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The swelling characteristics of weathered Coal Measures mudrocks from Sydallt near Wrexham, Clywd, Wales.

by

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SUMMARY

Culshaw and Crummy (1988), in a report on the engineering geology of the Deeside area, noted that Coal Measures mudstones were considered for use only as fill if there was no alternative and then only for low embankments. The reasons for this are that the weathered clay is too wet and the mudrocks when, disturbed, have a tendency to weather rapidly, swell and settle. However, there were no data in site investigation reports to quantify this effect.

The Wrexham thematic mapping project (for an area adjacent to Deeside) included a short laboratory testing programme to investigate the swelling behaviour of weathered Coal Measures mudstones. Three block samples of weathered mudstones (silty clay) were collected from an opencast coal mine north of Wrexham. Two direct techniques were used to measure swelling properties: a) one dimensional, zero-volume change swelling stress and b) three dimensional unconfined swelling strain on undisturbed samples. Also, indirect methods involving index tests were used. The mineralogy of the three samples was determined to aid in the interpretation of the swelling test results, and the degree of weathering.

The swelling behaviour of the three samples was found to be greatly influenced by their moisture content. However, at natural moisture contents these samples are unlikely to cause problems due to swelling.

Other clays derived from weathered Coal Measures mudrocks, found elsewhere, for example in the Deeside and Castleford-Pontefract areas, with high or very high plasticities may contain more expansive clay minerals such as mixed layer smectite and illite, increasing swelling potential.

The major volume change in the Coal Measures mudstones probably occurs during the weathering from fresh to highly weathered rock or residual soil. This process increases moisture content and volume, and decreases density, producing a material which cannot be used in embankments. The rate of weathering is accelerated by disturbance such as "working" during embankment construction resulting in a material which is not favoured for embankment construction.

This limited laboratory programme suggests that weathered Coal Measures mudrocks in the Wrexham area have a low swelling potential. However, there may be higher plasticity and higher swelling materials within the same formation. To improve the understanding of the swelling characteristics of weathered and fresh Coal Measures mudstones further research is necessary.

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CONTENTS

TABLES

FIGURES

1. INTRODUCTION

During the Deeside (North Wales) thematic mapping project (Cambell and Haines 1988) it was noted by Culshaw and Crummy (1988), from site investigation reports, that Coal Measures mudrocks were not considered suitable as fill materials unless there was no alternative; if this were the case, they were only to be used for low embankments. This is because mudrocks have a tendency to weather rapidly, swell and settle and the weathered mudrocks are often too wet for use as fill. However, there was no quantification of their swelling behaviour in the site investigation reports examined for the project. As part of the Wrexham thematic mapping project for the Department of the Environment (on behalf of the Welsh Office - project PECD/7/1/290), the swelling characteristics of some weathered Coal Measures mudrocks were determined in a laboratory study.

1.1. SWELLING

Swelling describes a process whereby an increase in volume of a soil or rock takes place which results in an increase in voids ratio (or porosity) and, usually, in an increase in moisture content, with a resulting decrease in bulk and dry density. If the swelling is confined, preventing volume increase, then a swelling stress (or pressure) develops.

The mechanism of swelling involves the attraction of water molecules to clay to provide an effective repulsion between the clay particles; this is normally associated with volume increase (Hobbs et al. 1982). Within clay minerals there are a) forces of attraction, b) forces of repulsion and c) so-called "contact forces".

a) forces of attraction are:
- (i) Van der Waals forces
- (ii) Coulomb forces
- (iii) Bonding due to non-clay minerals, for example, cementing

b) forces of repulsion are:
- (i) Forces of hydration
- (ii) Osmotic forces

c) "contact" forces are associated with unbending and elastic rebound of clay particles which can be important in overconsolidated clays.

Factors affecting swelling capacity are as follows:

a) Clay mineralogy
The clay minerals present in a rock or soil have an important effect on the swelling potential. In general, the higher the plasticity of the clay minerals the greater will be the tendency to swell. Smectite has the greatest swelling potential followed by illite and kaolinite.

Most engineering problems associated with swelling (and shrinkage) are due to the presence of smectite and illite. The surface area, plasticity and activity are good indicators of swelling potential (Fig. 1, after Holtz and Gibbs [1956], and Fig. 2, after Lambe [1960]). A swelling potential classification is given in Table 1 (after O'Neill and Poormoayed [1980]).

Table 1 Swelling potential classification (after O'Neill and Poormoayed [1980])

Liquid limit %	Plastic limit %	Potential Swelling strain %	Classification
< 50	< 25	< 0.5	Low
50-60	25-30	0.5-1.5	Marginal
> 60	> 35	> 1.5	High

b) Microstructure
There are a number of microstructural characteristics which affect the swelling behaviour of weathered materials. These are the presence and removal of cementing minerals including carbonates, iron oxides and sulphides, and the effects of induration. The rate of swelling is controlled by the permeability of the clay and may be accelerated by sedimentary structures and discontinuities.

c) Pore fluid chemistry
The concentration of salts in the pore water also can control swelling. Pore water with high salt concentrations will reduce, or stop, the swelling of the clay. However, this may be changed if fresh water with a low salt concentration is introduced, allowing swelling to commence. This process is unlikely to cause changes in weathered Coal Measures mudrocks because the pore water is probably derived from rain water and this is unlikely to change.

d) Depositional history
The depositional history of a sediment will have a profound effect on swelling capacity. The microstructure, state of compaction and clay/water chemistry depend on it. Induration may follow burial, tectonic pressure or low-grade metamorphism due to heating. The lithification produced will cement the material together reducing or stopping swelling. The effects of lithification may be reduced or removed by weathering.

Overconsolidated and indurated clays may exhibit considerable swelling capacity even though they may not contain high swelling clay minerals. This is probably due to stress relief and a tendency to attain a new equilibrium in the normally consolidated state near or at surface. This may occur in Coal Measures mudrocks.

e) Other factors

Swelling may occur because of changes in moisture content associated with seasonal variations in the depth of the water table or the presence of surface water. This is seen in Mediterranean countries and was also experienced in Britain during, and following, the dry summer of 1976. Rising water tables in some major cities, notably London, due to reduction in borehole pumping can also produce changes in the mechanical behaviour and stress conditions, inducing swelling.

Swelling may be caused also by the reaction between minerals producing secondary minerals of greater volume. This is discussed below in section 1.2.

1.2. WEATHERING

Weathering of mudrocks can be classified into two types (Taylor 1988):

a) physical disintegration
b) chemical weathering

Physical and chemical weathering usually remove cement and the effects of induration; this allows the clay minerals to swell.

The principal controls of physical disintegration are:

(i) The incidence of sedimentary structures and discontinuities.
(ii) Slaking and freeze/thaw.
(iii) Expansion of mixed-layer clay minerals with smectite layers.

Other factors such as permeability and mineralogy may affect the rate of weathering. In mudrocks, chemical weathering, near surface, normally produces a relative increase in the quartz fraction along with an increase in kaolinite at the expense of chlorite.

The major sulphide mineral in Coal Measures rocks is pyrite (FeS) which is usually found in low concentrations. However, it can be concentrated in coal and associated sediments. Pyrite can oxidise under water but the process is accelerated by a factor of about 10^6 in warm, moist oxygenated environments due to the activity of bacteria. Therefore, rapid pyrite oxidation occurs in the partly saturated near-surface zone above the water table. Local oxidation can produce volume changes. The main carbonate species in mudrocks is siderite ($FeCO_3$) which is more stable than calcite.

Changes in the mineralogy due to weathering may produce changes in volume. A typical example is the reaction of calcite and pyrite, the weathering products of which (for example, gypsum) have a greater volume than original minerals. This reaction is more common in mudrocks of marine origin, such as Fullers Earth and Oxford Clay. In Coal Measures mudrocks this reaction is less important as calcite is found in very small quantities, usually below X-ray detection, although gypsum may be formed with a calcite content of 0.5% by weight.

The change in geotechnical properties between fresh and weathered Coal Measures mudrocks is dependent upon the degree of weathering. Weathering, and progressive softening due to stress relief and ingress of water at, or near, the surface, increases moisture content and reduces strength. The cohesion may reduce to zero to produce a material which behaves as a normally consolidated clay which has a much higher moisture content and lower bulk and dry density resulting in swelling (Early and Skempton 1972, Spears and Taylor 1972).

Most geotechnical properties of Coal Measures mudrocks are affected by weathering and the trends are summarised in Table 2 (based on Cripps and Taylor 1981). This is also shown in the different weathering grades documented in the Deeside thematic mapping project (Cambell and Hains 1988). The changes of plasticity, due to weathering, for Coal Measures mudrocks for the Castleford-Pontefract and Deeside areas are shown in Fig. 3. An engineering classification of weathered mudrocks (Anon 1977) is given in Table 3.

Table 2 The change of geotechnical parameters by weathering of Coal Measures mudrocks.

Parameter	Weathering condition	
	Fresh	Completely weathered
Moisture content	increases ------>	
Density	decreases------->	
Plasticity	increases------->	
Undrained shear strength	decreases------->	
Effective cohesion	decreases------->	

Table 3 Engineering classification of weathered mudrocks (after Anon 1977).

Term	Grade	Description
Fresh	1A	No visible sign of weathering
Faintly weathered	1B	Discolouration on major discontinuity surfaces
Slightly weathered	II	Discolouration
Moderately weathered	III	Less than half of rock material decomposed
Highly weathered	IV	More than half of rock material decomposed
Completely weathered	V	All rock material decomposed; original mass structure still largely intact
Residual soil	VI	All rock material converted to soil. Mass structure and material fabric destroyed

Weathering of Coal Measures mudrocks generally produces clay minerals dominated by kaolinite with mica (illite) and subordinate chlorites (Perrin 1971) as well as quartz and siderite (Taylor 1988, Spears and Taylor 1972). A good indicator of the degree of chemical weathering (Milodowski et al. 1985) is the production of mixed layer illite-smectite which may be present in "frayed edge" mica. The proportion of the illite-smectite interlayers can increase in highly active weathering conditions. The mixed layer clays have a greater swelling potential than the parent mineral, mica.

2. SITE AND GEOLOGY

The opencast coal mine (SJ 3145 5485) from which the test samples were taken was located to the east of the Wrexham to Mold road (A 541) between Gwersyllt Park and Sydallt (Fig. 4). Geologically, the mine is in the upper part of the Middle Coal Measures (Bettisfield Formation), which consist mainly of mudrocks with sandstones. The strata generally dip at low angles in an easterly direction. The samples were obtained from mudstones. A description of the section is presented in Section 3.1. Spoil from the opencast coal mine had been placed on the top of the weathered exposure, the top soil and trees having been removed from the surface prior to spoil dumping. Because of this the original ground surface was assumed.

Two types of geotechnical laboratory test were undertaken:

a) **Index tests**, which were used as indicators of swelling behaviour, they are: moisture content, bulk and dry density, Atterberg limits (liquid limit, plastic limit and linear shrinkage), spacific gravity and particle size analysis. These tests methods and their derived functions, plasticity index, liquidity index and activity are given in the Appendix and from BS 1377 (Anon 1975).

b) **Direct swelling measurements**, which were carried out using two methods: one dimensional swelling stress (Anon 1975) and three dimensional swelling strain (Anon 1981). The methods used are described in the Appendix.

The mineralogy determinations were carried out by A. Bloodworth of the Mineral Science Group. The method is detailed in the Appendix.

3. RESULTS

3.1. SAMPLE DESCRIPTION

Block sample 1 (depth below probable old ground surface 0.10-0.20 m) was a stiff, completely weathered (weathering grade V), pale grey to light buff or orange brown, silty clay or mudstone.

Block sample 2 (depth below probable old ground surface 0.50-0.60 m) was similar to block sample 1.

Block sample 3 (depth below probable old ground surface 0.90-1.00 m) was a weak, moderately to highly weathered (weathering grade III to IV), grey, thinly bedded mudrock.

3.2. TEST RESULTS

The results of the Atterberg limit tests and particle size analyses are given in Table 4. Moisture content, density and liquidity index for the swelling test samples are given in Table 5, and maximum swelling stresses and strains are given in Table 6.

Table 4. Atterberg limits and particle size results.

Sample No.	Atterberg limits LL %	PL %	PI %	Particle size Gr %	Sd %	St %	Cl %	Activity	Specific Gravity	Linear Shrinkage %
1	41	25	16	1	7	39	53	0.30	2.661	8.4
2	40	25	15	0	4	47	49	0.31	2.660	8.6
3	31	16	15	1	5	51	43	0.35	2.676	7.1

Table 5. Moisture content, density and liquidity index results for the swelling test samples.

Sample No.	Swelling stress tests M.C. %	LI	Density Bulk Mg/m^3	Dry Mg/m^3	Swelling strain tests. M.C. %	LI	Density Bulk Mg/m^3	Dry Mg/m^3
1a	20.4	-0.29	2.07	1.74	21.2	-0.24	2.10	1.74
1b	16.2	-0.55	2.07	1.80	17.2	-0.49	2.07	1.76
1c	14.4	-0.66	2.19	1.92	14.2	-0.68	2.04	1.79
2a	18.1	-0.46	2.07	1.76	19.7	-0.35	2.09	1.75
2b	13.6	-0.76	2.14	1.88	15.2	-0.65	2.07	1.80
3a	12.1	-0.26	2.18	1.94	12.1	-0.26	2.14	1.91
3b	6.0	-0.67	2.15	2.03	6.7	-0.62	1.93	1.81

Table 6. Maximum swelling pressure, swelling strain and volumetric strain results.

Sample No.	Max. swelling stress kPa	Maximum swelling strain % ε_1	ε_2	ε_3	Maximum volumetric strain % ε_v
1a	31.2	2.13	2.11	1.41	5.8
1b	58.2	1.95	1.72	1.60	5.4
1c	340.0	3.80	2.63	2.22	8.9
2a	23.2	1.56	1.40	0.41	3.4
2b	80.0	1.68	1.08	0.61	3.4
3a	30.0	0.71	0.65	0.46	1.8
3b	280.0	2.12	2.03	1.76	6.0

3.2.1. Index Test Results

The moisture content profile (Fig. 5) shows an increase in moisture content to a depth of 0.50 m and then a rapid decrease to 0.90 m.

The block samples had higher initial moisture contents than those from the profile. This is probably due to some surface drying of the south facing pit wall from which the samples were taken, even though all the moisture content samples were taken from a depth of 0.3 m behind the exposed face.

The more highly weathered samples, blocks 1 and 2, had similar Atterberg limits and on an A-line plot classify as intermediate plasticity, inorganic clays; block sample 3 was a low plasticity, inorganic clay. An A-line plot of these plasticity results are given with data from Coal Measures mudrocks from elsewhere in the Wrexham and Deeside areas in Fig. 6.

Linear shrinkage results are low or intermediate.

The specific gravities for block samples 1 and 2 are very similar and for block sample 3 are slightly higher.

Block samples 1 and 2 contained about 50% clay size (<2μm) particles, and block sample 3, 43%. A particle size distribution graph is given in Fig. 7. All samples had over 90% fines (silt and clay, <0.06 μm). There is a trend of decreasing clay content with increasing depth.

The activity of the samples is low indicating that the main clay mineral is probably kaolinite.

3.2.2. Swelling

The results of the swelling tests are given in Table 6. Eight swelling pressure tests were carried out, three for block sample 1 (test samples 1a,b,c), and two each for block sample 2 and 3 (test samples 2a,b and 3a,b), at different moisture contents. The final swelling pressure varied between 23.2 kPa for test sample 2a to 340 kPa for test sample 1c. A decrease in moisture content, which produces an increase in dry density, tends to increase swelling pressure. The swelling pressure tests were completed within a day.

Eight swelling strain tests were carried out using the same test regime as for the swelling pressure tests. The three dimensional swelling strain vs. time plots are shown in Figs 8-14 which indicate that total strain varies between the different axes with ε_1 (perpendicular to the original bedding plane) having the greatest strain in all cases. Most of the swelling was completed within 24 hours. Sample 1 had the largest swelling strain.

There were some experimental problems (see Fig. 11 and possibly Fig. 13) in that swelling did not start along axis ε_3 on the addition of water although swelling did commence along the other axes. This may have been due to poor contact between micrometer and the plate on the sample. The reduction of swelling along axis ε_3 also reduces the volumetric strain for samples 2a and 3a.

Some of the values of density for the drier samples, especially sample 3, may not be accurate as the material becomes friable and pieces fell out of the cube during preparation. The calculated volume from Vernier caliper measurements probably overestimates the true volume of each sample so the densities are probably too low.

Tables 5 and 6 and Figs 15 and 16 show that there is an increase in swelling pressure and strain with decreasing moisture content. The swelling pressures at natural moisture content for all three block samples varied between 23 and 30 kPa and maximum strains between 2.13% and 0.71%. The swelling pressure increased to 340 kPa and 280 kPa with a 6% decrease in moisture content in block samples 1 and 3 respectively. However, the increase in swelling strain for the same decrease in moisture content is much less marked. Liquidity index, which expresses the change in moisture content and relates it to the consistency of the sample, is plotted against swelling pressure on Fig. 17 and swelling strain on Fig. 18. Swelling strain tends to increase with dry density. Block sample 1 had the greatest swelling pressures and strains at natural moisture content. Block sample 2 was intermediate in behaviour between block samples 1 and 3. At similar liquidity indices block samples 1 and 3 had similar swelling pressures (Fig. 17). However block sample 1 produced greater swelling strains than sample 3 for similar liquidity indices.

3.3. MINERALOGY

The clay mineral assemblage was dominated by kaolinite, with subordinate mica and trace amounts of chlorite (A. Bloodworth, written comunication, July 1989). Quartz was the major non-clay component, with minor siderite. Pyrite and/or gypsum were not detected in any of the samples. Block samples 1 and 2 are very similar, whilst block sample 3 contained a higher proportion of clay minerals relative to quartz. Comparison of whole-rock and clay size ($<2\mu m$) fractions indicated that the mica component consisted dominantly of discrete (detrital) mica, together with a smaller component of mixed layer illite-smectite with a low proportion of smectite interlayers. The mixed layer clay is virtually indistinguishable from "frayed-edge" mica which is typical of weathered rock of this type. The proportion of illite-smectite (or smectite interlayers) was appreciably lower in block sample 3, the least weathered sample, than in block samples 1 and 2.

4. DISCUSSION

Block samples 1 and 2 had the same weathering grade and similar mineralogy, particle size distribution, specific gravity and Atterberg limits. Block sample 3 was less weathered and contained fewer clay size particles and less illite-smectite than the other two samples. The Atterberg limits reflected the mineralogy, as the first two samples were more plastic than block sample 3.

The cementing of these Coal Measures mudrocks was probably due to the effects of induration or lithification as none of the major cementing minerals (calcite or pyrite) were found in high enough quantities. There was probably little increase in volume due to the genesis of secondary minerals during weathering.

The mineralogy and index test results suggested that these weathered Coal Measures mudrocks were of low swelling potential and this conclusion is supported by the results of the swelling tests. At natural moisture content these samples have a low swelling potential. However, the drying has a significant effect on swelling pressures, though not swelling strains, confirming the low swelling potential of these samples. Drying in-situ due to seasonal variations in moisture content would only affect a thin surface crust of material.

The samples selected were of low to intermediate plasticity. The plasticity data of similar Coal Measures mudrocks from the adjacent Deeside area show the presence there of high and very high plasticity clays. However, there are no comparable plasticity data available for the Wrexham area for these materials. Therefore, it is not possible to estimate the swelling behaviour of Coal Measures mudstones in the Wrexham area from index test data, though it is likely that properties will be similar. The evidence available from this short laboratory programme indicates that the materials tested are unlikely to cause problems due to their swelling characteristics.

Measurement of swelling stress and strain as part of site investigations is very uncommon, so it is important to relate regularly measured geotechnical parameters, such as plasticity, to swelling potential to assist in identifying materials which may produce swelling problems. The indicators of high swelling potential were summarised by Komornik and David (1969) for clays at shallow depth as:

$$\text{Log } P = 0.0208\ LL + 0.665\ \gamma_d - 0.0269\ m - 1.868 \qquad (1)$$

where P is the swelling pressure (kg/cm)
LL is the liquid limit (%)
γ_d is the dry density (kg/m^3)
m is the moisture content (%).

This relationship is a reasonable predictor for the higher moisture contents of block samples 1 and 2 but underestimates swelling pressures of low moisture content samples (Table 7). Madsen and Müller-Vonmoss (1985) use a complex relationship involving inter-layer distance calculated from mineral surface area and moisture content for saturated clays and mudrocks which has successfully predicted swelling pressure (Oral communication, S T Horseman, May 1989). A negative linear correlation is suggested by Erol and Dhowain (1982) between swelling pressure and liquidity index (log) for active Saudi Arabian clays which appears to be specific to these materials (Hobbs and Loucaides 1986).

Vijayvergiya and Sullivan (1974) correlated one dimensional swelling strain, liquid limit and dry density for Beaumont Clay from the Texas-Louisiana Gulf Coast area (Fig. 19). It is not possible to compare directly the volumetric strain from three dimensional tests and percentage one dimensional strain. However, a similar relationship could be used to classify fresh and weathered Coal Measures mudrocks.

Table 7. Measured and predicted swelling pressure using equation (1)

Sample No.	Swelling pressure, kPa. Measured	Predicted
1a	31.2	38.4
1b	58.2	54.6
1c	340.0	73.4
2a	23.2	43.5
2b	80.0	69.1
3a	30.0	54.0
3b	280.0	90.5

The potential for surface movement is a function not only the swelling characteristics of the clay but also of the groundwater, the variation of lithology (sandy or fissured material "absorb" heave, reducing its surface expression) and the depth below surface of the swelling material.

The use of Coal Measures mudrocks as fill in the Deeside area, suggests that the change from fresh, hard, low moisture content, high density, indurated mudrock to weathered, firm to soft, higher moisture content, lower density mudrock or soil produced an increase in volume or swelling. The rate of weathering is accelerated by "working" during construction of embankments which may produce a material which is more prone to weathering and will probably be copacted to lower densities than the original undisturbed rock. The degree of swelling and loss in strength will be increased in high or very high plasticity clays.

These weathered mudrocks (weathering grades III to VI) normally have high dry densities and low moisture contents and if this is associated with high plasticity, for example, liquid limit >60% and plasticity index >35%, with a high degree of weathering then swelling potential will be probably be high.

There is little or no swelling data available from site investigation reports. Further studies into the swelling behaviour of weathered Coal Measures mudrocks, especially those of high plasticity, and the correlation between weathering grade and index parameters are needed so that swelling behaviour can be more accurately predicted.

5. CONCLUSIONS

Three block samples of weathered Coal Measures mudrocks were obtained from an opencast coal mine north of Wrexham. The geotechnical index properties, one dimensional swelling stress and three dimensional swelling strain were measured to determine the swelling characteristics of these mudrocks.

The swelling characteristics were related to the index properties and indicated that these materials are of low swelling potential.

The clay mineralogy of these Coal Measures mudrocks is dominated by kaolinite, with illite and chlorite.

Weathering may increase plasticity but there are no other data available from site investigation reports for this lithology in the Wrexham area. Other areas have weathered Coal Measures mudrocks of high to very high plasticity and will probably have greater swelling potential than those studied here. More index property data are required to indicate whether other Coal Measures mudrocks will swell.

The consequence of weathering is the reduction, or removal, of induration producing an increase in moisture content and volume (swelling) and a reduction in density. The weathering may produce changes in the clay mineralogy resulting in higher plasticity mixed layer illite-smectite. The change from fresh to weathered mudrocks, which may be accelerated by working, probably explains the restricted use of Coal Measures mudstones in embankments in the Deeside area.

A decrease in moisture content increased the swelling stress and strain. This behaviour normally would be observed only near the ground surface where moisture content variations are most marked.

It is suggested that high plasticity clays (liquid limit >60% and plasticity index >35%) derived from Coal Measure mudrocks (weathering grades III to VI) may require measurement of their swelling characteristics.

The main civil engineering concern in relation to the Coal Measures mudrocks is probably due to the change in behaviour between fresh and weathered states. The acceleration of weathering by remoulding or working will produce a material which is probably intermediate between the in-situ condition and a residual soil.

A more extensive study is required to quantify fully the swelling behaviour of these mudrocks and to relate it to index properties which are available in site investigation reports.

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APPENDIX

METHODS USED

1. SAMPLING

Block, bag and moisture content samples were extracted from a freshly cut face which was topped with about 2.0 m of coal mine spoil. Three types of samples were taken:

i) for moisture content determination; samples weighing about 100 g were taken every 0.10 m from 0.10 to 0.90 m below the assumed original ground surface;

ii) for swelling (and index) property determination; block samples weighing between 20 and 30 kg were taken from three parts of the profile, at 0.10-0.20 m (block sample 1), 0.50-0.60 m (Block sample 2), 0.90-1.00 m (block sample 3);

iii) for index property determination; disturbed samples were taken which supplemented the block samples and were stored in sealable plastic bags.

The moisture content samples were placed in tins of known weight, reweighed and sealed for oven drying in the laboratory.

The bulk samples were covered in "Clingfilm" and then coated in wax. Once back at the laboratory they were stored in a cool, humid store (10°C and >90% humidity) until required for one dimensional swelling stress and three dimensional swelling strain tests.

The disturbed samples were placed in heavy duty self-sealing bags and were used for particle size analysis and Atterberg limits determination.

The testing techniques used were devised to find the swelling characteristics and swelling potential of different grades of the weathered Coal Measures mudrocks. The testing programme included moisture content, density, Atterberg limits, specific gravity and particle size determinations, as well as direct measurement of zero volume change swelling stress and three-dimensional swelling strain. The effect of different moisture contents on swelling response was also investigated. The mineralogy of the samples was determined by Mr A. J. Bloodworth of the Mineral Sciences Group, B.G.S., Keyworth.

2. LABORATORY TESTING

2.1. Index parameters

2.1.1. Moisture Content

The moisture content of rock or soil is defined as the mass of water which can be removed from the soil by heating at 105-110°C, expressed as a percentage of the dry mass.

$$\text{Moisture Content} = (W_1 - W_2) \;/\; W_2 \qquad (2)$$

where W_1 = wet weight of sample.
W_2 = oven dry weight of sample.

This test was carried out in accordance with BS 1377 (Anon 1975) test 1(A).

2.1.2. Bulk and Dry Density

The bulk and dry density are defined as the mass of material per unit volume. Bulk density includes both solid particles and any contained water whereas dry density includes only solid particles dried to a constant mass at 105-110°C.

The test was carried out as part of the one dimensional zero strain test (see Section 3.2.2.1.) using the oedometer ring as a density ring.

$$\text{Bulk density } (\gamma_b) = W_1 \;/\; \text{ring volume} \qquad (3)$$

$$\text{Dry density } (\gamma_d) = W_2 \;/\; \text{ring volume} \qquad (4)$$

where W_1 = wet weight of the soil.
W_2 = oven dry weight of the soil.

A nominal bulk and dry density was also obtained from the three dimensional swelling strain test.

2.1.3. Atterberg Limits

Atterberg limits were determined for each bagged sample. Liquid limit was determined using the penetrometer apparatus as described in BS 1377 (Anon 1975) test 2A and plastic limit limit by using test 3 of the same publication.

Liquid limit (LL) is defined as the moisture content at which a soil passes from the plastic to the liquid state as determined by the liquid limit test. Plastic limit (PL) is the moisture content at which a soil becomes too dry to be in a plastic condition as determined by the plastic limit test.

Linear shrinkage (LS) was carried out in accordance with BS 1377 (Anon 1975) test 5 and is defined as the change in length of a bar sample of soil when dried from about its liqid limit, expressed as a percentage of the initial length.

2.1.4. Specific Gravity

Specific gravity, the unit weight of solids divided by the unit weight of water, was determined using BS 1377 (Anon 1975), test 6B.

2.1.5. Particle Size Distribution

Particle size distribution was determined using BS 1377 (Anon 1975) test 7A and 7D, that is, by wet sieving and hydrometer analysis respectively.

2.1.6. Derived Functions

From the above determinations a number of derived parameters can be obtained. They are plasticity index, liquidity index and activity. Plasticity index is often used for classification purpose in the form of "A-line" plots.

$$\text{Plasticity Index (PI)} = LL - PL \qquad (5)$$

Liquidity index is used to relate the natural moisture content to the liquid limit and plastic limit.

$$\text{Liquidity Index (LI)} = (\text{moisture content} - PL)/(LL - PL) \qquad (6)$$

Values of Liquidity index in relation to sample state are given in Table A1.

Table A1 Liquidity Index values and the sample state.

Liquidity index value	Sample state
>1	Liquid
1	Liquid limit
0-1	Plastic
0	Plastic limit
<0	Solid

Activity is a good indicator of the clay mineralogy and, therefore, the behaviour of clayey soils. Activity is defined as:

$$\text{Activity} = PI \ / \ \% \text{ Clay size fraction } (<2\mu m) \qquad (7)$$

Typical values of activity are 0.38 for kaolinite, 0.9 for illite and 7.2 for sodium montmorillonite.

2.2. Swelling Testing

Two types of swelling tests were undertaken.

a) The first method determines the stress produced, in one dimension, when a disc shaped sample is confined under zero volume change and water is added. The technique is based on the oedometer test as discussed in BS 1377, (Anon 1975) Test 17. This method is sometimes used as the first stage of consolidation tests. These parameters can be used to aid foundation design and is expressed as a stress, kPa (or kN/m^2).

$$\text{swelling stress} = \text{Load applied/area of sample} \qquad (8)$$

b) The second method determines the strain produced in three dimensions of an unconfined cube of material in three orthogonal directions. The change in the length of each side on flooding is measured with fixed micrometers and expressed as a strain.

$$\text{Swelling strain \% } (\varepsilon_x) = \delta L_x \cdot 100\% / L_{ox} \qquad (9)$$

where δL_x = change in length of side x
L_{ox} = original length of side x
x = one of the orthogonal directions 1, 2 or 3.

$$\text{volumetric strain \% } (\varepsilon_v) = \delta V \, . \, 100\% / V_o \qquad (10)$$

where δV = change in volume
V_o = original volume

2.2.1. One Dimensional Swelling Stress

The oedometer technique of determining the swelling stress is sometimes used as the first stage of a consolidation test. Instead of adding a load and noting the deflection of the micrometer over a 24 hour period (as in the consolidation test) the micrometer reading is kept constant (or near constant) and loads added to maintain this state. This normally takes between 1 and 5 days. The oedometer ring used was 75 mm in diameter and 20 mm in high. An undisturbed sample was prepared by trimming the sample using the ring as a template, pushing the ring over the sample and then trimming the top and bottom flush and level with the ring. The ring and sample was inserted into the cell which was then placed on the oedometer load frame. A GDS computer logging system with Mitutoyo Digimatic indicators (dial gauges) was switched on and the indicator set to zero. Shortly after the logging started, deionised water was poured into the cell. The resultant swelling strain was negated by the addition of weights to a lever arm set to a 9:1 ratio, (which results in 20 kPa for the addition of 1 kg). When an equilibrium of zero strain at a given load was attained for a number of hours then the test was terminated. The sample was taken out of the oedometer, dried in the oven and weighed to determine the moisture content and dry density prior to testing.

2.2.2. Three Dimensional Swelling Strain

This method is derived from the International Society for Rock Mechanics suggested methods (Anon 1981) and was carried out using apparatus designed by the Engineering Geology Group of B.G.S. A schematic diagram of the geometry of this test is given in Fig. 20.

The requirements for unconfined swelling strain are:

i) A cell to contain the specimen and capable of being filled with water to a level above the top of the sample.

ii) Three micrometer dial gauges reading to 0.002 mm, or better, mounted to measure the swelling displacement of the specimen in three orthogonal directions.

iii) Bearing plates of metal or porous "stone" used to cover the faces to reduce slaking.

Cuboidal samples were prepared using a 60 mm square shear box cutting shoe. The sample dimensions were measured in three orthogonal directions at the mid-line of each face with Vernier calipers. The sample was then weighed and placed in the apparatus.

The initial or zero readings were taken and then de-ionized water was carefully poured into the container and a stopwatch was started. Readings were taken at log time intervals until they reached a constant level or passed a peak (this may take two weeks). At the end of the test the water was poured out of the container and the sample weighed, dried at 105-110°C for 24 hours and reweighed to obtain initial moisture content and density.

Moisture content is an important factor in swelling so tests were carried out at different moisture contents, for both types of swelling testing, by allowing the block to dry after the first test sample had been taken. This was repeated where enough material remained.

3. MINERALOGY

X-ray diffraction (XRD) analysis was used to determine mineralogical composition. Randomly oriented powder mounts were prepared from a hammer-milled and micronized sub-sample of the bulk sample. XRD analyses were carried out using a Philips PW 1700 automatic x-ray diffractometer controlled by a DEC PDP 11/24 mini-computer. The radiation used was Co-ka at 45kV and 40 mA over an angular range of 3-50° 2θ at a scan speed of 1.2° 2θ/minute.

To facilitate identification of clay mineral species, orientated XRD mounts were prepared from nominal <2 μm fractions. These fractions were separated by suspending a portion of the hammer-milled material in water and the subsequent removal of a nominal <2μm fraction, after sedimentation for a time period calculated according to Stokes Law. Mounts prepared from the <2 μm material were examined by XRD over the angular scanning range 2 - 35° 2θ, a scanning speed of 0.75° 2θ/minute other instrumental conditions being identical with those given for random powder mounts.

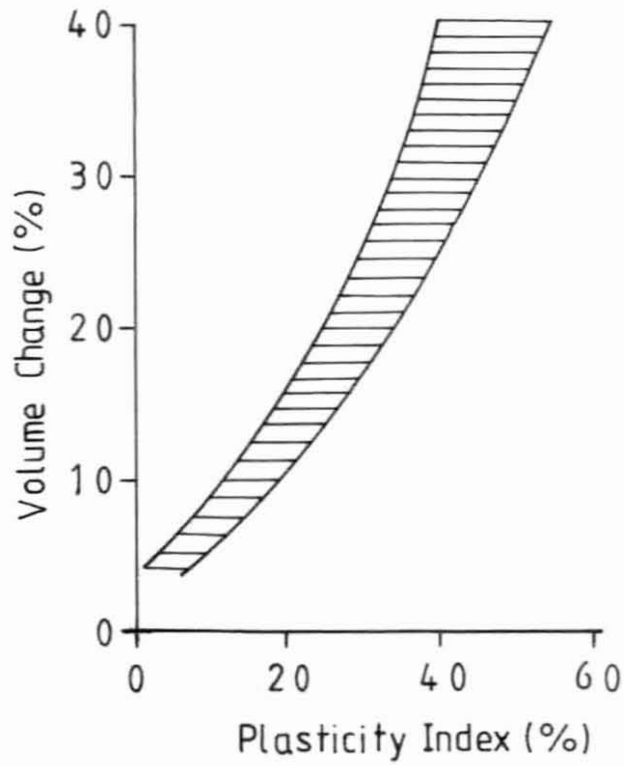


Fig. 1 The relationship between volume change and plasticity index

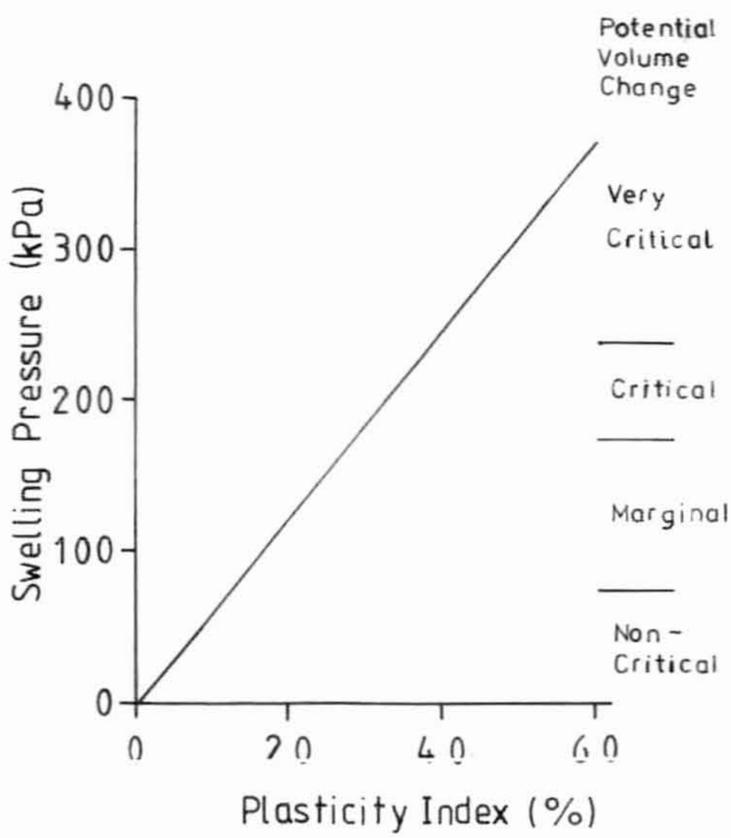
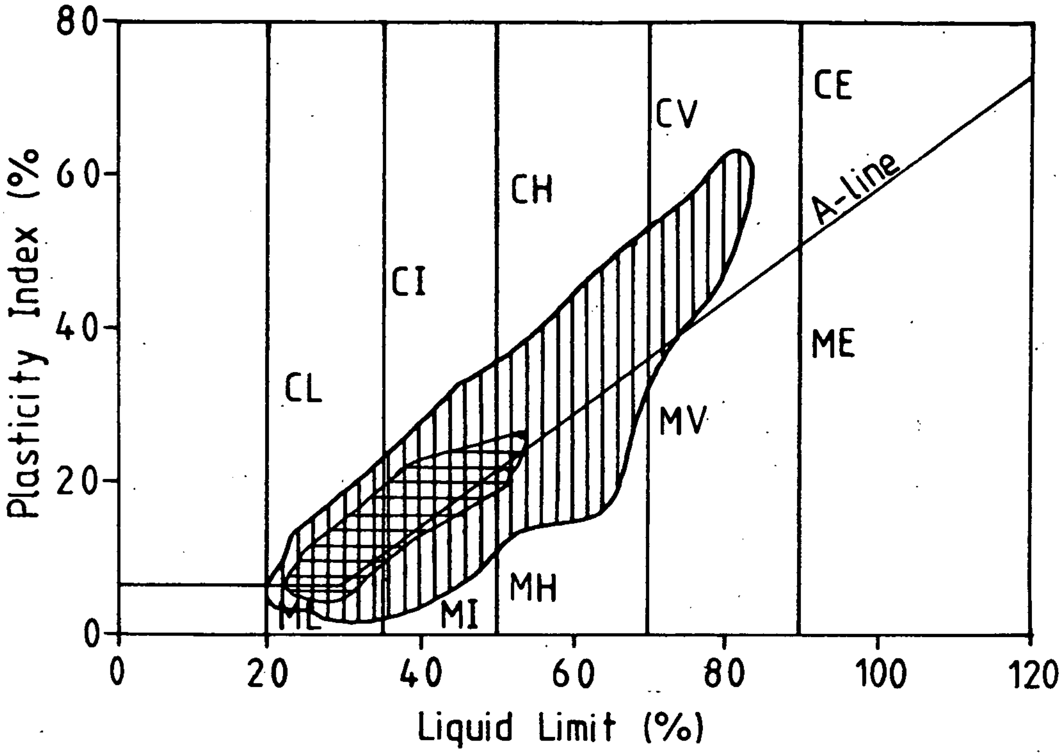


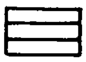
Fig. 2 The relationship between swelling pressure and plasticity index with reference to qualitative volume change potential



Key

C=Clay
M=Silt

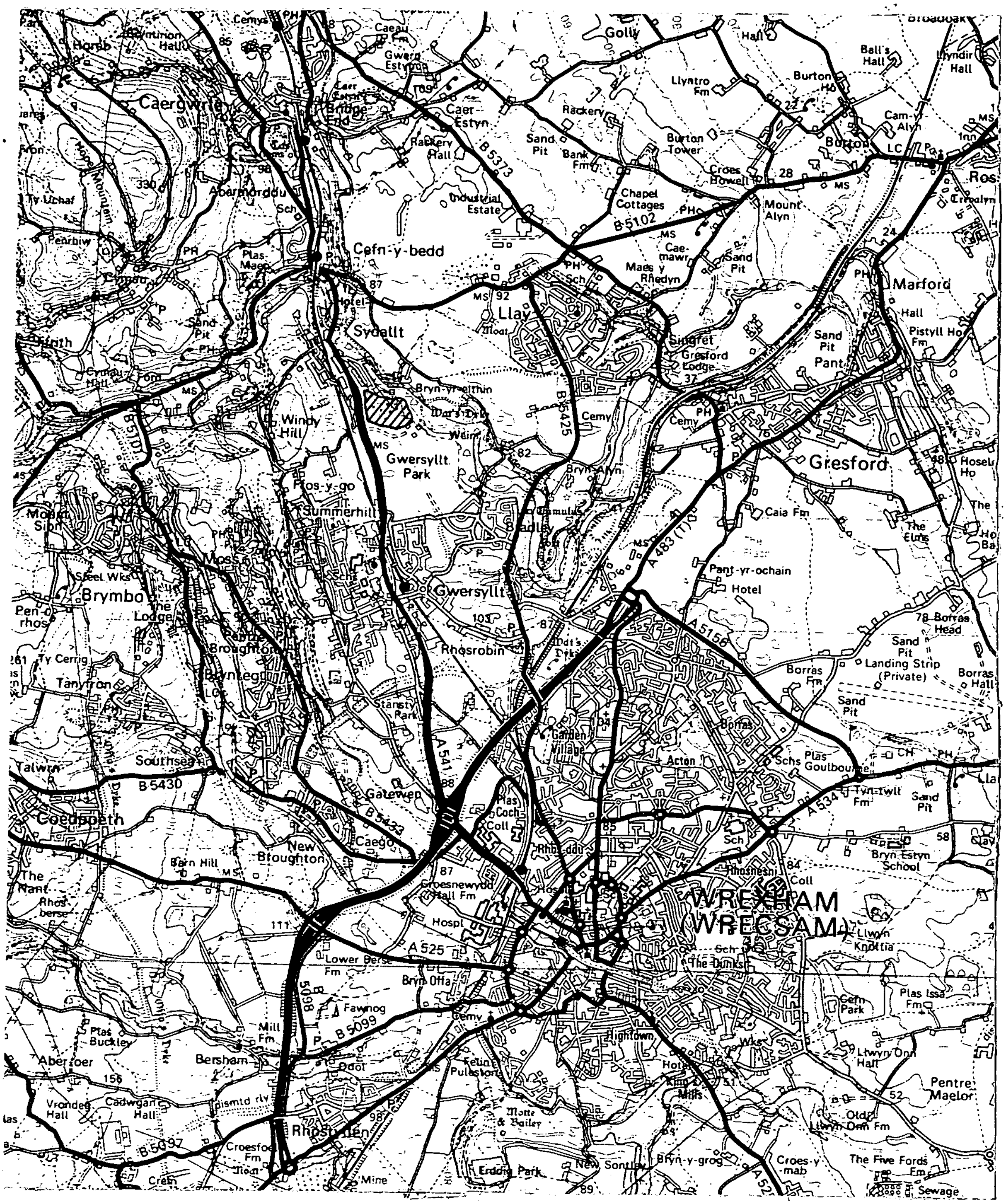
L=Low plasticity
I=Intermediate plasticity
H=High plasticity
E=Extremely high plasticity


Coal Measures mudrock - fresh to slighly weathered


- moderately to highly weathered

Fig. 3 A-line plot of weathered and unweathered Coal Measures mudrocks

Fig. 4 Site location



Scale 1 km

Key

Open cast coal mine sampled

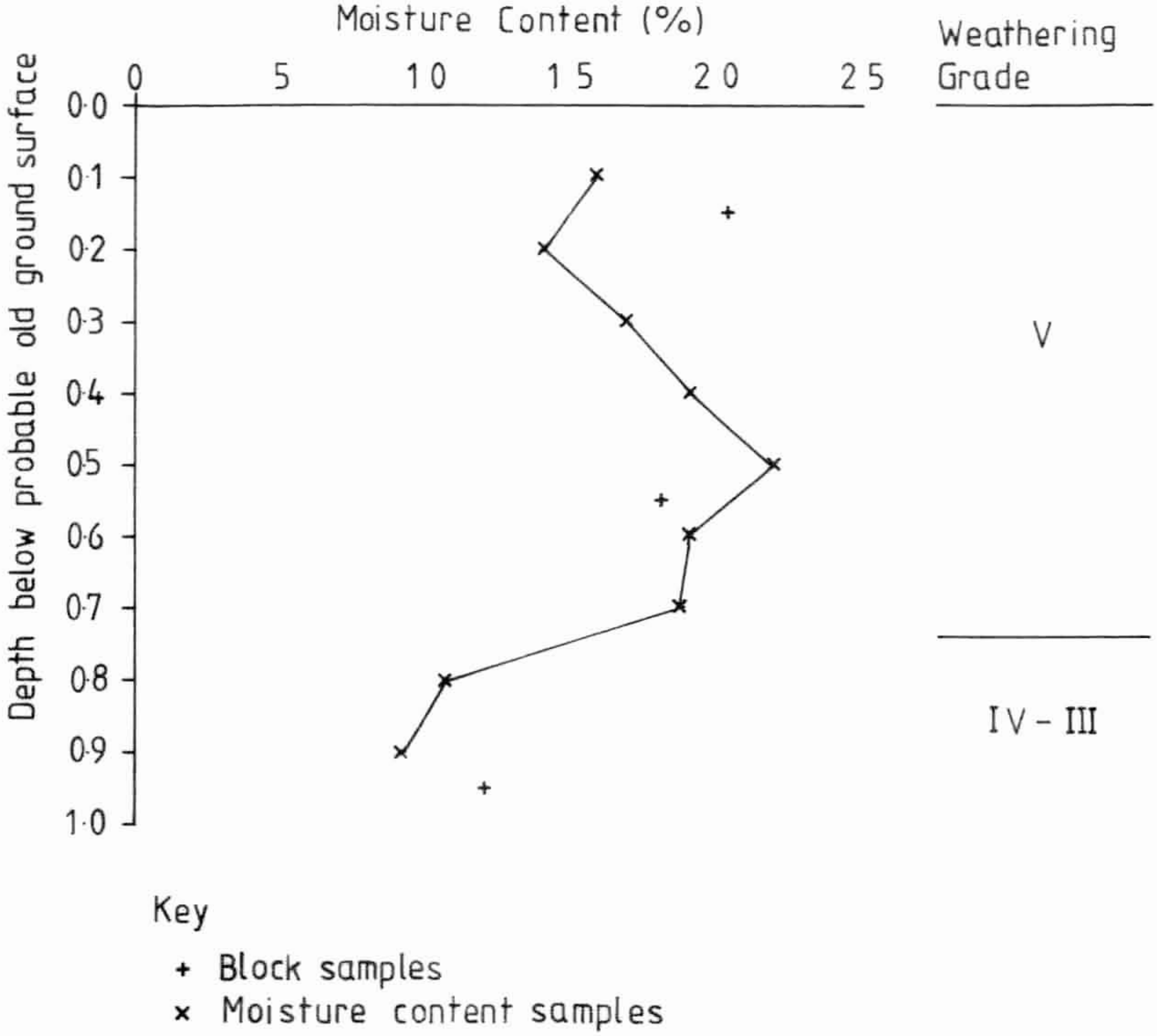
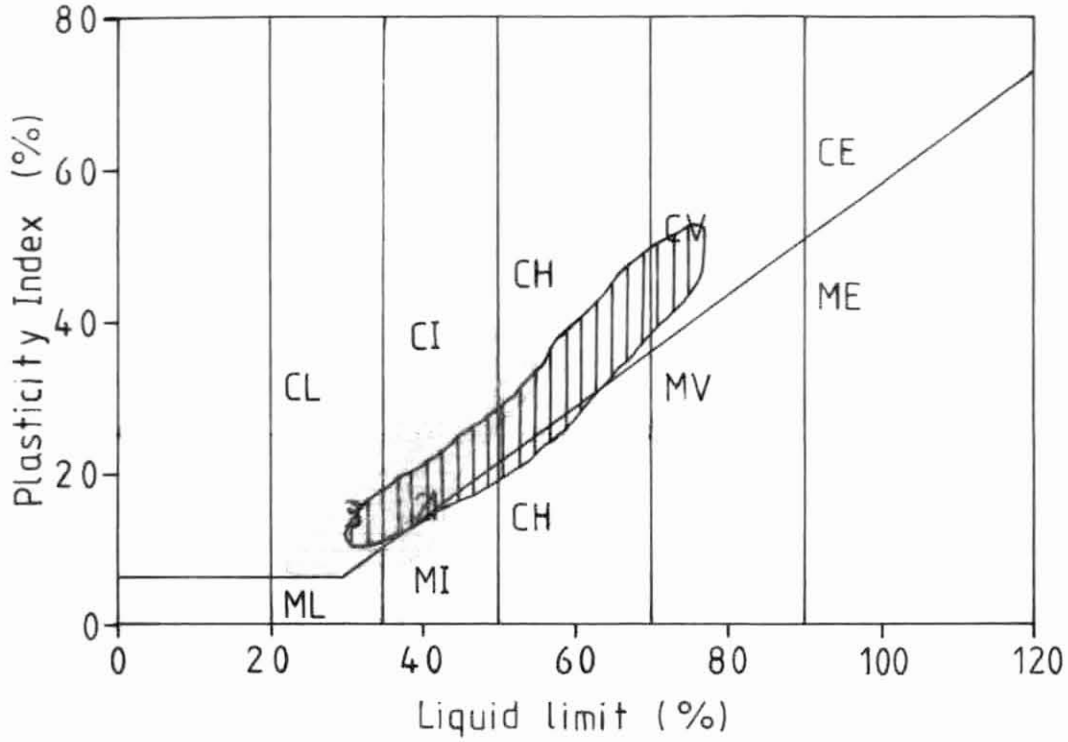


Fig. 5 Moisture content profile



Key

Wrexham data, samples 1, 2 and 3.

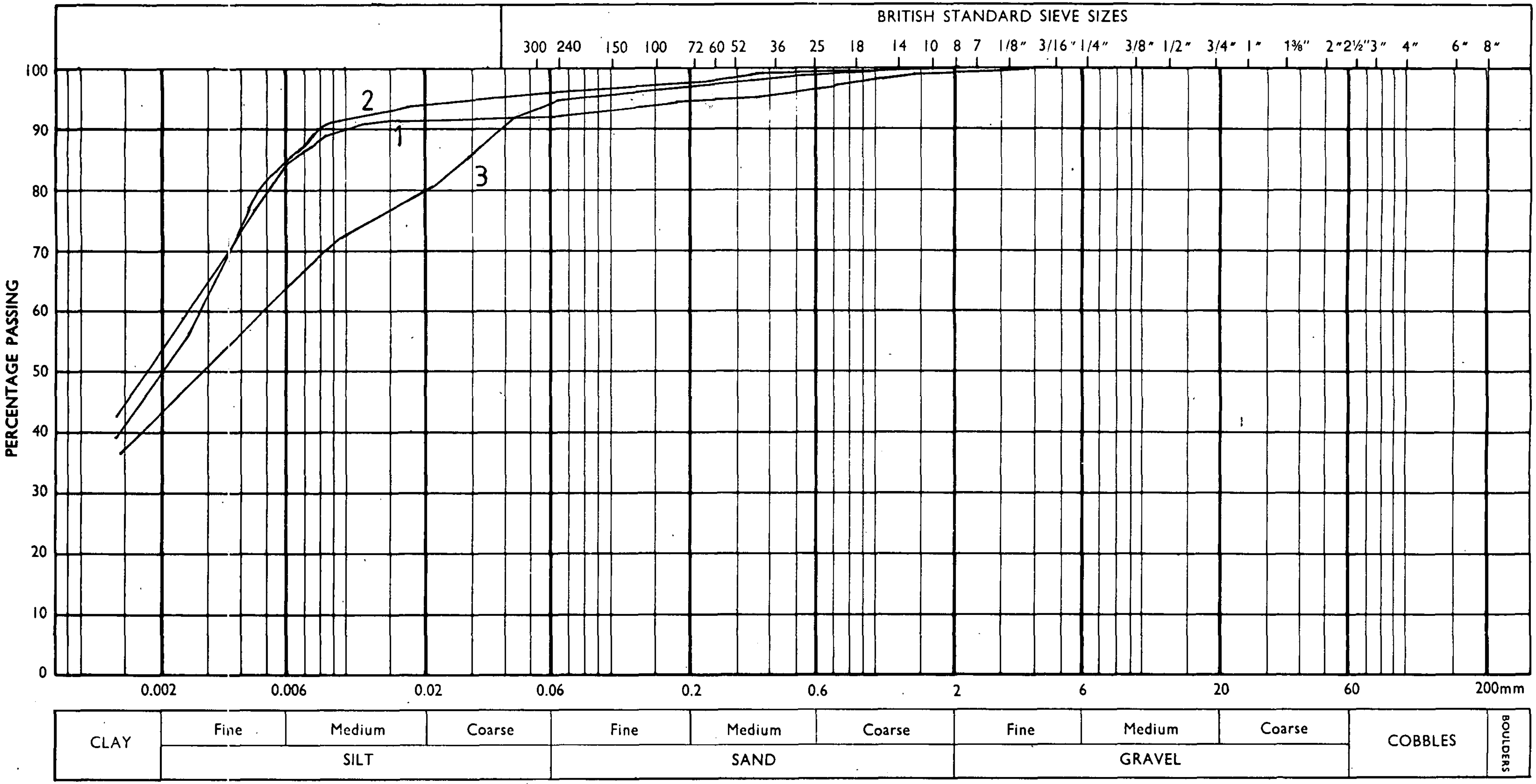
Deeside data

Fig. 6 A-line plot of the test results and for the Deeside area

Fig. 7 Particle size distribution

Project Wrexham Borehole No Sample No 1-3 Pretreatment details

Date of test Description Weathered Coal Measures Loss on pretreatment



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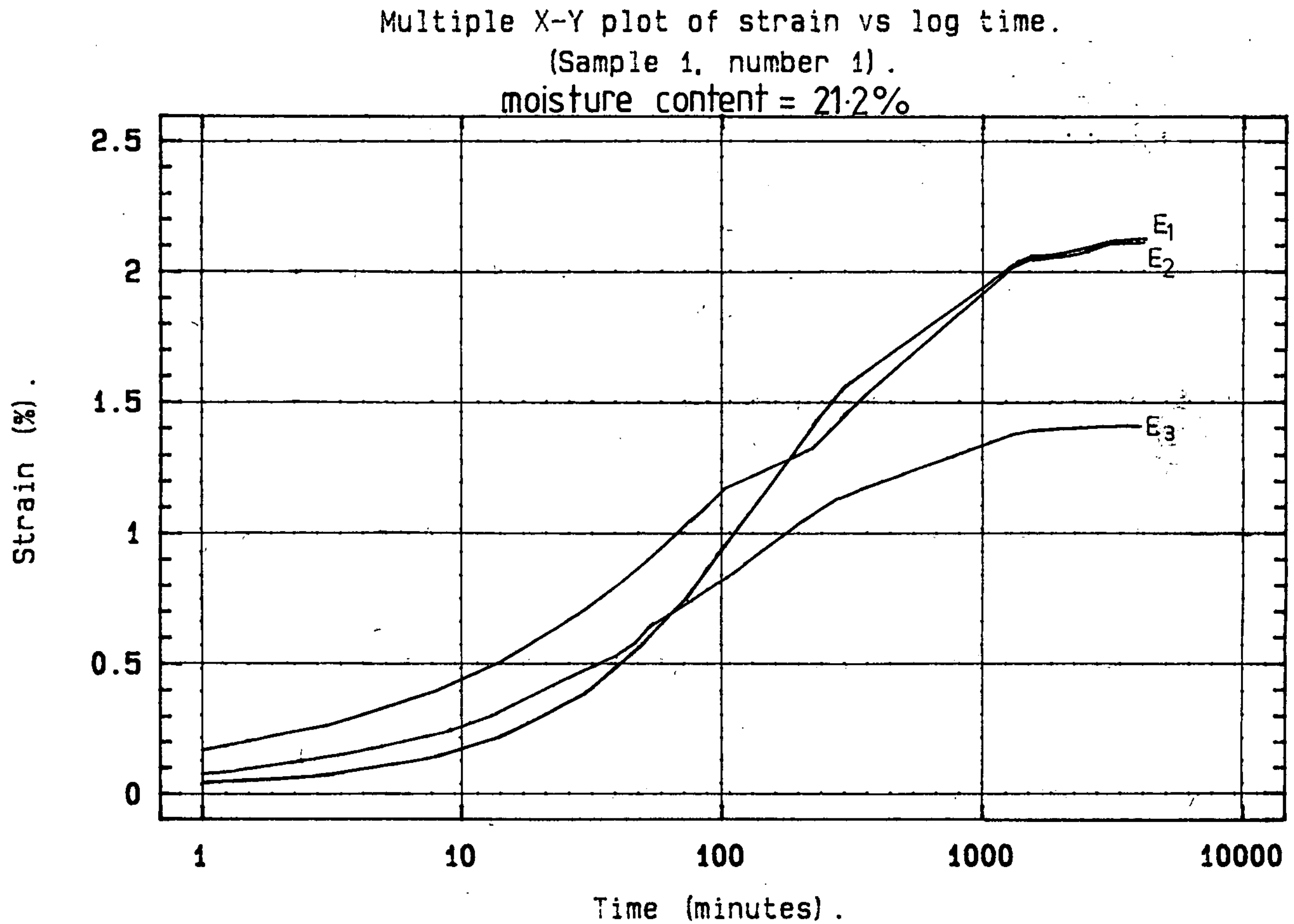

Fig. 8 Multiple X-Y plot of strain vs time for sample 1, number 1

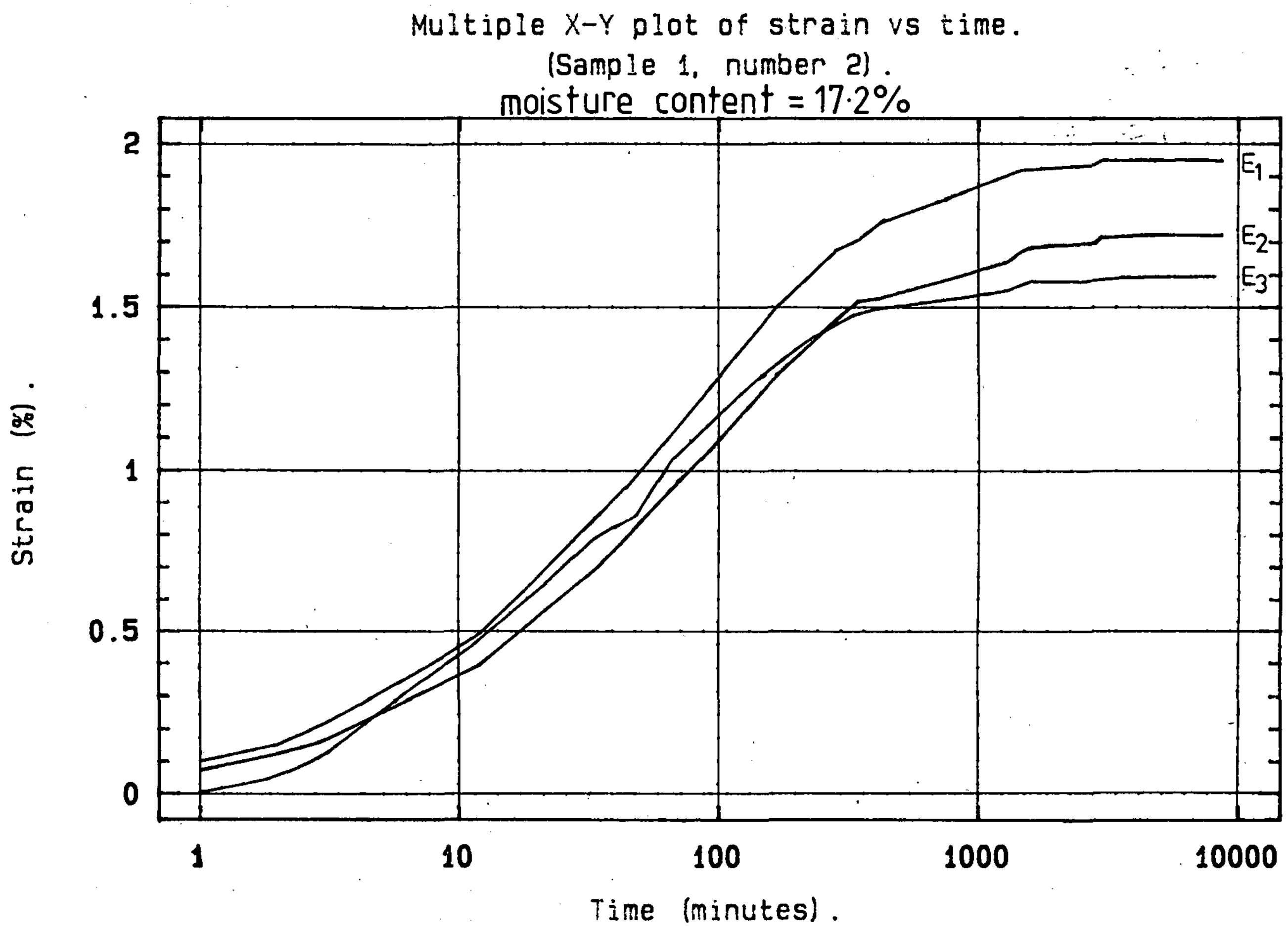

Fig. 9 Multiple X-Y plot of strain vs time for sample 1, number 2

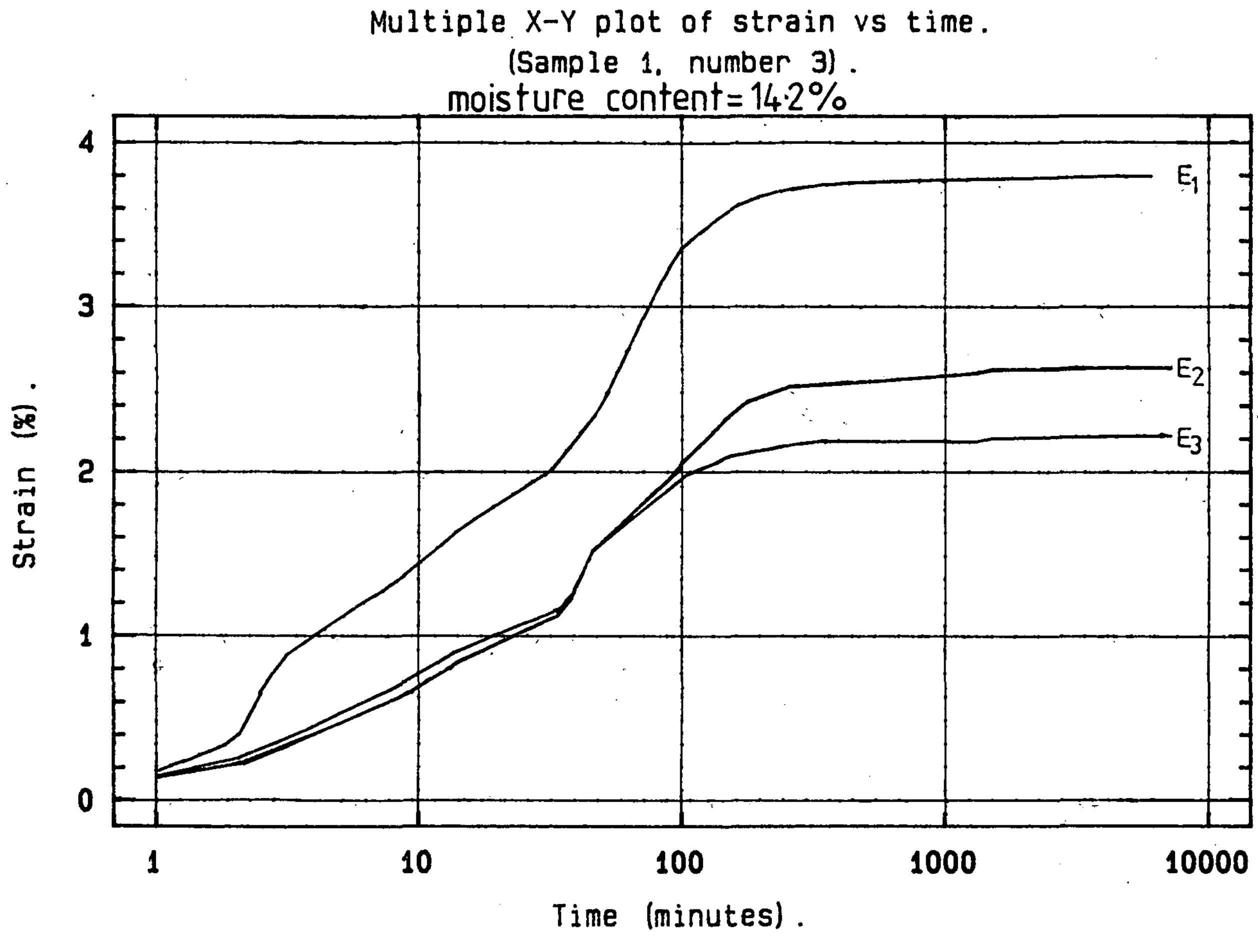

Fig. 10 Multiple X-Y plot of strain vs time for sample 1, number 3

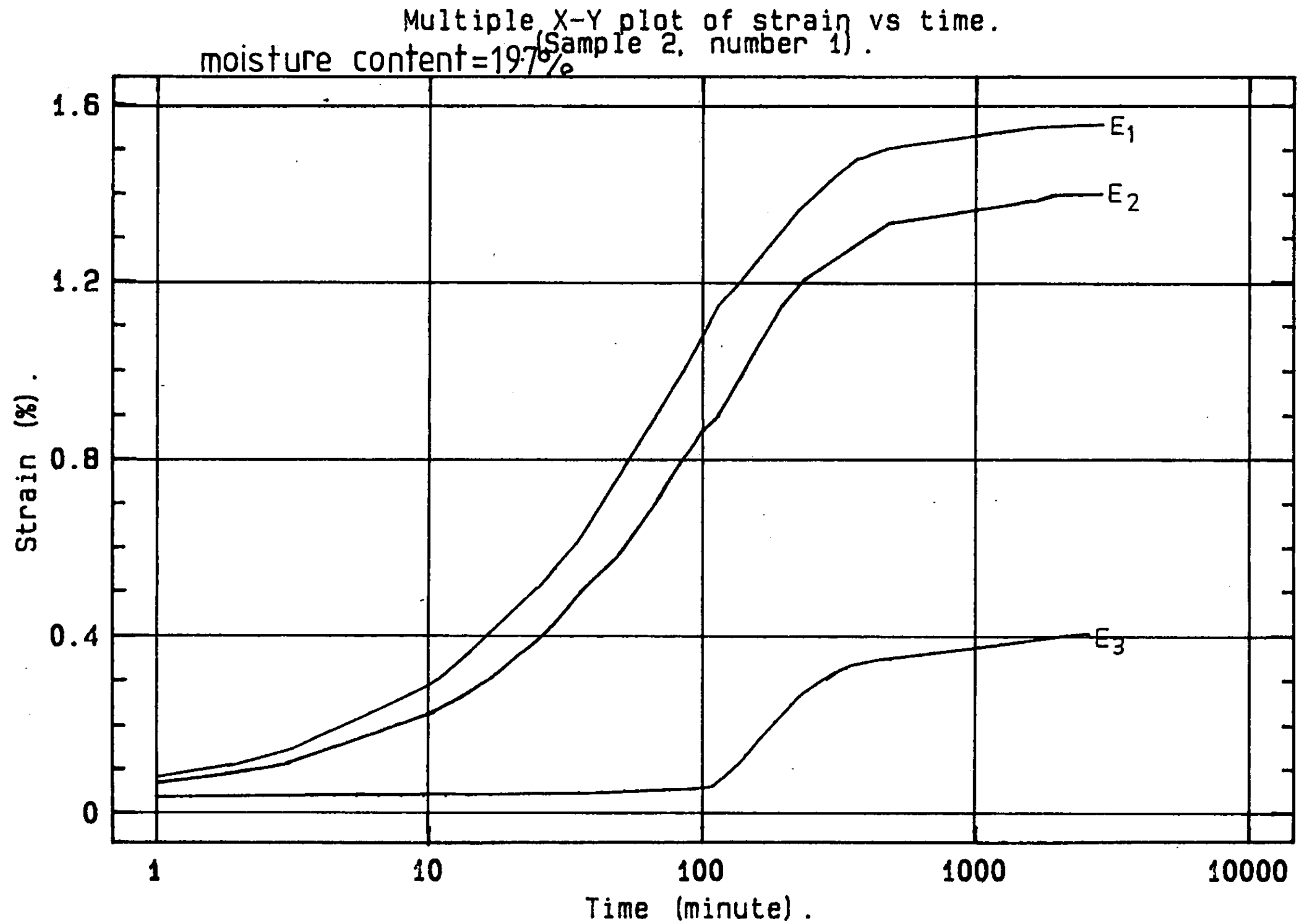

Fig. 11 Multiple X-Y plot of strain vs time for sample 2, number 1

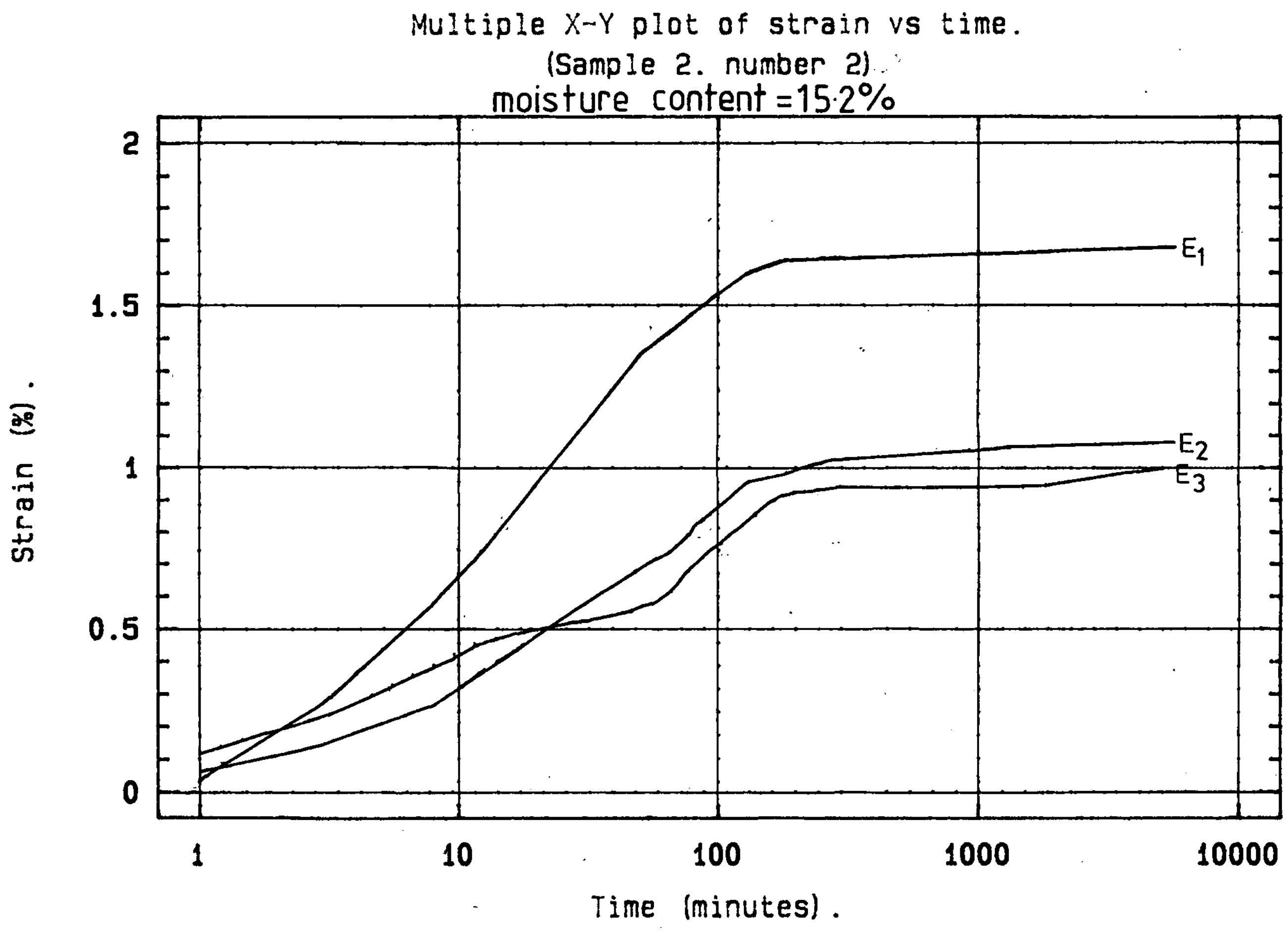

Fig. 12 Multiple X-Y plot of strain vs time for sample 2, number 2

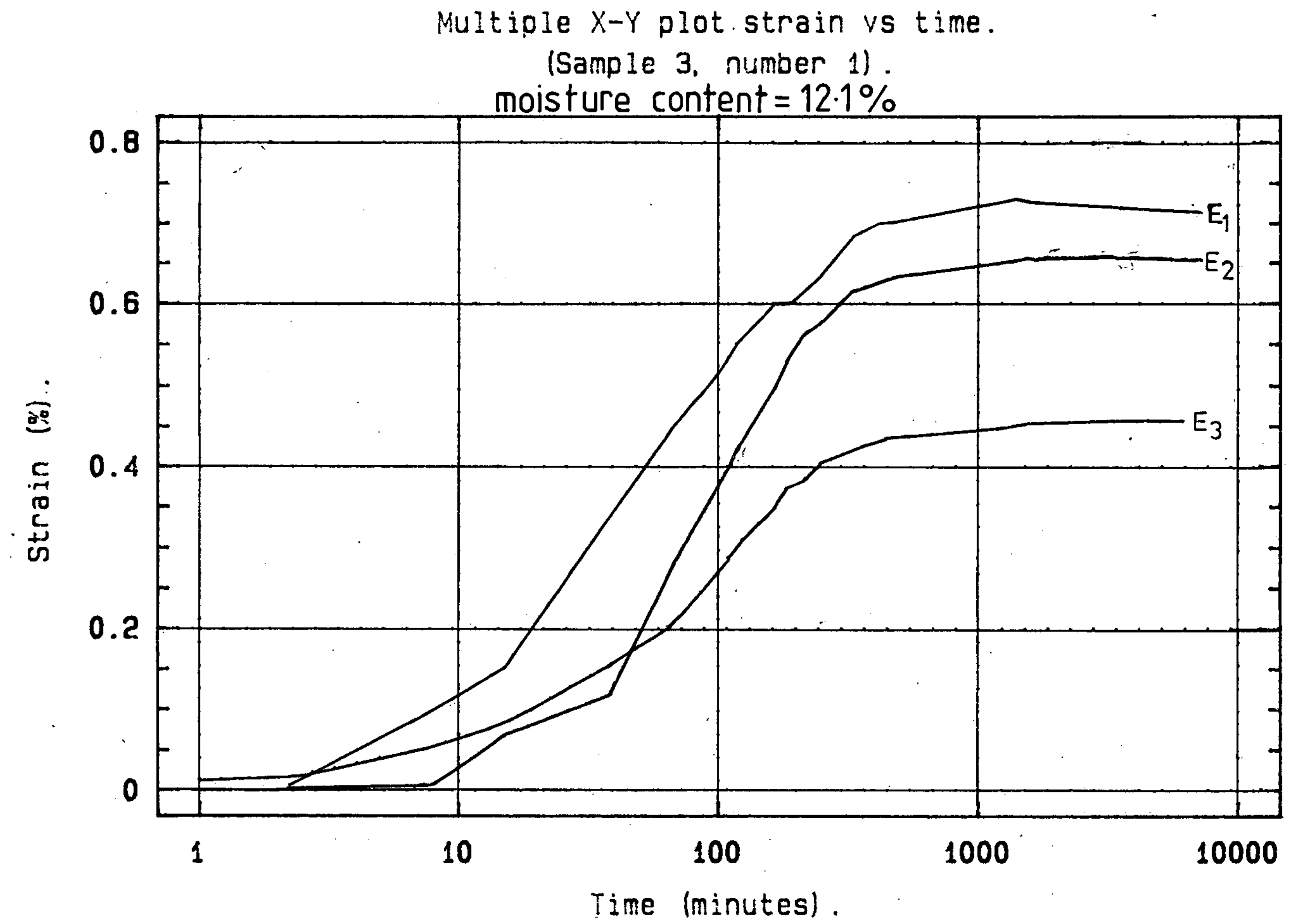

Fig. 13 Multiple X-Y plot of strain vs time for sample 3, number 1

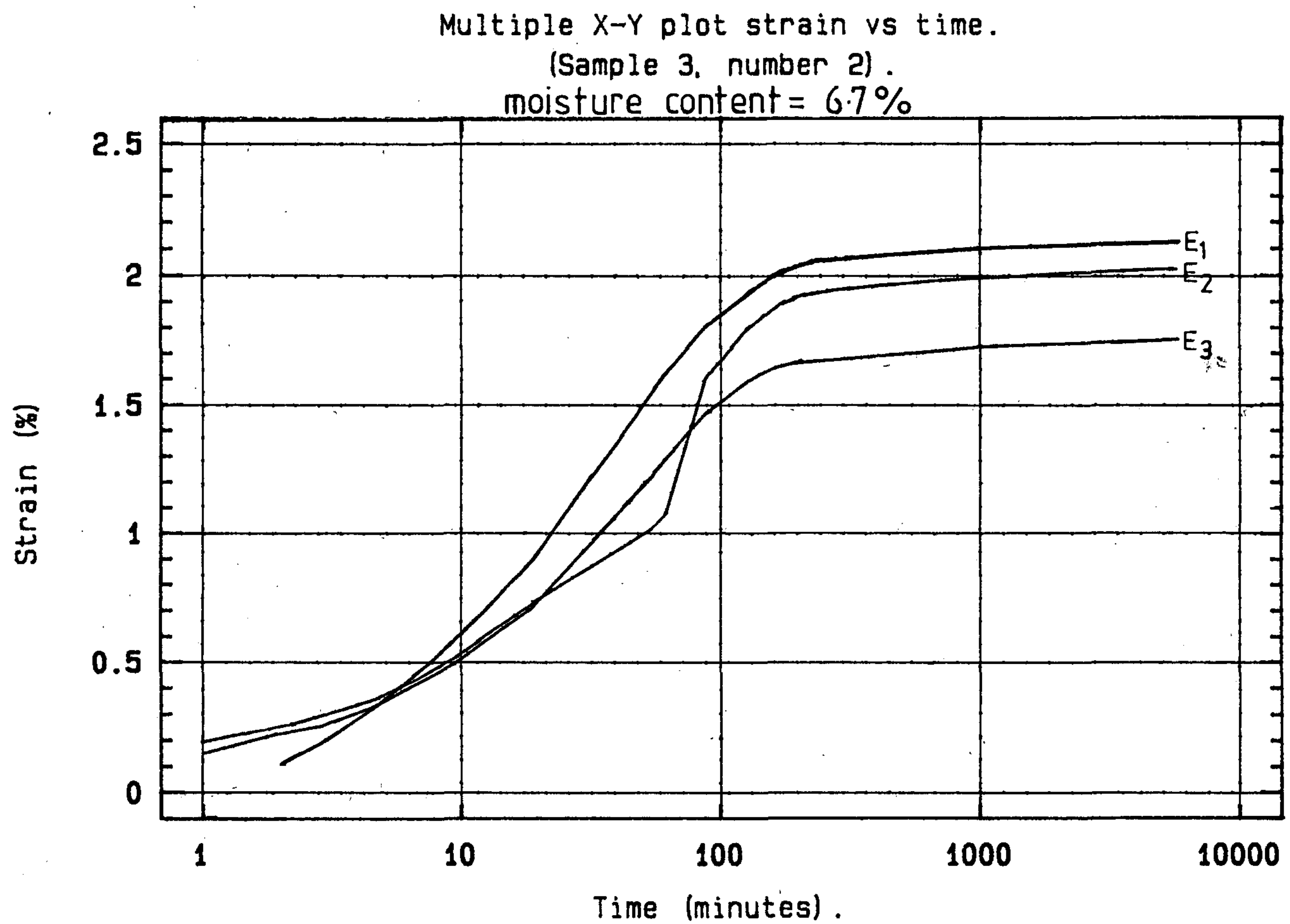

Fig. 14 Multiple X-Y plot of strain vs time for sample 3, number 2

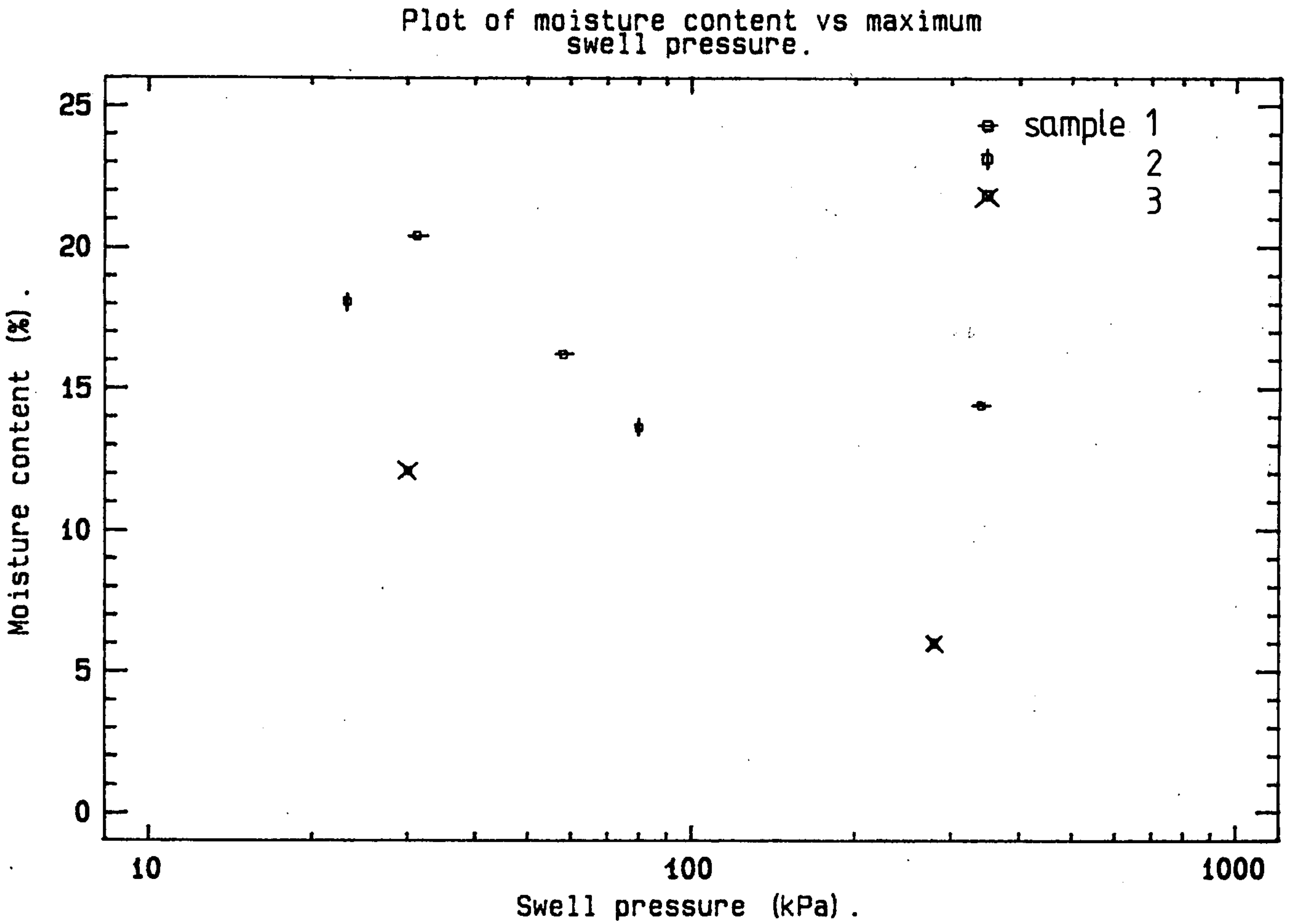

Fig. 15 Plot of swelling pressure vs moisture content

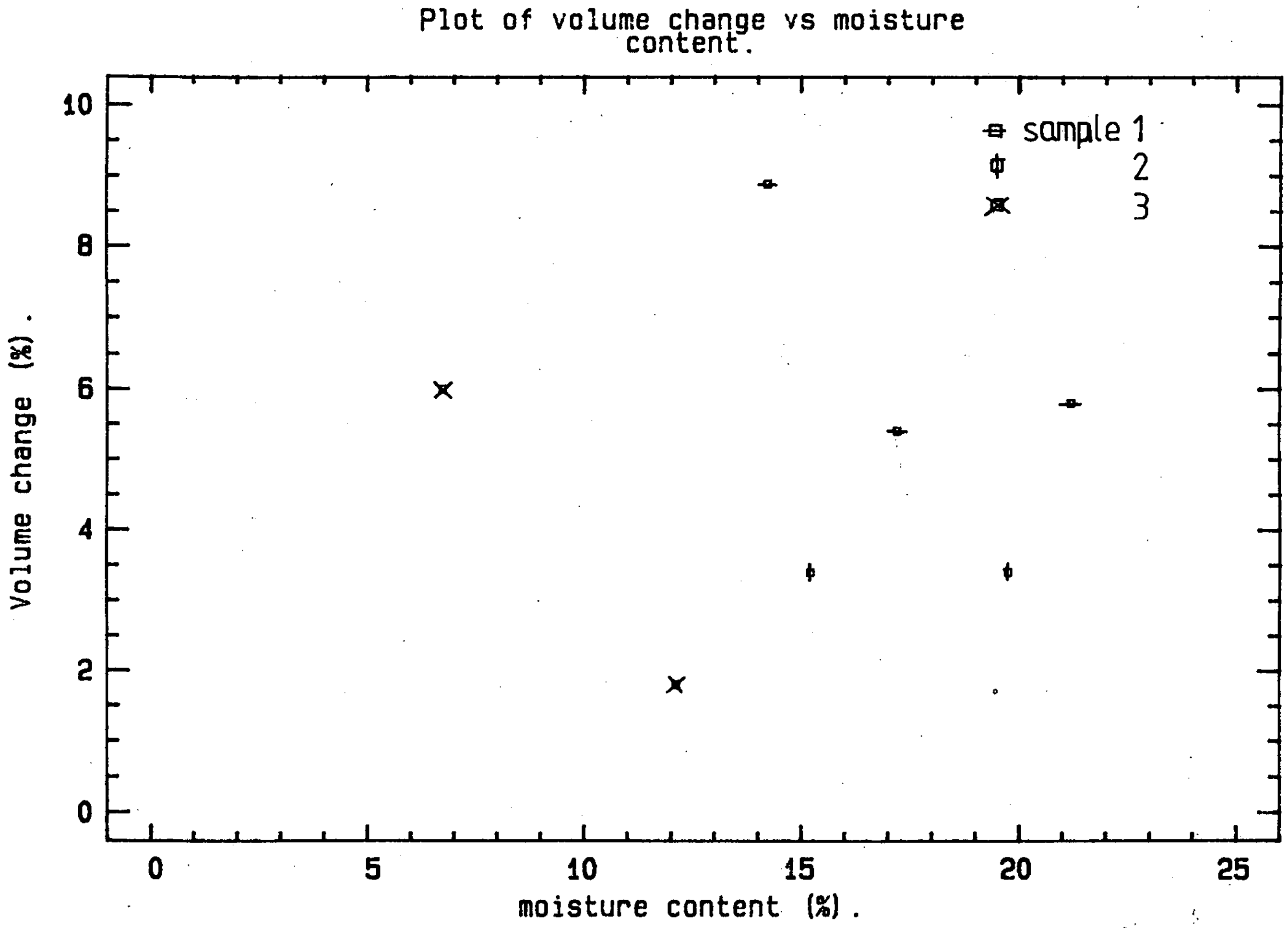

Fig. 16 Plot of volume change vs moisture content

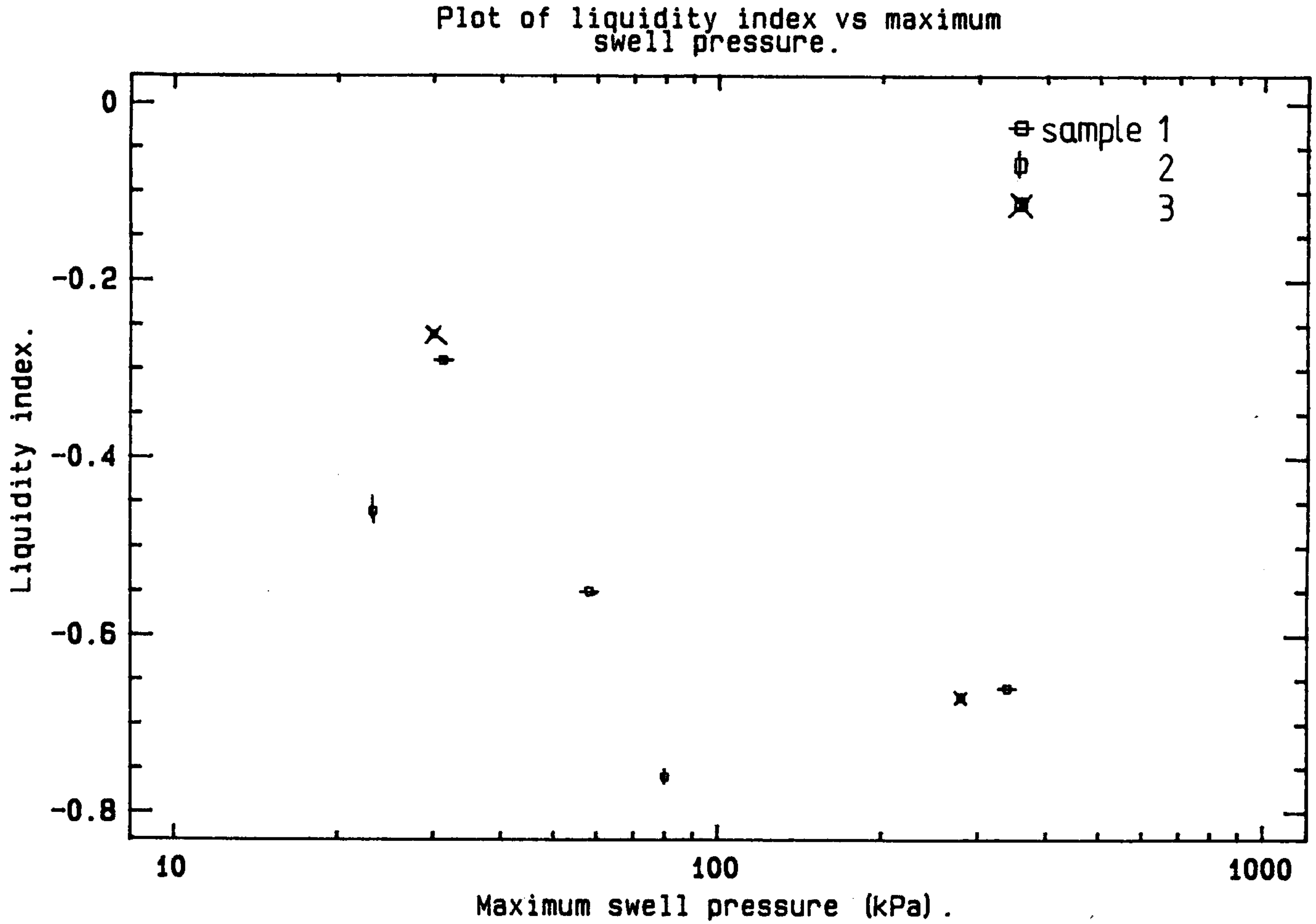

Fig. 17 Plot of swelling pressure vs liquidity index

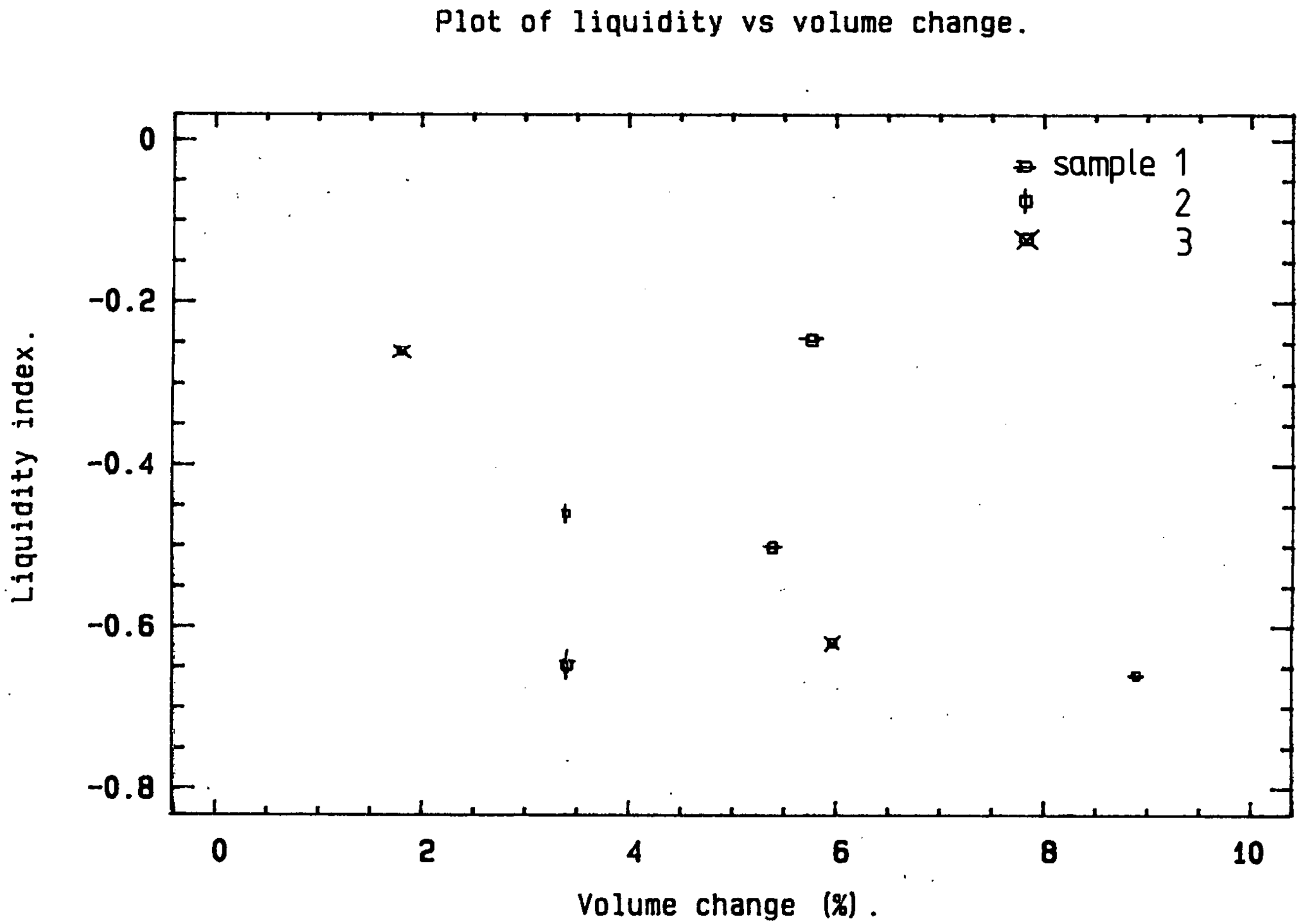

Fig. 18 Plot of volume change vs liquidity index

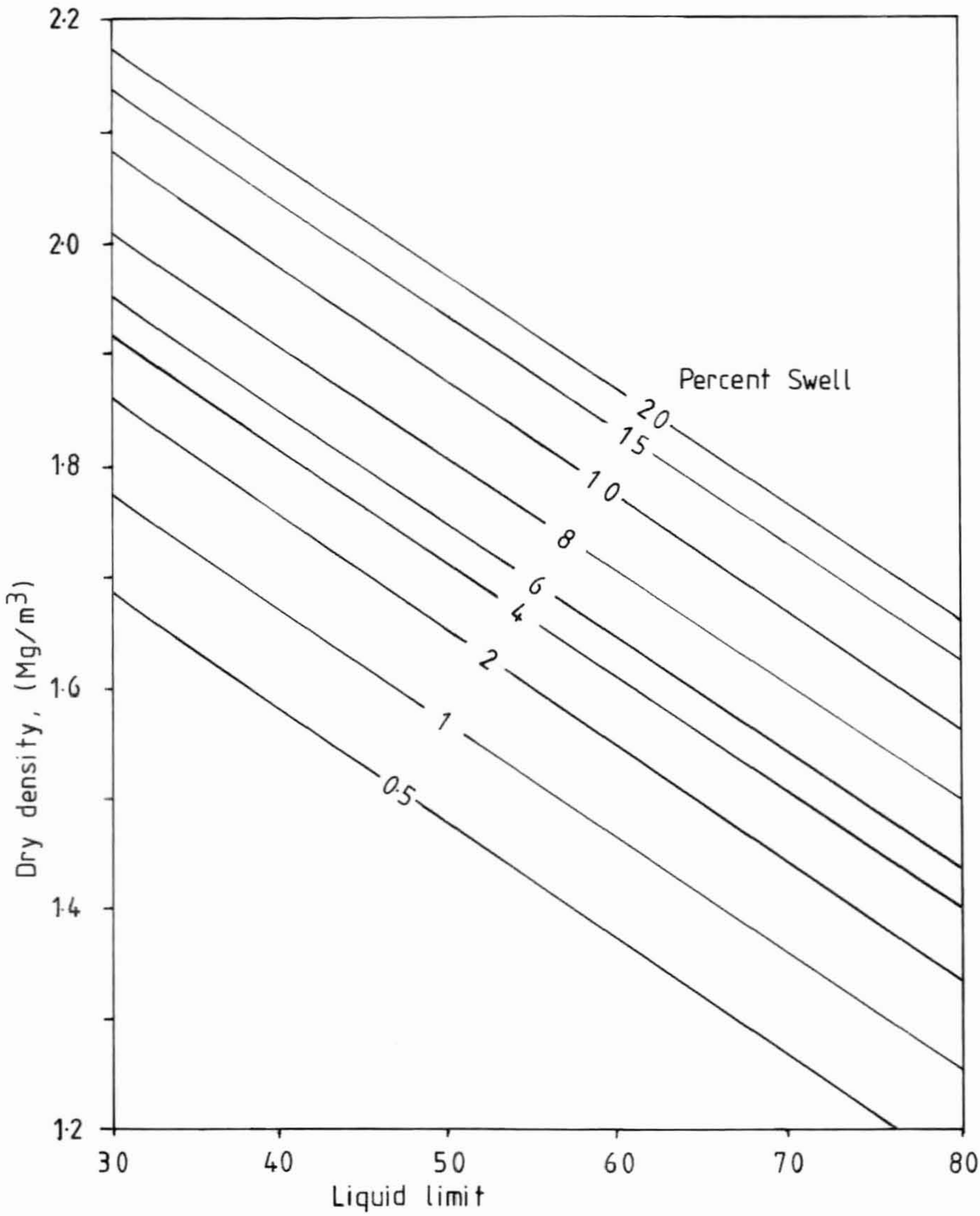

Fig. 19 Correlation of percent swelling strain, liquid limit and dry density (After Vijayvergiya and Sullivan 1974)

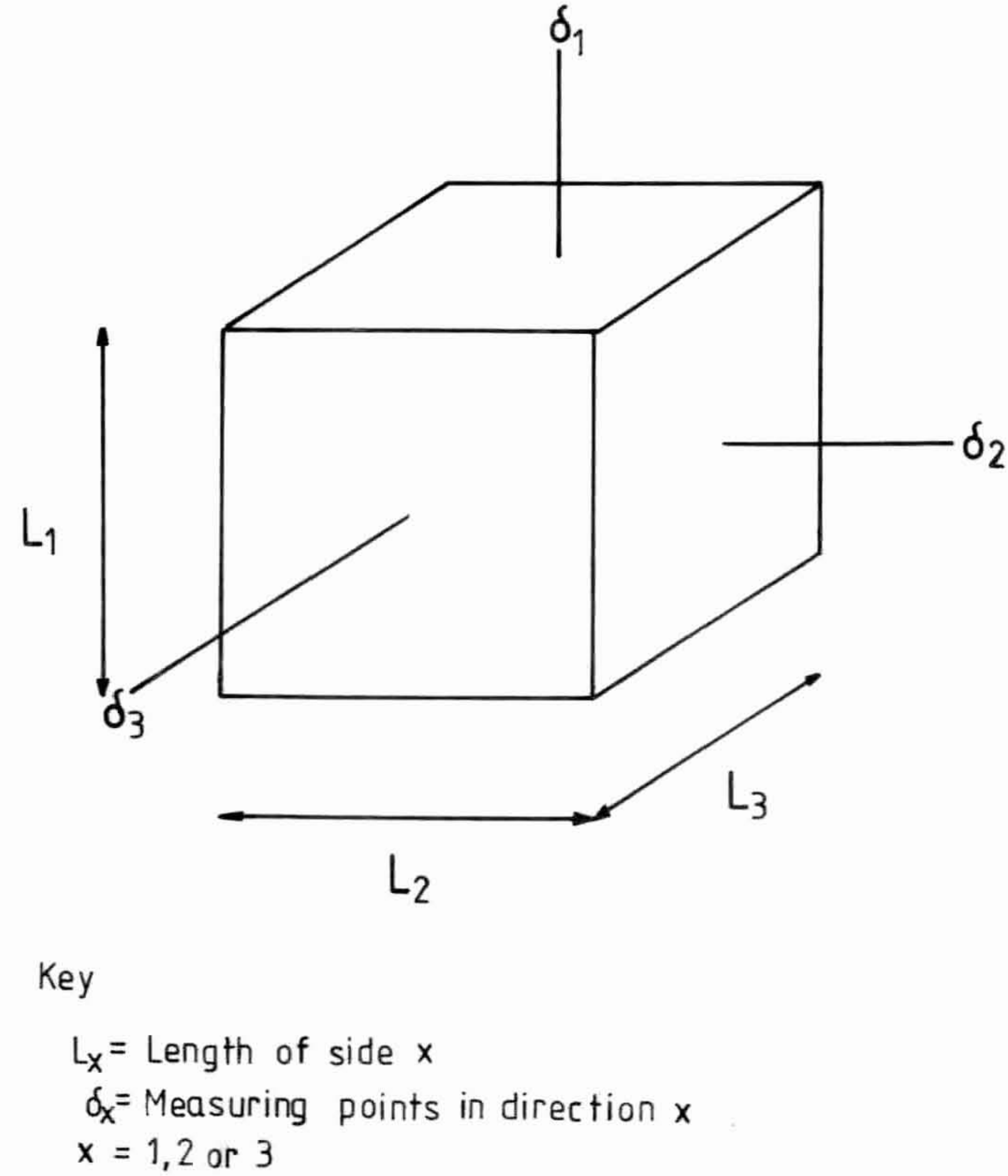

Fig. 20 Schematic diagram of the three-dimensional unconfined swell strain test