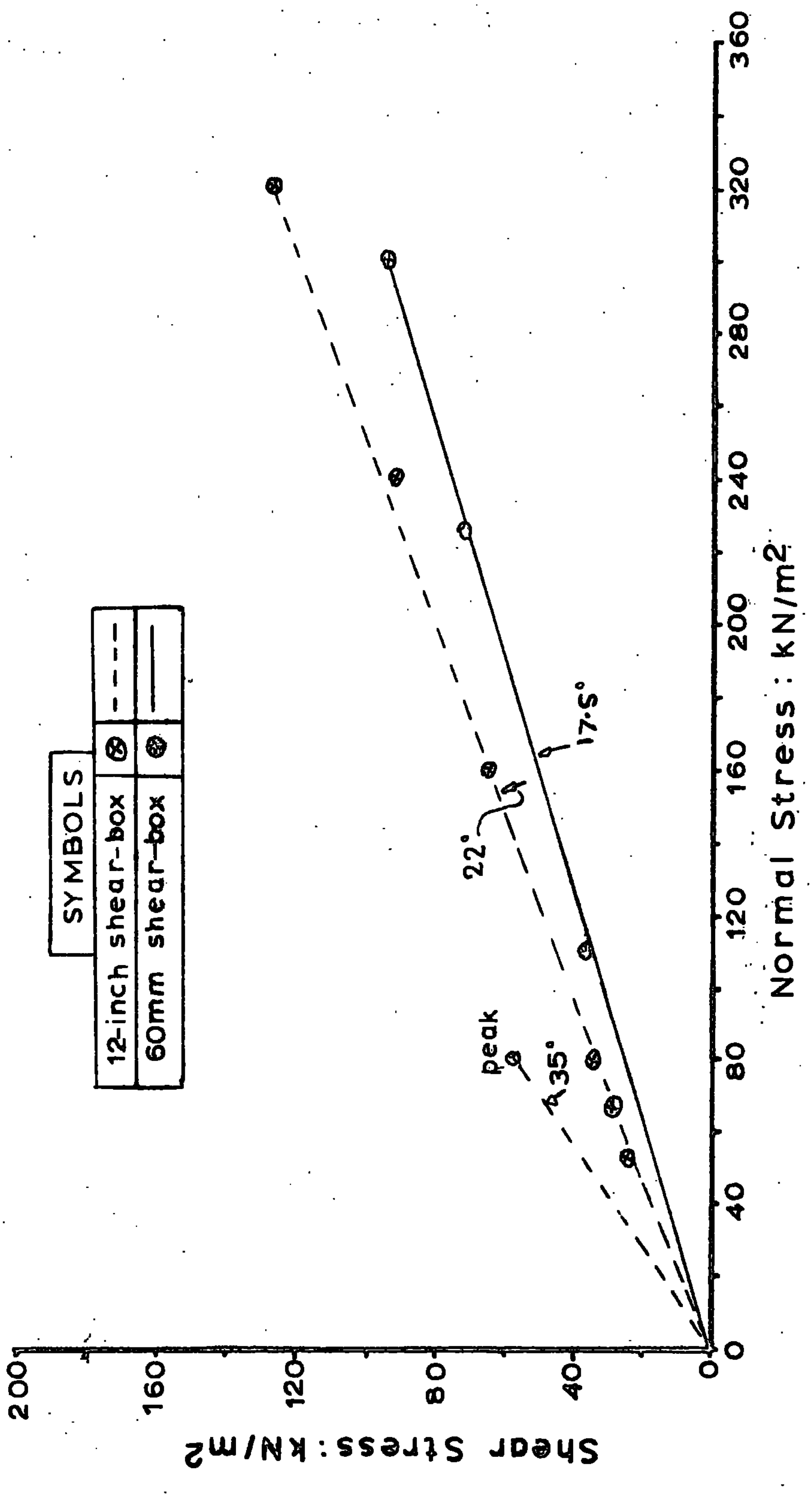


Figure 3·30

Particle size distributions

Askern discard

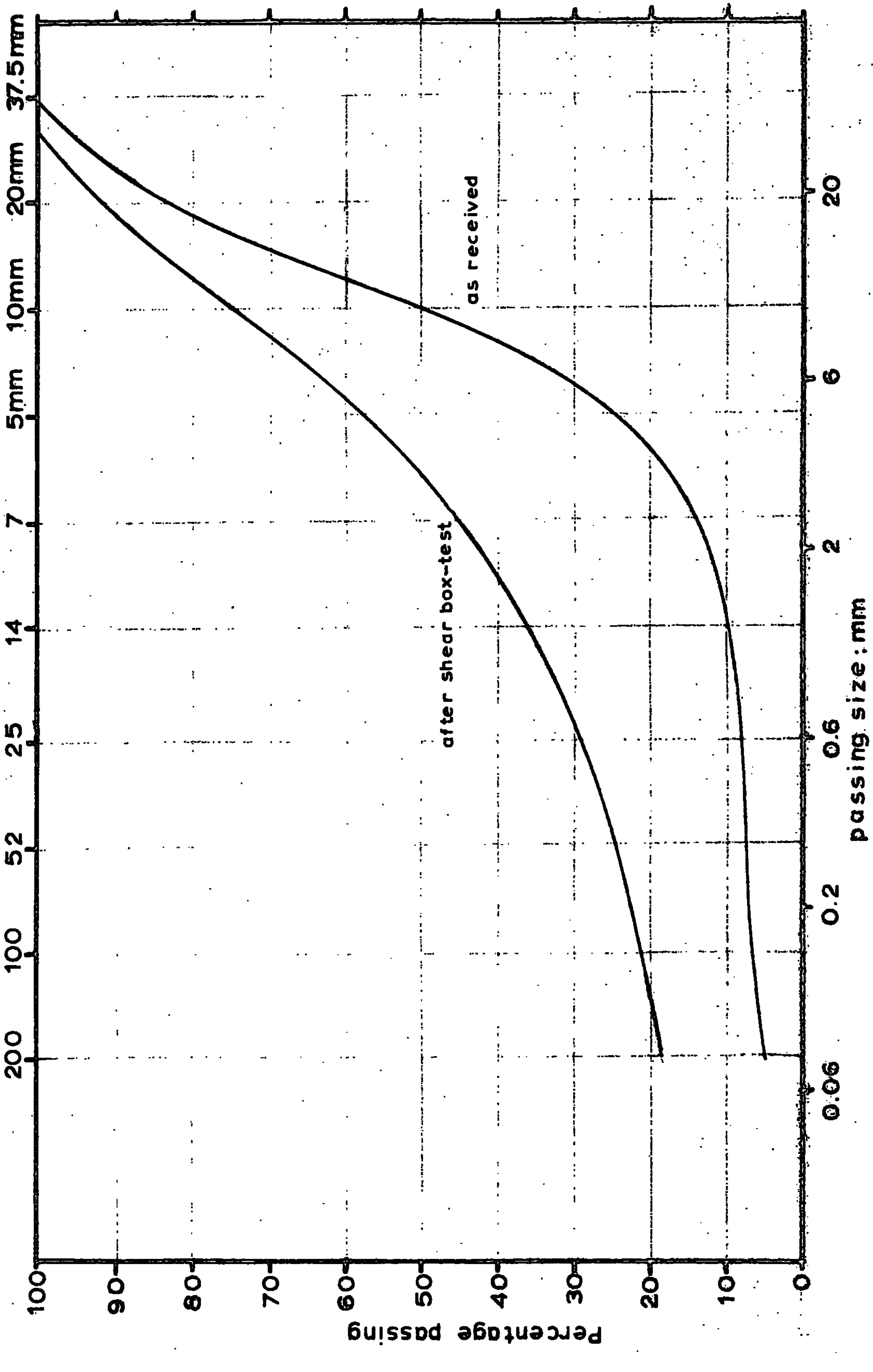


Figure 3.31.

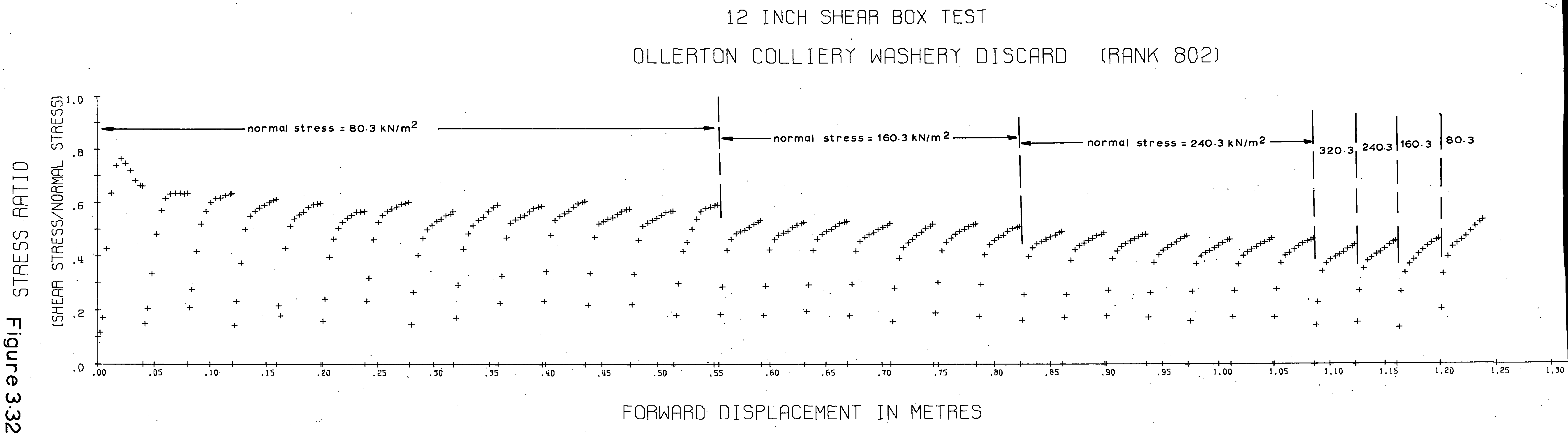

12 INCH SHEAR BOX TEST
OLLERTON COLLIERY WASHERY DISCARD (RANK 802)
STRESS RATIO
(SHEAR STRESS/NORMAL STRESS)
1.0
.8
.6
.4
.2
.0
normal stress = 80.3 kN/m²
normal stress = 160.3 kN/m²
normal stress = 240.3 kN/m²
320.3
240.3
160.3
80.3
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
.75
.80
.85
.90
.95
1.00
1.05
1.10
1.15
1.20
1.25
1.30
FORWARD DISPLACEMENT IN METRES

Figure 3.32

Ollerton discard
60mm shear-box test
stress-displacement curve

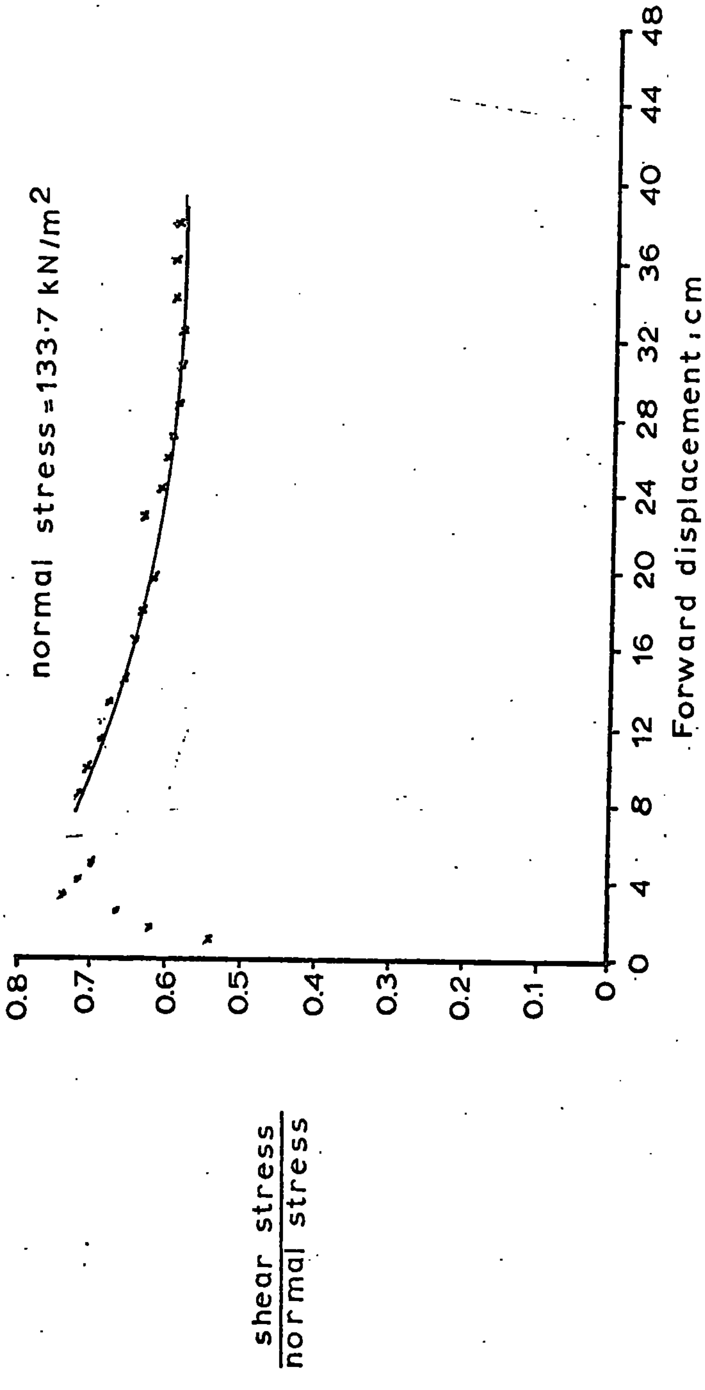


Figure 3·33

Ollerton discard failure envelopes

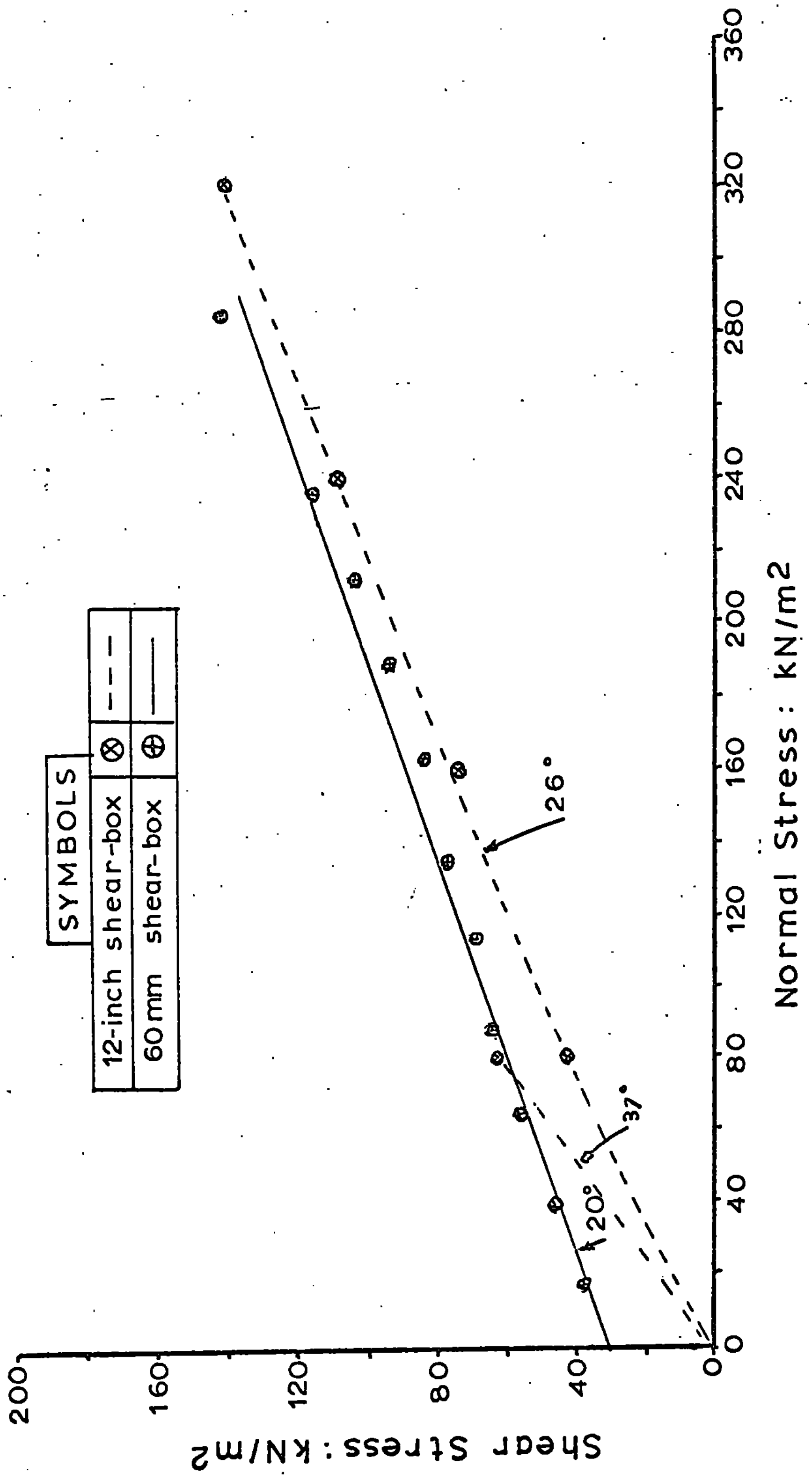


Figure 3.34

Particle size distributions
Ollerton discard

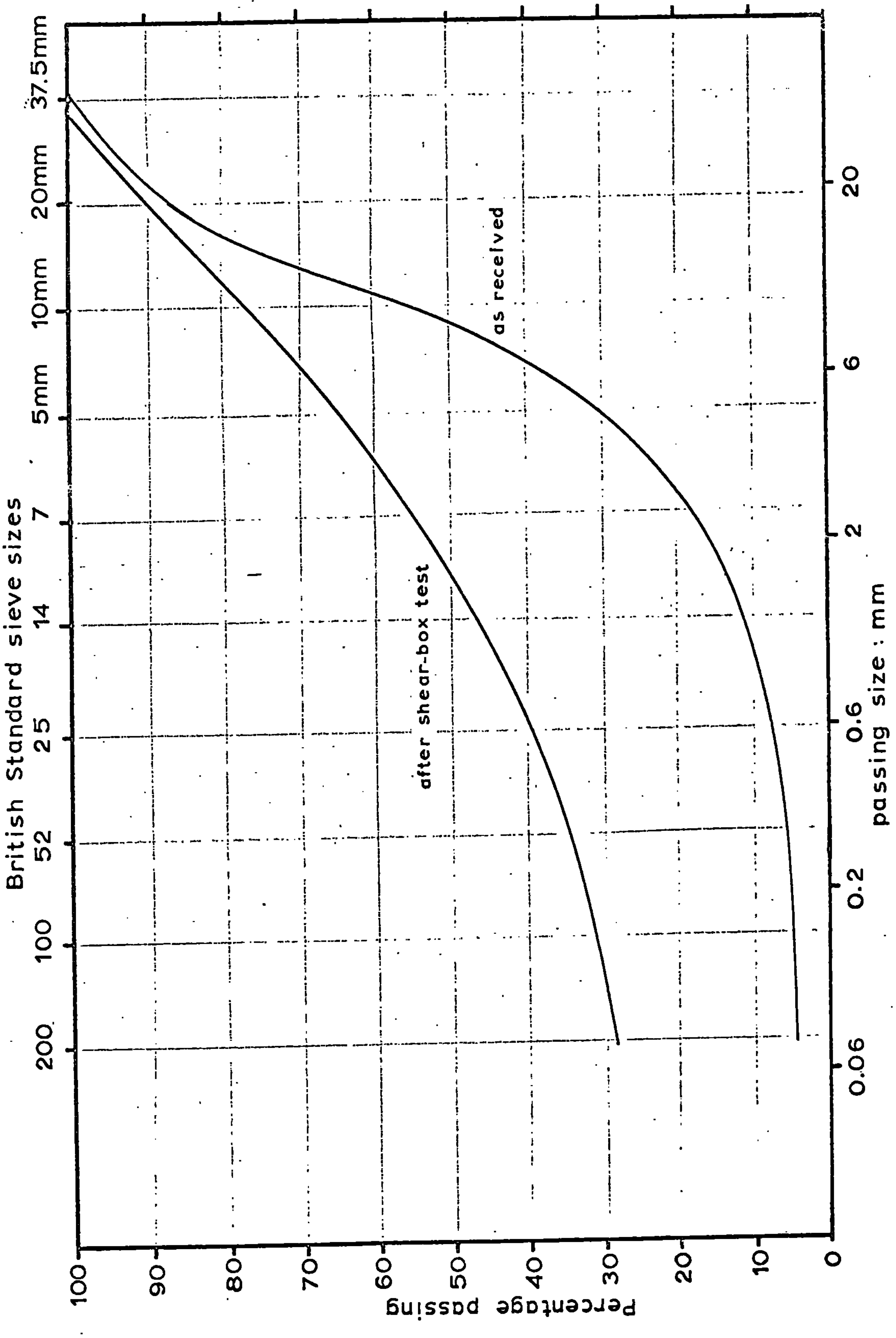


Figure 3.35

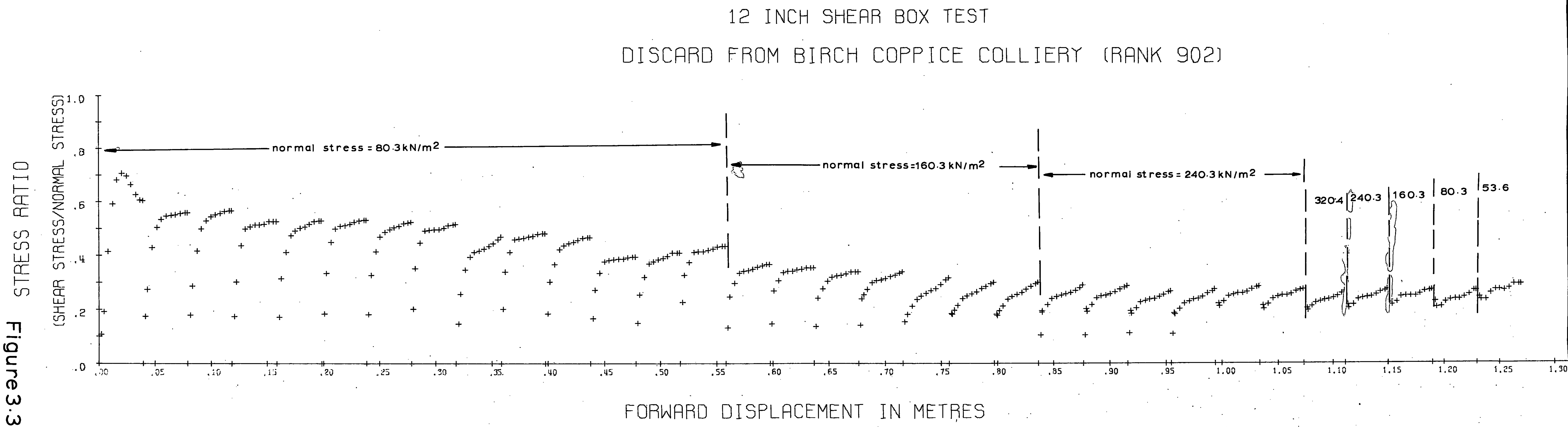

12 INCH SHEAR BOX TEST
DISCARD FROM BIRCH COPPICE COLLIERY (RANK 902)
STRESS RATIO
(SHEAR STRESS/NORMAL STRESS)
1.0
.8
.6
.4
.2
.0
normal stress = 80.3 kN/m2
normal stress=160.3 kN/m2
normal stress = 240.3 kN/m2
320.4
240.3
160.3
80.3
53.6
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
.75
.80
.85
.90
.95
1.00
1.05
1.10
1.15
1.20
1.25
1.30
FORWARD DISPLACEMENT IN METRES

Figure 3.36

Birch Coppice discard
60mm shear-box test
stress-displacement curve

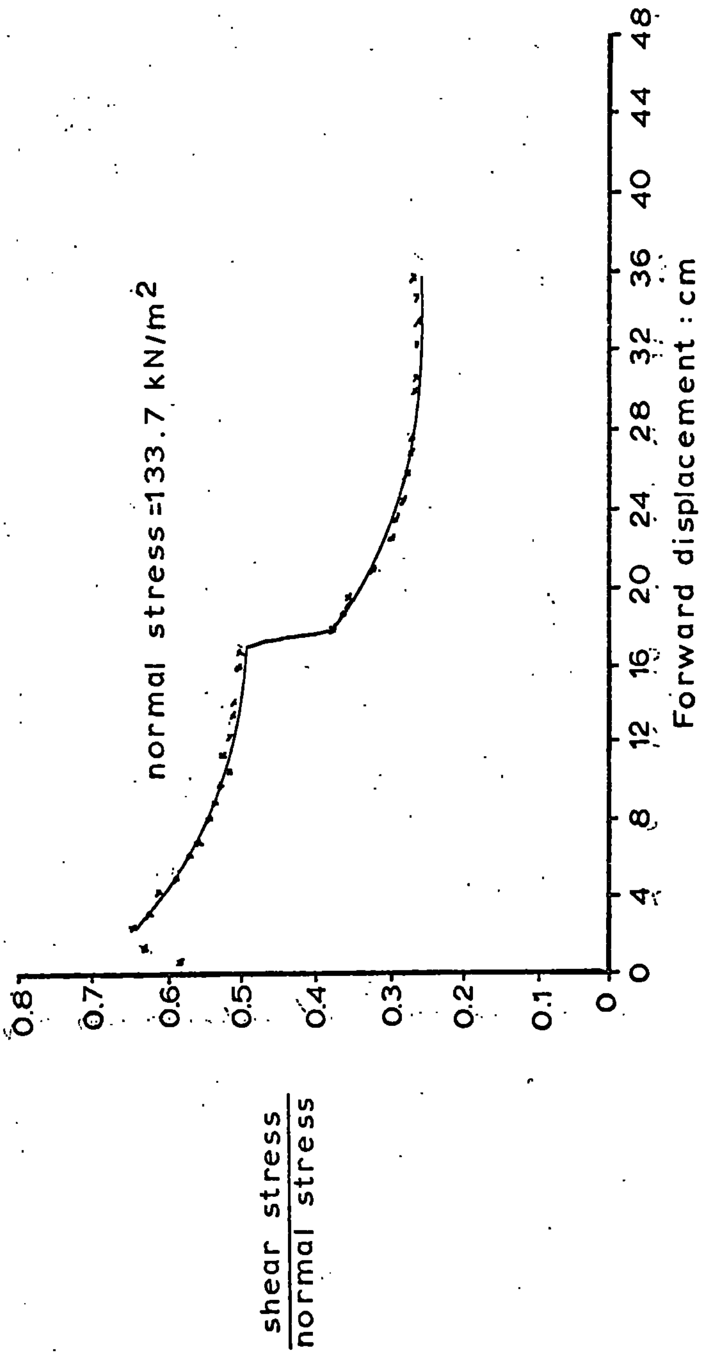


Figure 3·37

Birch Coppice discard failure envelopes

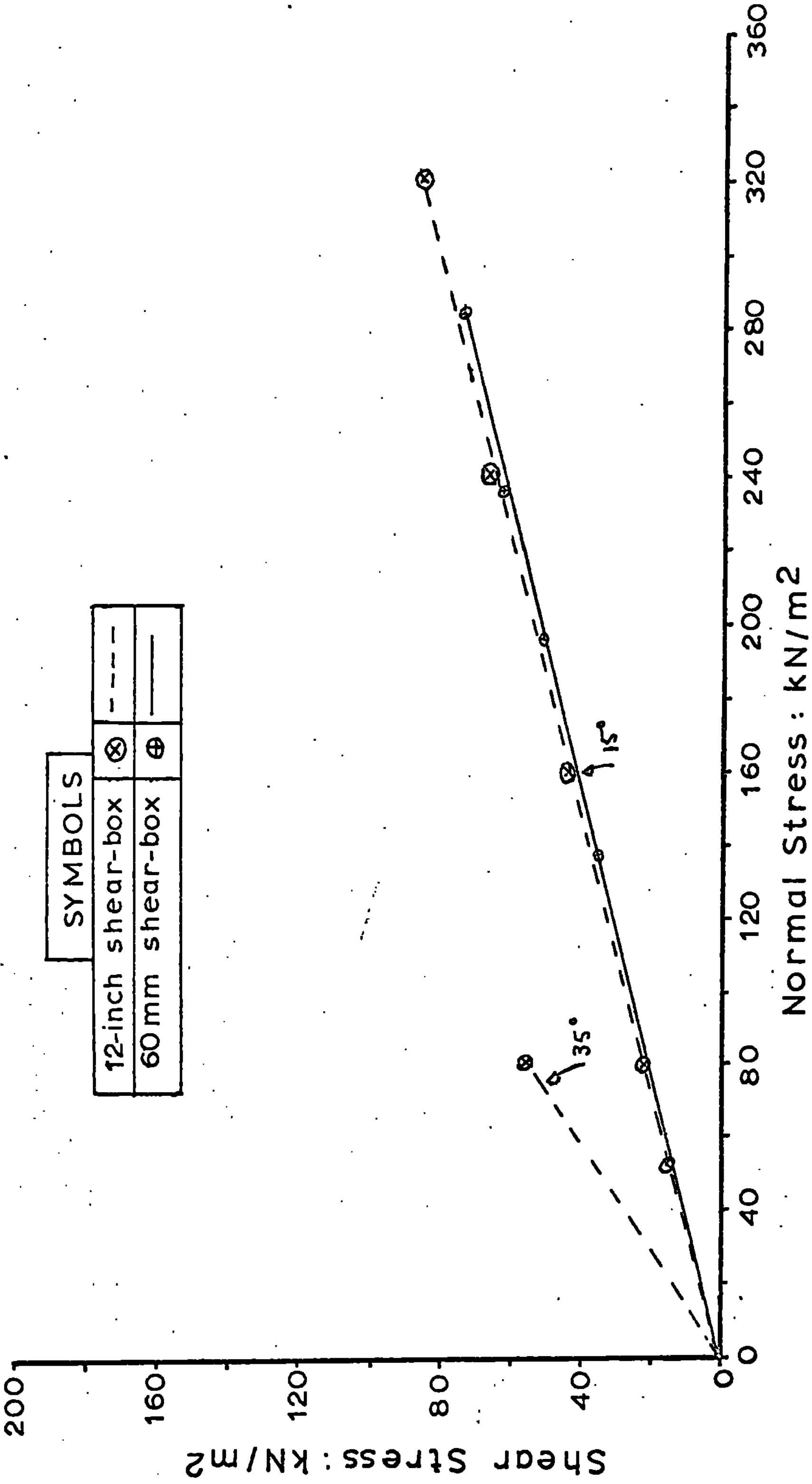


Figure 3.38

Particle size distributions

Birch Coppice discard

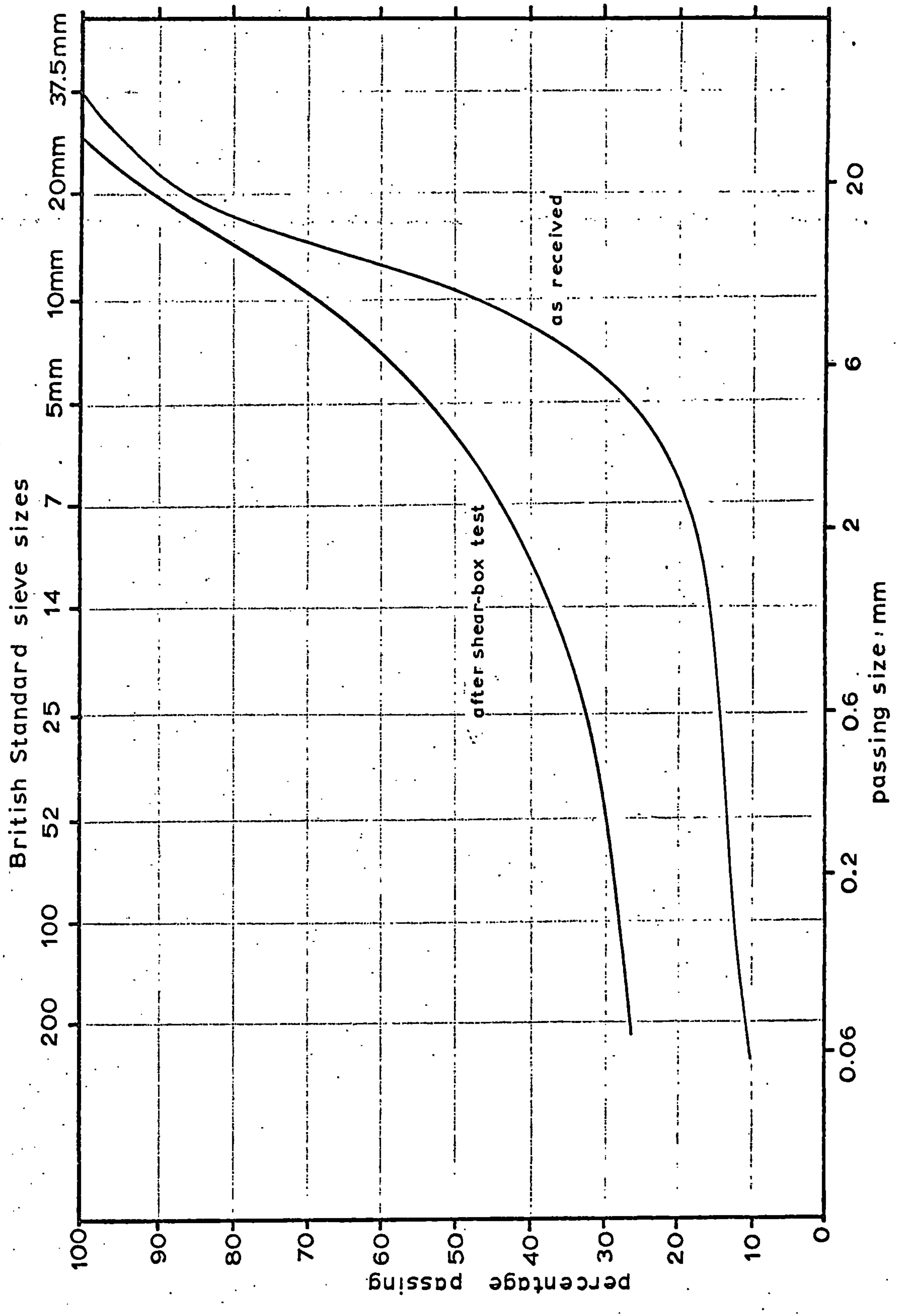


Figure 3.39

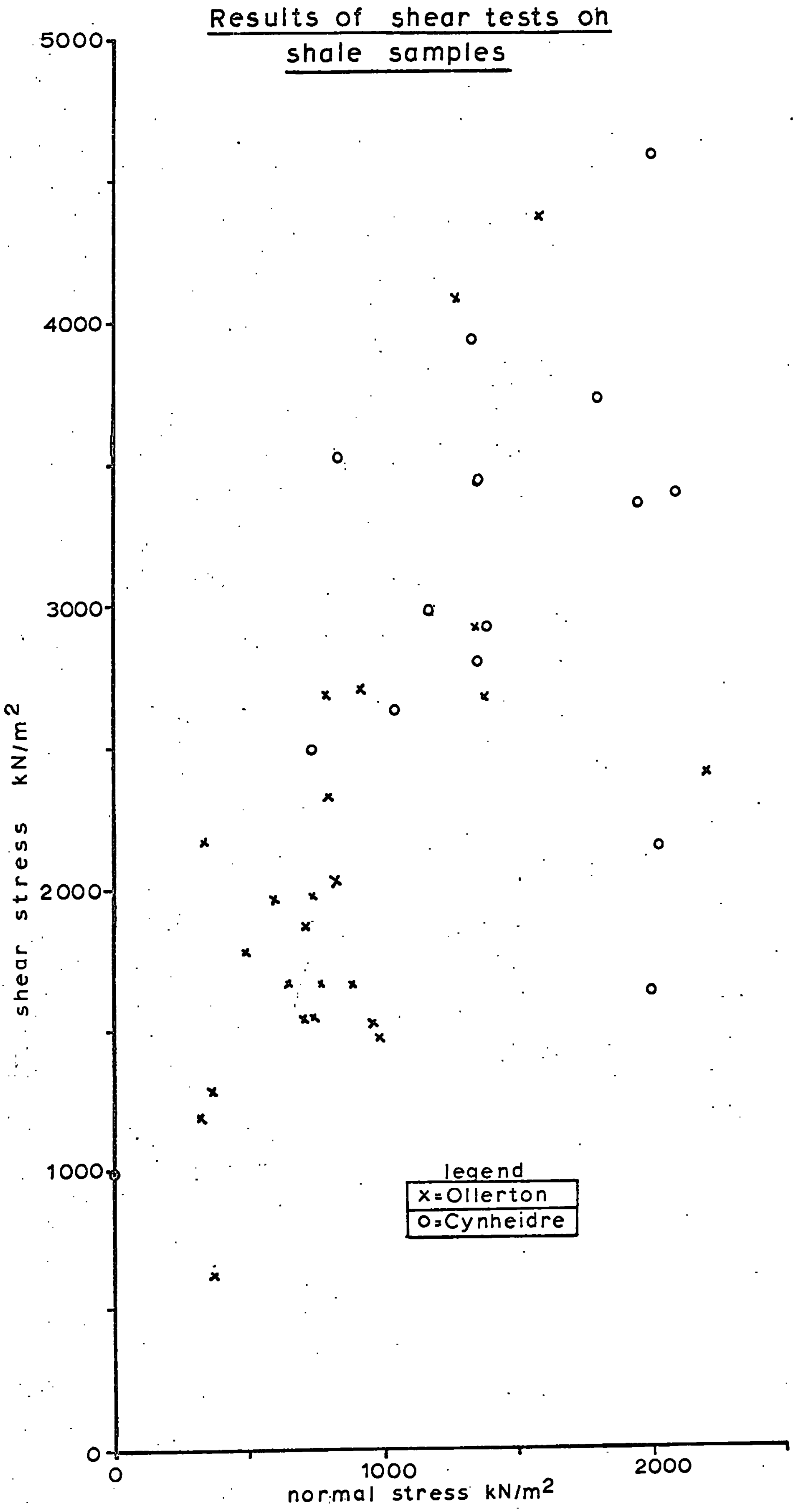

Results of shear tests on shale samples
5000
4000
3000
2000
1000
0
shear stress kN/m²
0
1000
2000
normal stress kN/m²
legend
x=Ollerton
o=Cynheidre

Figure 3.40

Ollerton discard

stress displacement curves for different normal stresses

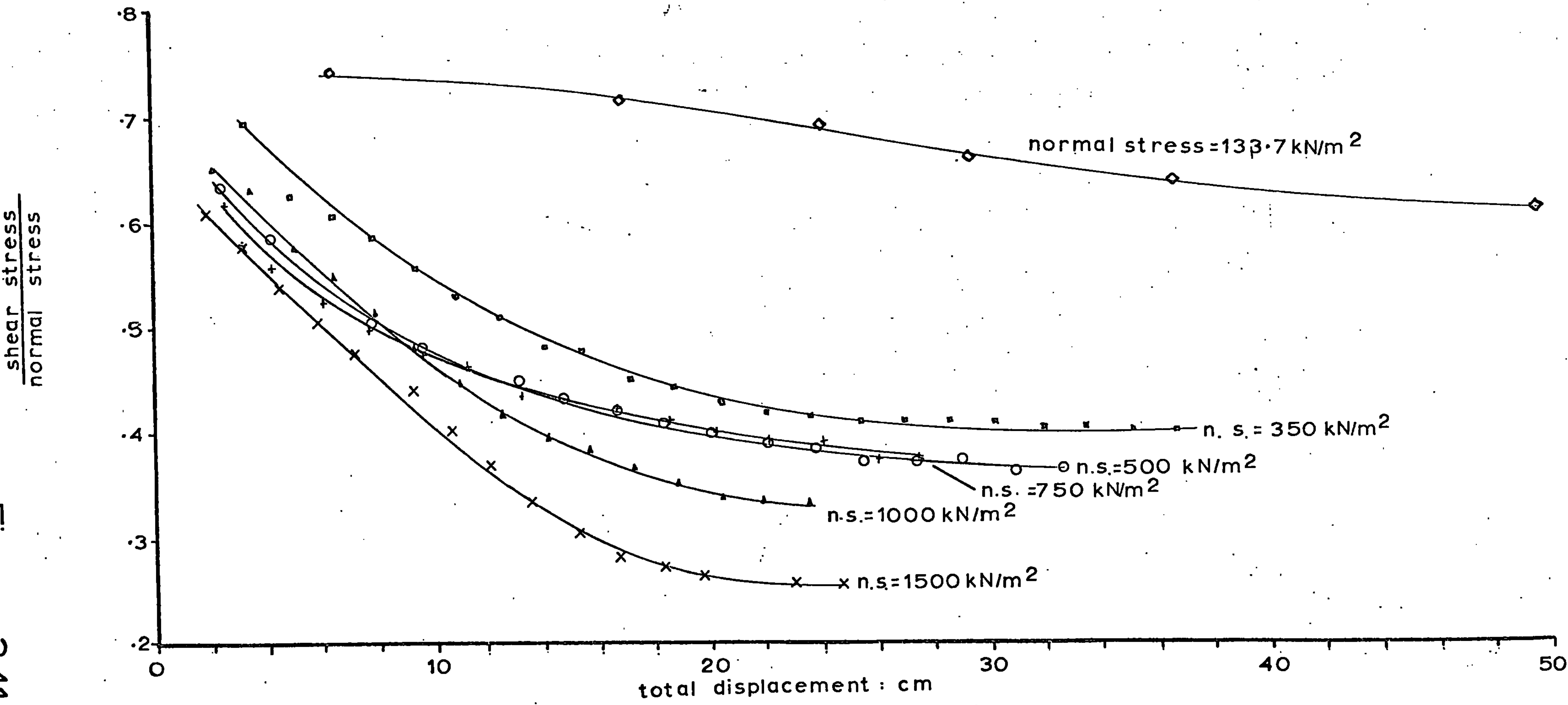


Figure 3.41

Ollerton discard peak and final failure envelopes from tests at different normal stresses

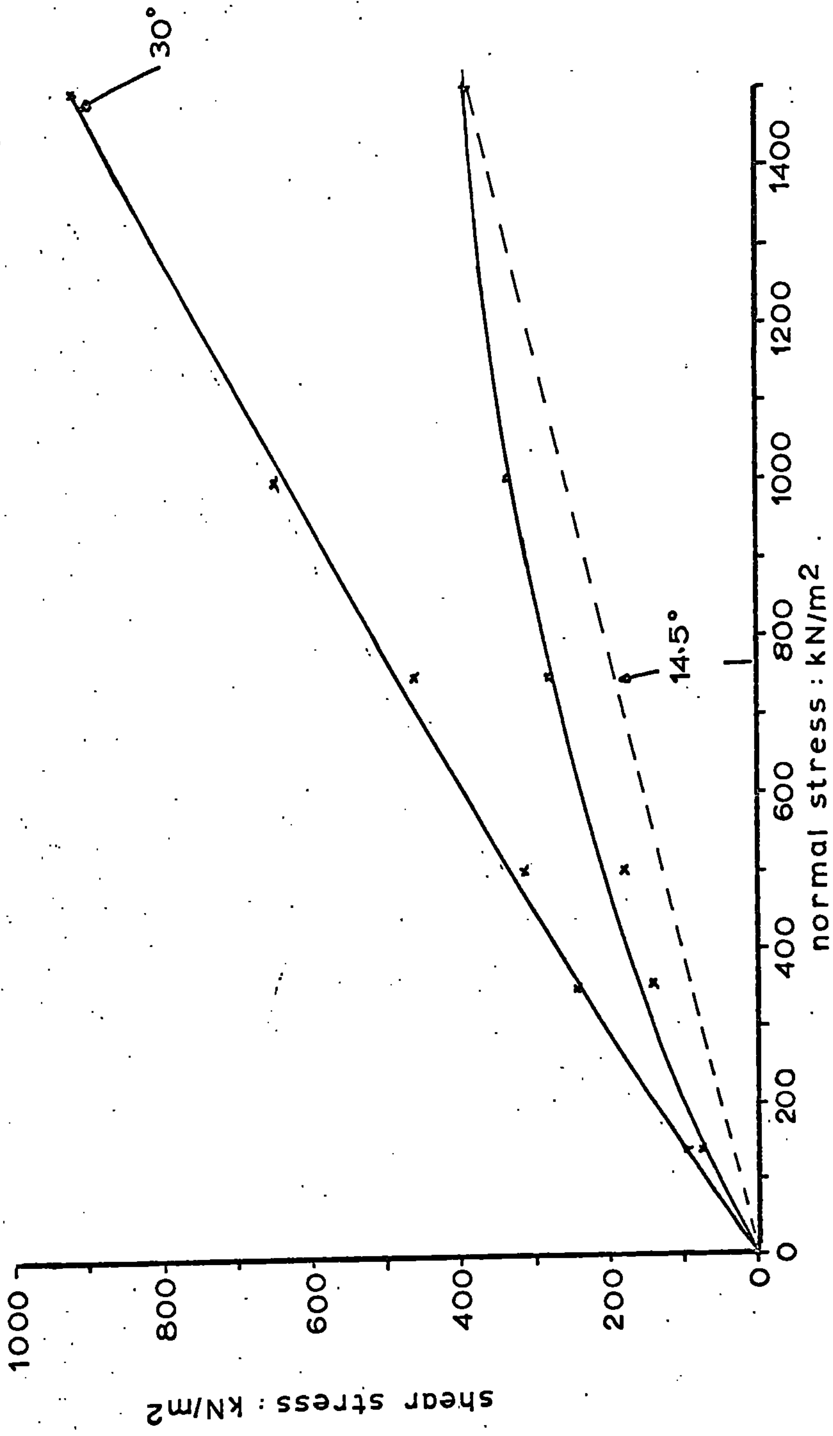


Figure 3.42

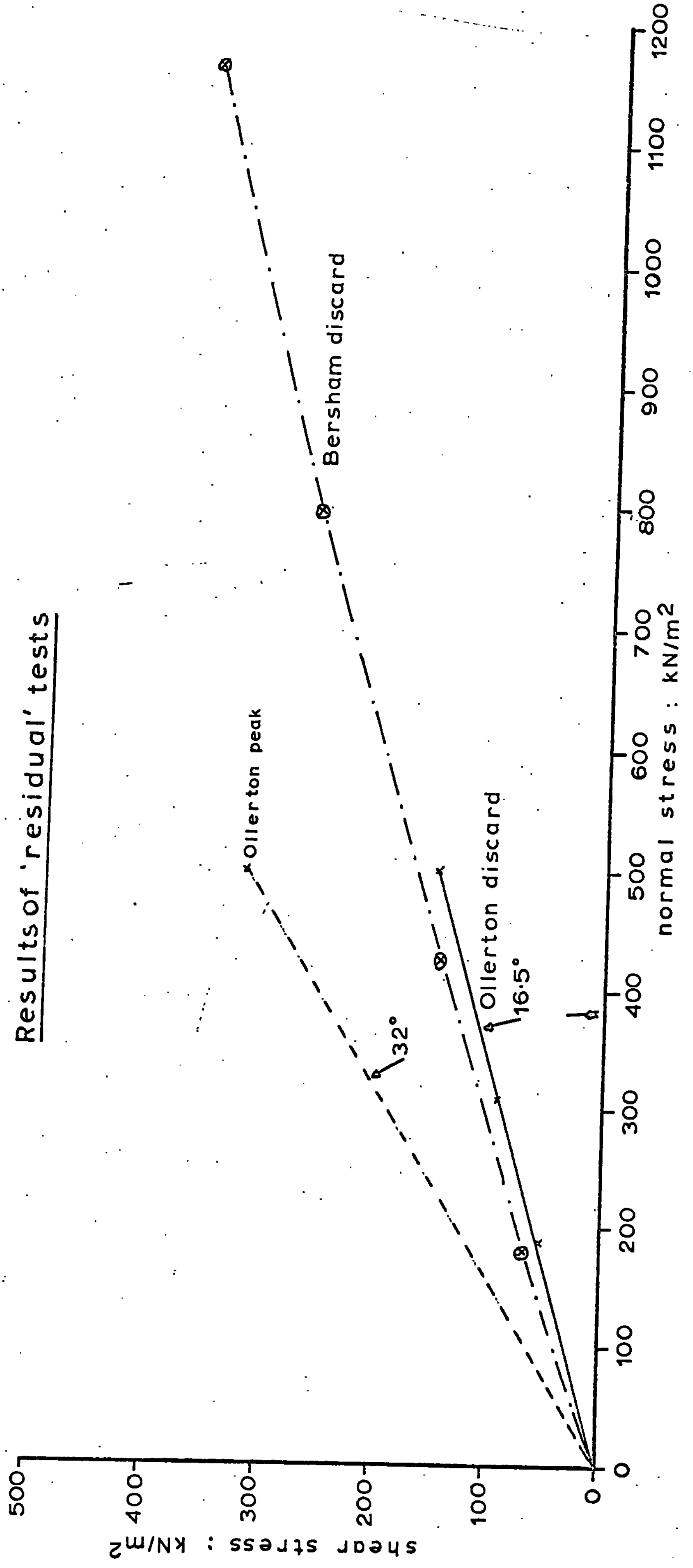

Results of 'residual' tests
shear stress : kN/m²
normal stress : kN/m²
0
100
200
300
400
500
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Ollerton peak
32°
Ollerton discard
16·5°
Bersham discard

Figure 3·43

Ollerton discard particle size distribution after shear-box tests

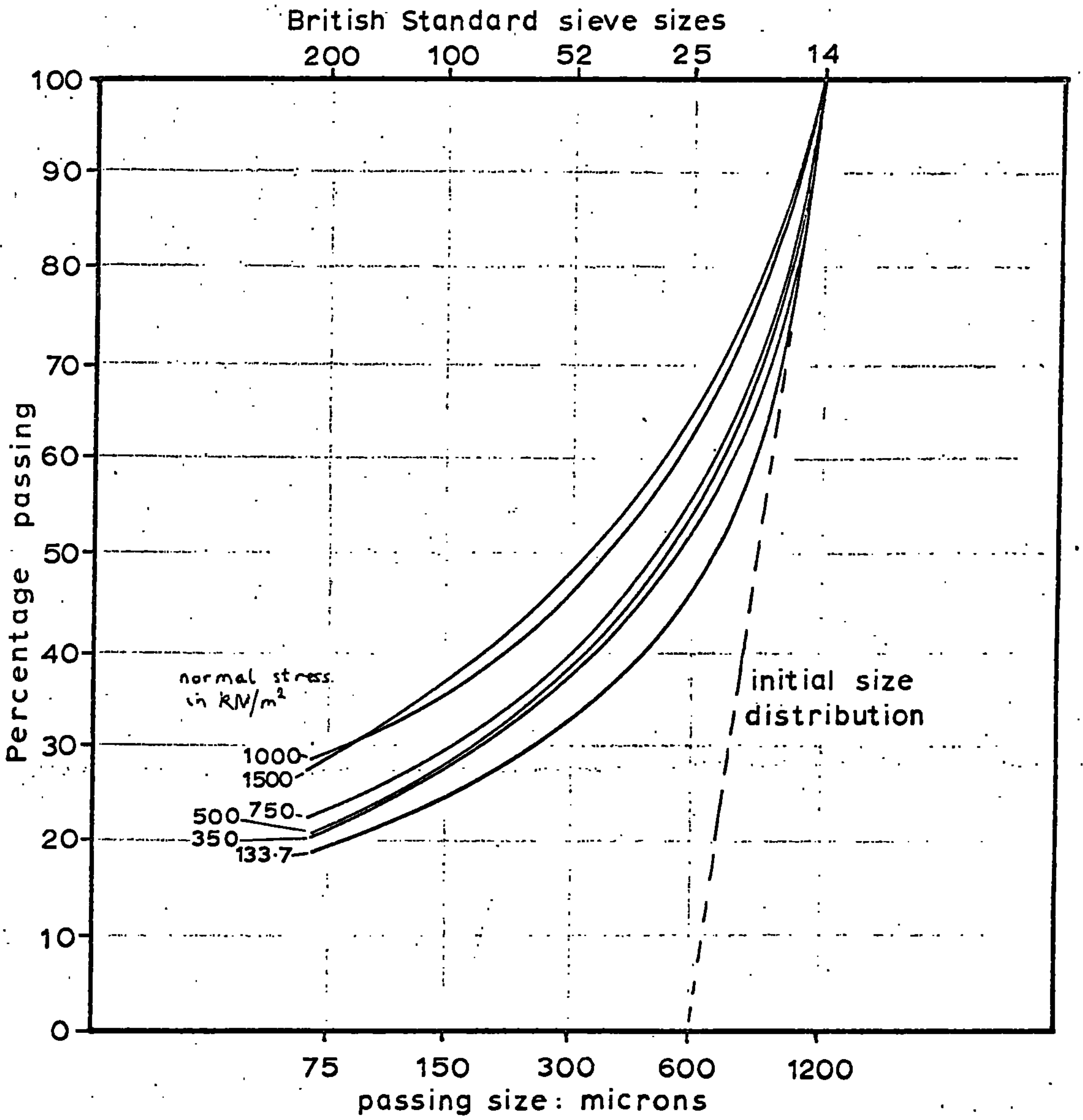


Figure 3.44

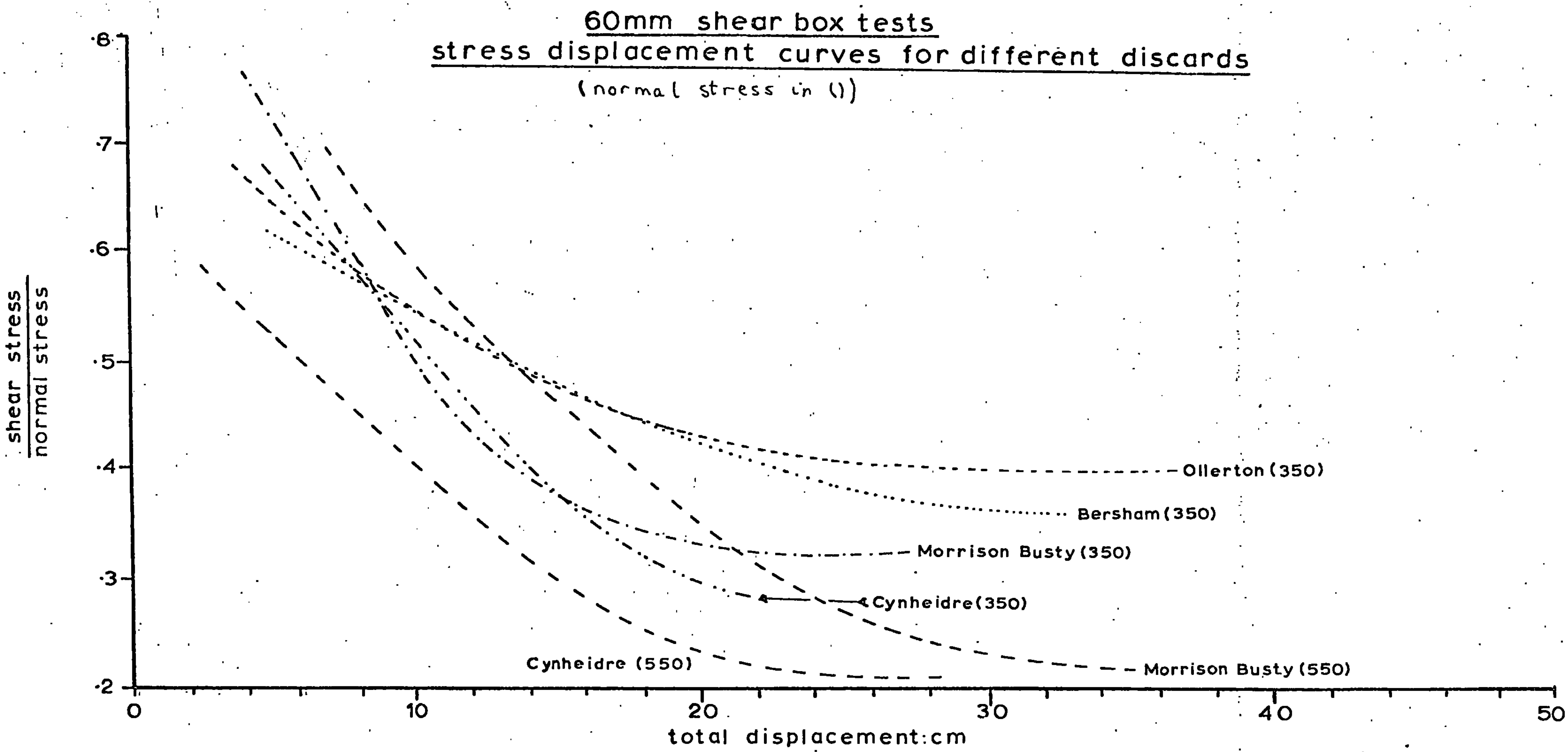

60mm shear box tests
stress displacement curves for different discards
(normal stress in ())

Figure 3·45

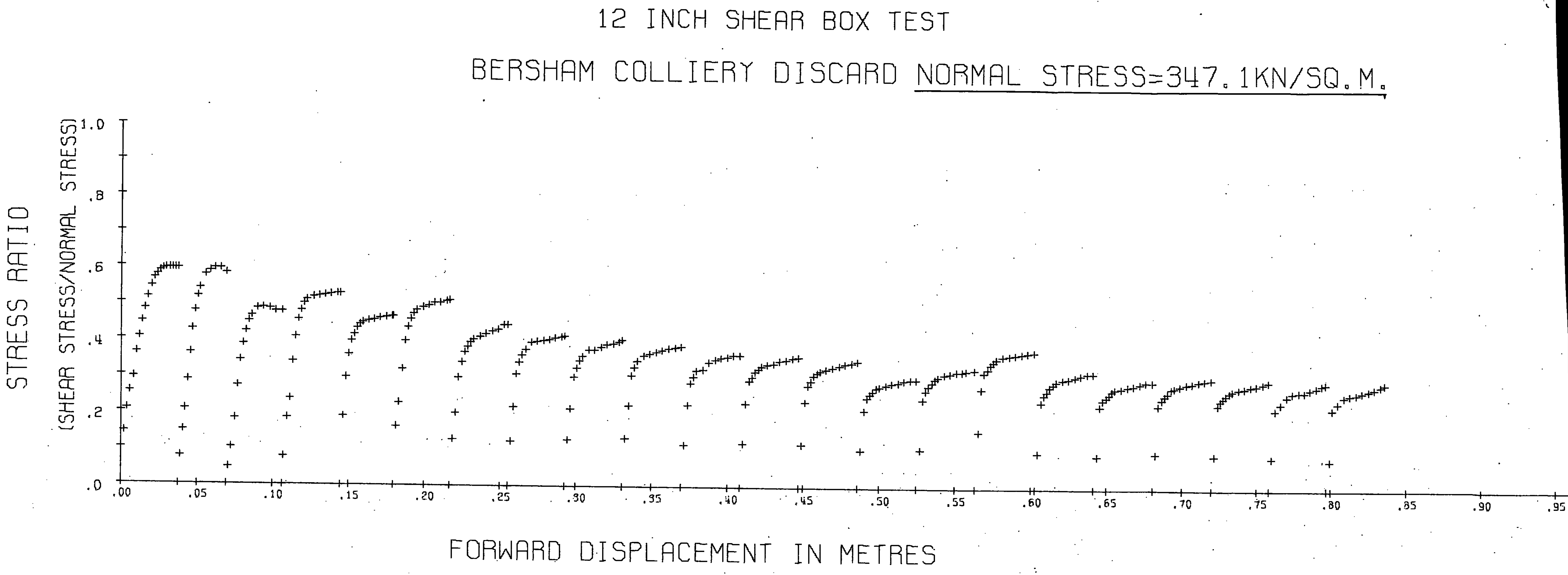

12 INCH SHEAR BOX TEST
BERSHAM COLLIERY DISCARD NORMAL STRESS=347.1KN/SQ.M.
STRESS RATIO
(SHEAR STRESS/NORMAL STRESS)
1.0
.8
.6
.4
.2
.0
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
.75
.80
.85
.90
.95
FORWARD DISPLACEMENT IN METRES

Figure 3.46

CHAPTER 4

CONCLUSIONS

4.1 Shear strength and coal rank

Apart from the possibility of the low rank West Midlands material, there seems to be no specific correlation between the shear strength characteristics of the discards tested and the associated coal rank code numbers. That such a relationship does not exist has not been proven by this research, but it can be stated that other properties are more dominant.

There are two main factors masking any dependency on coal rank:

(i) Variations in the type of material tested (proportions of roof, floor, coal and sandstone);

(ii) The regional mineralogical variations.

The material which proved to have the most durable shear strength properties was the medium rank material from Easton Colliery, Scotland. This material was found to have a very low expandable mixed-layer clay component, and also a high kaolinite content. Both of these properties enhance the resistance of the material to inter-particle breakdown. In addition, the sample tested included a small number of very durable ironstone nodules, and also contained a high proportion of quartz and carbon (34 per cent).

It is not possible to apply the converse to the material which showed greatest reduction of shear strength during the shear tests. This material, from Birch Coppice Colliery, also contained 34 per cent quartz and carbon, of which all but 9 per cent was carbon. The expandable mixed-layer clay content was the highest of those samples tested (22 per cent), but most of the other samples were within 3 or 4 per cent of this value. This sample had a much greater content of fine material in the 'as received' condition when compared with the other samples. In this case it is feasible that coal rank is a dominant factor in so far as the low shear strength properties of this material are concerned.*

The three highest ranking ex-washery samples all showed reasonably similar shear strength characteristics, with peak values for ϕ' varying from 38 to 42°, and the values for ϕ' at the end of the tests varying between 31.5 and 35° (Figures 3.3 and 3.4). With all, the extent of material breakdown was limited (Figures 3.6 and 3.7).

The samples from Askern and Ollerton proved to have similar shear strength characteristics. For the Askern material ϕ' dropped from 35° to 22° during the test, and the corresponding range with the Ollerton discard was from 37° to 26° during the 12-inch shear-box test. With these samples should be included the sample from Orgreave tip (Figure 3.4). Although the rank coding of the Orgreave sample should place it in the high rank group, the mechanical behaviour implies that this sample should be grouped with Askern and Ollerton, to which it is regionally and mineralogically close. There are two possible explanations for this. One is that the rank factor is insignificant, and geographical factors (hence mineralogical composition) are more influential. Alternatively, its shear strength properties were reduced during the period

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* Previous work on 'fine grained' in situ spoil from Littleton spoil heap favours this suggested rank dependence possibility for the low rank West Midlands spoils.

of burial in the heap. The effect of burial in a tip has already been investigated (Taylor and Spears, 1972), and from that investigation it can be concluded that once material is deeply buried in a tip, then breakdown is very limited. It thus seems reasonable to assume that in this case the regional factors are more dominant than coal rank.

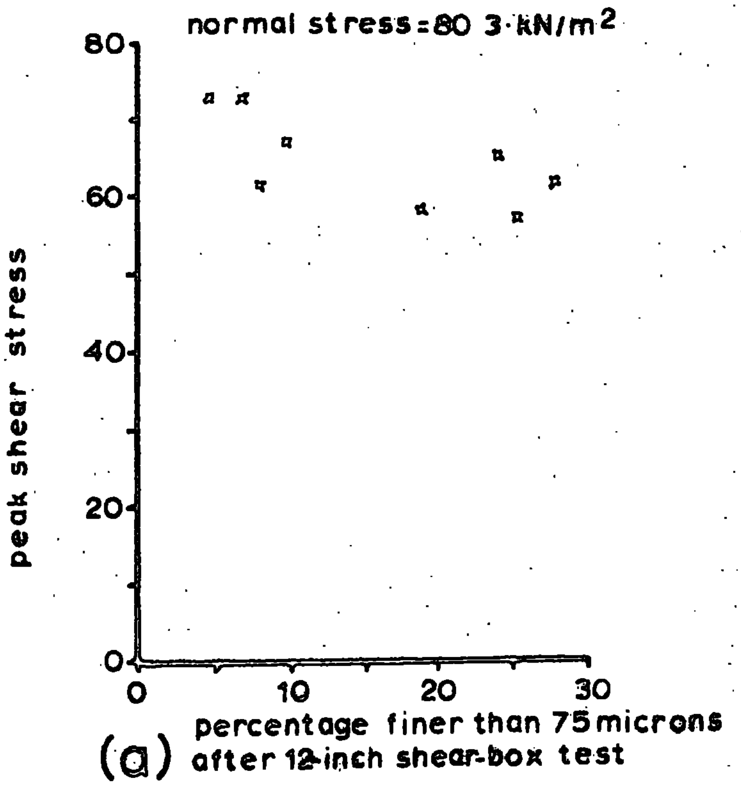
4.2 Shear strength characteristics

This series of tests has brought to attention several pertinent features.

(i) The peak strengths show a much greater degree of uniformity than the regional variations of McKechnie Thomson and Rodin (1972) could be expected to produce (ϕ' varying from 25 to 40°).

(ii) Particle size and grading are significant factors affecting the shear strength properties.

McKechnie Thomson and Rodin (1972) show a reasonable correlation between the peak strength and the proportion of the material passing the B.S. No. 200 sieve (75 microns) at the end of the test. For the current test series, such a correlation is possible (95 per cent confidence level), but statistically, this confidence level is not high. Figure 4.1 (a) shows a graph of peak strength against percentage passing the No. 200 sieve. The statistical correlation (Table 3.6) gave a highly significant (99.9 per cent confidence level) correlation between the degree of shear strength reduction after one metre displacement in the large shear-box and the content of fine material before the test started. This is illustrated in Figure 4.1(b).


normal stress=80 3·kN/m2
peak shear stress
80
60
40
20
0
0
10
20
30
percentage finer than 75 microns after 12-inch shear-box test
(a)

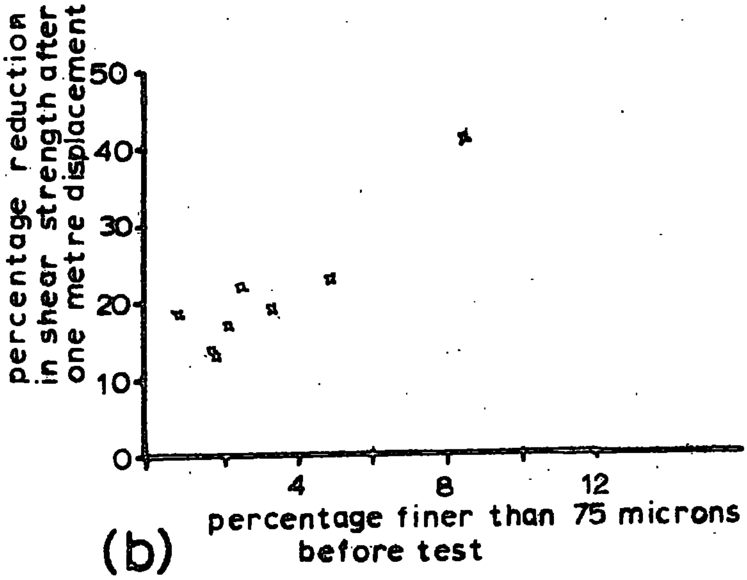

percentage reduction in shear strength after one metre displacement
50
40
30
20
10
0
4
8
12
percentage finer than 75 microns before test
(b)

Figure 4.1

Statistical analyses revealed that other grading parameters, especially the Trask sorting coefficient, correlate closely with the shear strength properties (Table 3.6).

It has been mentioned earlier (Section 3.4) that those samples which contained the greatest proportion of fine material after the tests all exhibited an initial rapid post-peak drop in strength after a displacement of only a few tens of millimetres. It is felt that a material with a high fines content will enable small local shear planes to form. This early formation of small areas of shear plane results in an early drop in shear strength. Further shear strength reduction, however, depends on the breakdown of the intervening regions.

4.2.1 Shear strength reduction

A critical factor in shear strength reduction is the normal stress used in the test. It is apparent from Figure 3.41 that for the material tested there is a transition in the rate of breakdown at a normal stress between 133.7 and 350 kN/m^2. Further increases in normal stress cause little further increase in the rate of breakdown, but instead cause lower values for shear strength through the reduction of the initial peak strength. It is possible that the degree of strength reduction may not have been fully realised due to disturbance of the specimen in a reversing shear-box.

Nevertheless, it is reasonable to suppose that somewhere in the normal stress range of 200 - 300 kN/m^2, material breakdown due to the stresses produced by the shearing action is becoming significant. A few of the earlier small shear-box tests revealed an increased rate of strength reduction at the higher stress levels then used (e.g. Figure 3.29), but by the stage in the test when such stress levels were reached much of the initial breakdown had already taken place.

At the normal stress levels used for most of the initial small shear-box tests, which were mainly below 200 kN/m^2, the principle agent producing material breakdown was inter-particle attrition. An exception to this was the Birch Coppice material, with which extensive shear strength reduction took place, even at the lower normal stress levels. It appears that this material is generally mechanically weaker, and major breakdown can take place under normal stresses of only about 100 kN/m^2, or even lower.

The shape of the stress-displacement curves of Figure 3.41 suggest that it may be possible to closely approximate to these curves by an exponential equation of the form:

$$\text{shear stress} = (SSP-SSR).e^{-kD^p}+SSR$$

where: SSP = peak shear strength
SSR = residual shear strength
k = a constant
D = the displacement
p = a constant

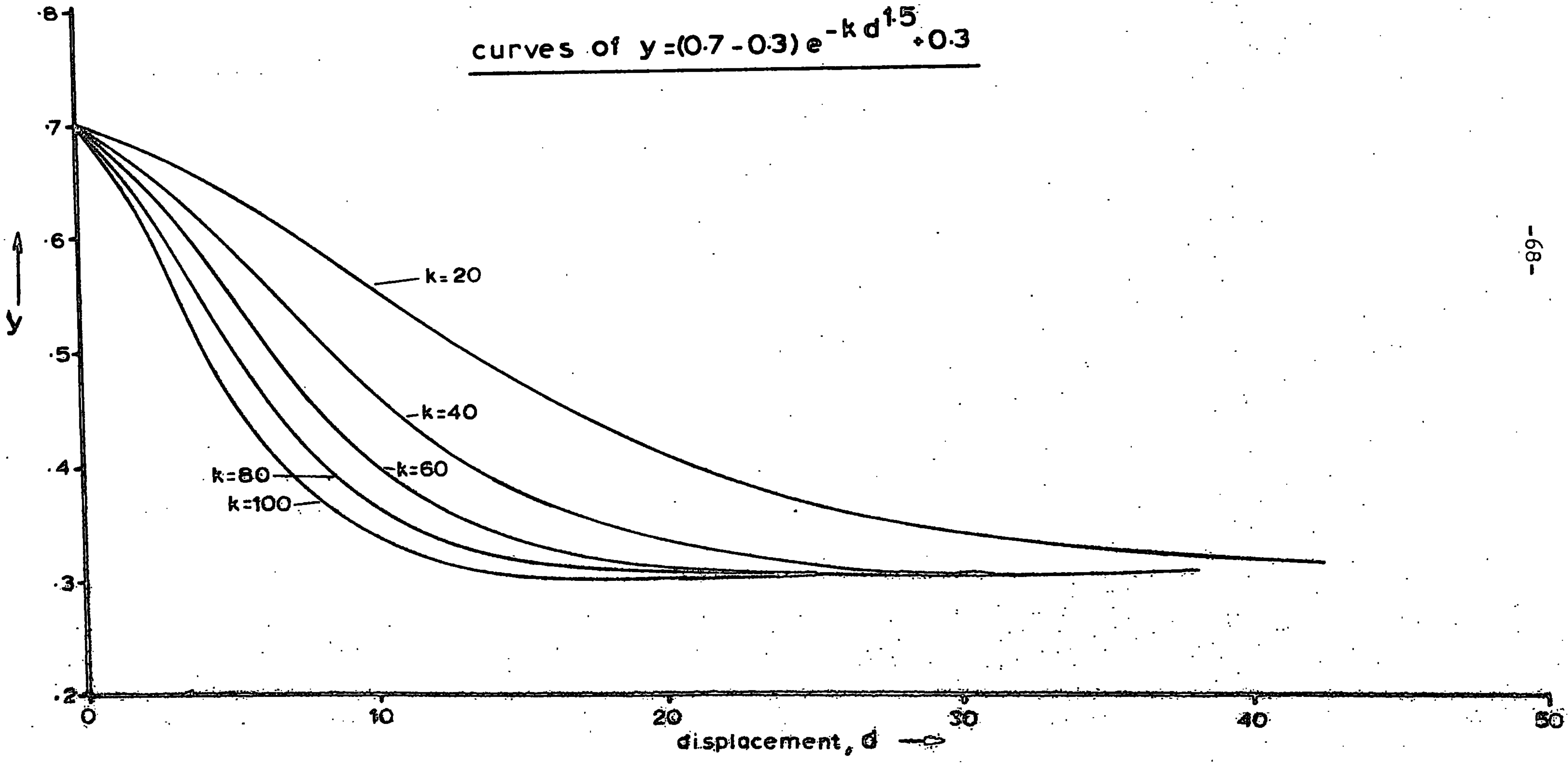
It is possible that either k and/or p may be normal stress-dependent. Further work may show that a basic set of normal stress-dependent constants can be derived for a given material. Further expansion of the basic equation would be needed, however, to allow for the variation of peak stress with normal stress. Figure 4.2 shows the effect of varying the value of k in the above equation. The Figure shows that the curves are of the same basic shape, but are of different amplitudes along the displacement axis. Figure 4.3 illustrates the effect of variations in the value of p. The shape of the curve is altered. Observations suggest that a value of p of between 1 and 2 would be of the correct order.

4.2.2 Shear plane development

The range of test results obtained have provided some indication of the processes involved in shear plane development.

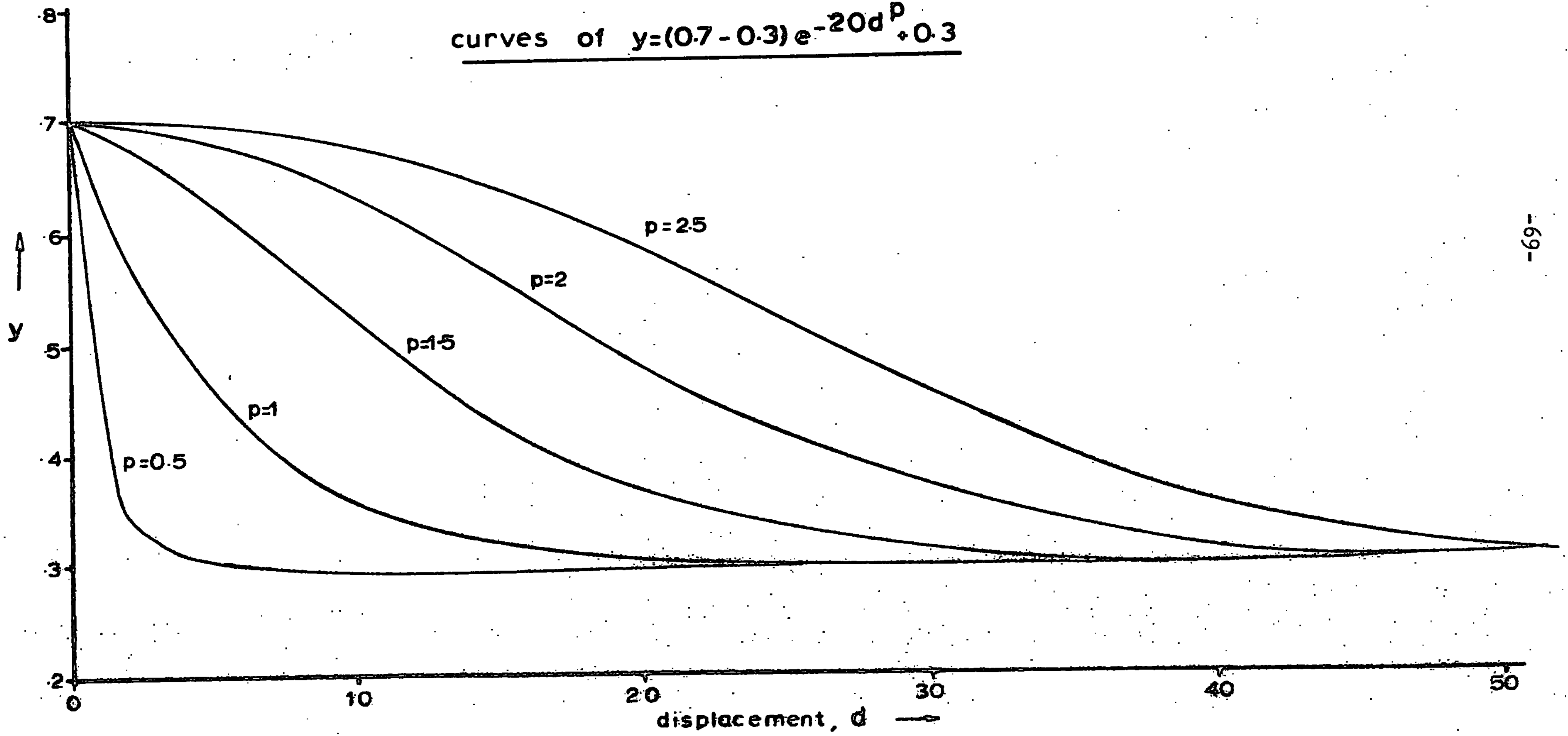
The evidence suggests that the first stage is the formation of a shear zone, in which the shearing movements and the stresses involved cause material breakdown. In this zone will occur minor 'riedal' shears as occurred with Morgenstern and Tchalenko (1967), although the nature of their work was somewhat different to the present investigation. The riedal shears may well develop in zones where sufficient fine material has been concentrated. As these minor shear planes develop it is presupposed that the overall shear strength will drop. Increased stresses should consequently be placed on the intervening regions, such that these will breakdown and enable the formation of a single shear plane. The final breakdown may be a sudden process, as is possibly demonstrated by Figure 3.37.

The result of the small shear-box test on the Ollerton material (Figure 3.33) suggest that other additional



curves of $y = (0{\cdot}7 - 0{\cdot}3)\,e^{-k d^{1\cdot5}} + 0{\cdot}3$

Figure 4.2



curves of $y=(0{\cdot}7-0{\cdot}3)e^{-20d^{p}}+0{\cdot}3$

Figure 4·3

mechanisms may be involved in shear plane development. This sample showed a much higher cohesion than any other of those tested.* For this sample it is thought that shear plane establishment was taking place, but was not complete when the test was terminated. The intervening zones, which would contain a considerable amount of clay material resulting from breakdown (predominantly inter-particle attrition in this test), could well be responsible for this cohesion. Further shearing would break through these zones, lowering the cohesion, but little further reduction in the value of ϕ' would be expected.

4.2.3 Residual shear strength

Tests in a reversing shear-box are unlikely to ever reduce a material to its lowest possible shear strength. The effects of the shear-box itself are most significant at low normal stresses. At very high normal stresses the shear-box effects are proportionally much reduced, and thus much lower "residual" values have been obtained than for tests at the lower stress values. Observations on sheared samples have revealed that for a distance at either end of the sample approximately equal to the displacement, no shear plane had developed due to the disturbance by the box, even though a well-developed shear plane existed in the centre of the sample.

It is expected that with a suitable shear-box (e.g.

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* The general order of this intercept is not dissimilar to some of the Yorkshire Main values (Taylor and Spears, 1972), and is too high to be ignored.

a ring-shear apparatus), the disturbance effects would be much reduced. Then, with sufficient displacement, the shear strengths for any value of normal stress should finally converge onto the same residual value. An indication of this is a test on Aberfan material by Bishop (in press) using a ring shear apparatus. In this test, at a normal stress of 100 kN/m^2, the shear strength of material passing a No. 7 B.S. sieve (2.4 mm) had been reduced to give a ϕ' of 20° after a displacement of one-sixth of a mile (270 metres), and was still dropping when the test was terminated. The writer feels that the breakdown in this test would be due to attrition only, and a three- or fourfold increase in the normal stress would reduce the displacement required by at least an order of magnitude. In the present series of tests values of ϕ' below 20° have been attained with displacements of less than 0.25 metres, although the material in this case had an initial maximum size of 1.2 mm.

The limited number of tests performed suggest that a given shear plane will provide a linear failure envelope (Figures 3.38 and 3.43). This is a completely different condition from the formation of a curved failure envelope by tests on different samples. In the latter case, each test in a reversing shear-box will reach its equilibrium condition (see Section 1.5) when sample disturbance caused by the reversing shear-box will counterbalance any further reductions in shear-strength. The linear failure envelopes have been obtained by forming a shear plane at a high stress level and then testing at reduced stress levels, where further reduction in the strength of the shear plane is unlikely to take place.

If the shear plane is tested at a higher normal stress than that at which it was formed, then further reduction in shear strength may occur as the increased stress levels cause further material breakdown around the shear plane.

The suggestion behind this is that the laws of simple mechanics can be applied to a fully developed shear plane, which can be treated as the interface between two sliding bodies.

4.3 Implications of the results in tip design and construction

For most discards the current series of tests have shown that at lower normal stress levels a reduction in shear strength is likely to be limited, even for moderate displacements (e.g. 1 metre). The implication of this is that vehicular activity during emplacement or regrading operations is not likely to cause the development of shear planes in the majority of new or existing tips.

However, the extreme low rank material deserves special care, for the shear strength characteristics of such materials stand out as being especially poor (e.g. Birch Coppice, Figures 3.3, 3.4 and 3.5).

More significant from the design aspect, however, is the effect of normal stress on the rate of reduction of shear strength. The few tests performed at the higher normal stress levels indicate that displacements of only a few metres are required to reduce shear strength considerably at the stress levels involved in the body of the tip (e.g. at σ_n' values above about 300 kN/m^2). It may prove possible to relate the reduction in shear strength to the normal stress and the displacement involved, but this will require a further research programme. However, if such a relationship did emerge, it would enable shear strength to be estimated within reasonable limits for a given displacement.

Perhaps it should be reiterated that the discards and tips (such as Littleton) in the West Midlands do present their own special problems, and even limited regrading operations may be sufficient to initiate a fully-developed shear plane with ϕ' tending to a low residual value (15 - 17°). Moreover, if future 'tipping' of these unique low rank discards is contemplated on a large scale there may be some merit in attempting to ascertain more precisely the weaker components from the stronger ones.

REFERENCES

BERKOVITCH,L,MANACKERMAN,M. and POTTER,N.M. 1959 'The shale breakdown problem in coal washing'. Part 1 - assessing the breakdown of shales in water. J. Inst. Fuel. 32, 579-589.

BISHOP,A.W., HUTCHINSON,J.N., PENMAN,A.D.M., and EVANS,H.F., 1969. 'Geotechnical Investigation into the causes and circumstances of the disaster of 21st October, 1966'. Item 1, 1 - 80,in'A selection of technical reports submitted to the Aberfan tribunal.' Welsh Office, London.H.M.S.O.

BISHOP,A.W. (in press, 1973) 'The stability of Tips and Spoil Heaps'. Q. Jl. Engng. Geol.

BRITISH STANDARD 1377. 1967 'Methods of testing soils for Civil Engineerring purposes'. British Standards Institution.

GROVES, A.W., 1951 'Silicate Analyses'. Allen and Unwin, London.

HOLLAND, J.G., and BRINDLE,D.W., 1966 'A self-consistent mass absorption correction for silicate analyses by X-ray flourescence'. Spectrochim. Acta. 22, 2083 - 2093.

KNOX, G., 1927 'Landslides in South Wales Valleys'. Proc. S.Wales Institute of Engineers, 43, 161-233.

MCKECHNIE THOMSON,G., and RODIN,S., 1972 'Colliery Spoil Tips - After Aberfan'. Paper 7522, Institution of Civil Engineers.

MORGENSTERN, N.R. and TCHALENKO, J.S., 1967 'Microscopic structure in Kaolin subjected to direct shear'. Geotechnique 17, 309 - 328.

NATIONAL COAL BOARD, Joint working party on soil mechanics testing, 1969. 'Technical memorandum relating to British Standard 1377. 1967.' National Coal Board, London.

NATIONAL COAL BOARD, Technical handbook, 1970. 'Spoil Heaps and Lagoons'. 2nd draft. National Coal Board, London.

NATIONAL COAL BOARD, Headquarters Research Project, 1972 'Review of Research on Properties of Spoil Tip Materials'. National Coal Board, London.

NATIONAL COAL BOARD, 1972, Internal report from Durham University. 'Compositional and Shear Strength Characteriestics of a tip at Littleton, Staffordshire.'

PEARSON, G.M. and WADE, E., 1967 'The physical behaviour of seat-earths'. Proc. Geol. Soc. London, No. 1637 24-33.

PENMAN, A.D.M. 1971 'Rockfill'. Building Research Station Current Paper. 10 pp.

PETLEY, D.J. 1966, 'The shear strength of soils at large strains'. PhD Thesis, University of London.

PRICE, N.J. 1966, 'Fault and joint development in brittle and semi-brittle rock'. Pergamon Press, London. 176 pp.

SPEARS, D.A., TAYLOR, R.K. and TILL, R, 1971 'A mineralogical investigation of a spoil heap at Yorkshire Main Colliery'. Q Jl. Engng. Geol. 3 239 - 252.

TAYLOR, R.K.(in press, 1973) 'Compositional and Geotechnical characteristics of a 100-year-old colliery spoil heap' Author's presentation and discussion. Trans. Ins. M.M. (Section A, mining industry).

TAYLOR, R.K. and SPEARS, D.A. 1970. 'The breakdown of British Coal Measure Rocks'. Int. J. Rock Mech. Min. Sci. 7, 481 - 501.

TAYLOR, R.K. and SPEARS, D.A. 1972. 'The Geotechnical Characteristics of a spoil heap at Yorkshire Main Colliery'. Q. Jl. Engng. Geol. 5, 243 - 263.

TEICHMULLER, M., and TEICHMULLER, R. 1968. 'Geological Aspects of Coal Metamorphism'. In 'Coal and Coal-Bearing Strata' (Eds Murchison, D., and Westoll, T.S.) Oliver and Boyd, London. 233-267.

APPENDIX 1

Computer program used for plotting 12-inch shear-box results

```
C     THIS PROGRAM PLOTS SHEAR BOX RESULTS USING MTS & 1130 PLOTTER
C
C         OVL = ORIGINAL VERTICAL LOADING
C         OSSR = ORIGINAL STRESS READING
C         OSNR = ORIGINAL STRAIN READING
C         SSR = STRESS READING
C         SNR = STRAIN READING
C
C         AA CONTROLS ZERO SHIFT FOR EACH SET OF READINGS
C     PENMBR REQUIRES DOUBLE PRECISION
      REAL*8 QQ
      REAL*8 RR
      REAL*4 K1,K2,K3,K4
      REAL *8 ITLE(7)
      READ(5,2)(ITLE(I),I=1,7)
2     FORMAT(7A8)
      WRITE(5,3)(ITLE(I),I=1,7)
3     FORMAT('0',7A8)
      AA=0
C         MM,MMM CONTROL LOCATION IN STORAGE ARRAYS
      MM=0
      MMM=0
      DIMENSION X(600),Y(600)
C         X,Y ARE STORAGE ARRAYS CONTAINING PLOTTING DATA
C         SET THE ARRAYS TO ZERO
      DO 10 L=1,600
      X(L)=0
      Y(L)=0
10    CONTINUE
C         N IS THE NUMBER OF SETS OF READINGS
      READ(5,23) N
23    FORMAT(I2)
      DO 99 I=1,N
C         M IS THE NUMBER OF READINGS IN EACH SET
      READ(5,24)M,OVL,OSSR,OSNR,K1,K2,K3,K4
24    FORMAT(I2,3F6.1,4F7.2)
      WRITE(6,26)M,OVL,OSSR,OSNR
26    FORMAT(1H0,I3,3F7.1)
      DO 51 J=1,M
      MM=MMM+J
      READ(5,25)SSR,SNR
25    FORMAT(2F5.1)
C         A = STRAIN IN METRES
      A=(SNR-OSNR)*K1/K2*1.0E-03
      A1=A
C         B = EFFECTIVE AREA OF BOX IN SQ METRES
      B=0.3048*0.3048
C         C = LOAD IN KN
      C=(SSR-OSSR)*K3/K4
      D=C/B
```

```
C         D = SHEAR FORCE (LOAD / AREA)
      D=DVL
C         E = VERTICAL LOADING
      Z=D/E
C         A PLOT OF D/E DOES NOT NORMALLY EXCEED ONE

      PHIR=ATAN(Z)
      PHI=PHIR*180/3.141592
      WRITE(6,100)SNR,SSR,A,Z,D,PHI
100   FORMAT(' ','SNR = ',F12.2,4X,'SSR = ',F12.2,4X,'A = ',F12.5,4X,
     1'D/E =',F12.5,4X,'D =',F12.5,3X,'PHI =',F8.3)
      A=A+AA
      X(MM)=A
      Y(MM)=Z
51    CONTINUE
C      SHIFT ORIGIN BY DISTANCE BOX HAS TRAVELLED
      AA=AA+A1
      MMM=MMM+M
99    CONTINUE
C
C
C         PAXIS(ABS XO, ABS YO, TITLE, NCHAR, AXLTH, THETA, XMIN,
C      SC FACT, D MARKS)
C         PLTOFS((XO, X SC FACT, YO, Y SC FACT, XC ABS, YC ABS)
C         PSYMB(X SYMB ABS, Y SYMB ABS, HGHT, WORD,THETA,NCHAR)
C         PLINE(XARRAY, YARRAY, NDATA, SPAC, PLOTTYPE,SET COORD TYPE)
C
      XX=FLOAT(N)*0.8
      K9=IFIX(XX)
      PL=FLOAT(K9)+1.
      XW=PL/2.-3.5
      XZ=PL/2.-2.
      CALL PLTXMX(PL)
C     PLOT X-AXIS
      CALL PAXIS(2.0,2.0,' ',-1,PL,0.0,0.0,0.0625,0.8)
C    PLOT Y-AXIS
      CALL PAXIS(2.0,2.0,' ',1,-4.0,90.0,0.0,0.25,0.4)
      YY=1.9
      RR=0.0
      DO 998 JJ=1,6
      CALL PENMBR(1.3,YY,0.10,RR,0.0,'F3.1*',1.0)
      YY=YY+0.8
      RR=RR+0.2
998   CONTINUE
C      DEFINE PLOTTING SYSTEM
      CALL PLTOFS(0.0,0.0625,0.0,0.25,2.0,2.0)
      CALL PSYMB(1.0,3.0,-0.2,'STRESS RATIO',90.0,12)
      CALL PSYMB(1.5,2.5,-0.15,'(SHEAR STRESS/NORMAL STRESS)',90.0,28)
      CALL PSYMB(XW,1.2,-0.2,'FORWARD DISPLACEMENT IN METRES',0.0,30)
      CALL PSYMB(XW,7.5,-0.22,ITLE,0.0,56)
      CALL PSYMB(XZ,8.1,-0.22,'12 INCH SHEAR BOX TEST',0.0,22)
      CALL PSYMB(9.0,9.5,-0.25,'DGL13',0.0,5)
C    PLOT POINTS
      CALL PLINE(X,Y,MM,1,-1,03,1.0)
      CALL PLTEND
      CALL EXIT
      END
```

APPENDIX 2

Shear-box test results

Note: The first pair of values in each set are the initial peak readings. The values thereafter are the final shear stress results for the normal stress recorded.

sample	12-inch shear-box		60mm shear-box	
	normal stress	shear stress	normal stress	shear stress
Cynheidre	80.3	61.3	133.7	95.6
	240.3	130.2	200.1	106.2
	160.3	89.3	128.7	78.6
	80.3	42.4	61.3	42.3
Morrison Busty	80.3	72.7	133.7	93.2
	80.3	62.4	188.7	107.4
	160.3	109.7	133.7	79.8
	267.1	169.1	87.8	59.1
			18.2	8.1
Bersham	80.3	66.7	133.7	104.3
	160.3	100.2	160.5	87.8
	53.6	35.7	133.7	73.4
	240.3	136.6	35.6	25.8
	347.1	180.3		
	80.3	49.2		
Orgreave	80.3	64.5	133.7	104.3
	267.1	108.7	188.7	75.7
	160.3	76.2	133.7	59.2
	80.3	43.7	87.8	44.1
			35.6	21.1

sample	12-inch shear box		60mm shear-box	
	normal stress	shear stress	normal stress	shear stress
Easton	80.3	64.6	133.7	104.6
	240.3	166.6	133.7	96.2
	160.3	112.2	87.8	54.1
	80.3	52.7		
Askern	80.3	57.9	133.7	95.2
	320.4	127.9	302.5	93.1
	240.3	92.8	225.7	72.3
	160.3	65.2	110.1	30.2
	80.3	34.9		
	53.6	24.6		
Ollerton	80.3	61.4	133.7	98.7
	320.4	141.6	285.4	142.3
	240.3	109.9	236.8	116.2
	160.3	74.7	212.2	103.9
	80.3	42.9	188.7	94.5
			160.5	84.1
			133.7	76.8
			61.3	36.9
			35.6	47.2
			17.0	36.7
Birch Coppice	80.3	56.8	133.7	98.7
	320.4	85.3	285.4	74.3
	240.3	66.0	236.8	63.2
	160.3	43.5	200.1	52.1
	80.3	21.7	133.7	37.3
	53.6	15.6		