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SWELLING CHARACTERISTICS OF SOME BRITISH MUDROCKS

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ABSTRACT

One-dimensional swelling tests were conducted on seven undisturbed and remoulded heavily-overconsolidated clays and indurated mudstones. The samples cover a wide range of properties in terms of geological age, mineralogy, plasticity and diagenetic bonds. It is found that swelling proceeds faster than is predicted by Terzaghi's theory of swelling at low overconsolidation ratios (OCR), but it is slower at high OCR values, probably due to the prominence of secondary swelling. The results show that swelling is of a progressive nature, regardless of plasticity and diagenetic bonds. The coefficient of swelling decreases and the ratio of secondary to primary swelling increases with increasing OCR. At high OCR's, the former drops by more than an order of magnitude below the coefficient of consolidation; the latter can be as high as 0.6 within a log-cycle of time. Progressive softening and failure phenomena in mudrocks are considered to be due to the combined effects of progressive swelling and breakdown of diagenetic bonds. Swelling pressure is found to be indicative of *in situ* stress conditions. The average swelling index generally increases with pre-consolidation pressure in remoulded samples. Three types of diagenetic bonds are postulated: carbonate cements, viscous-adsorbed-water-type, and mechanical adhesion. Bonds tend to decrease the swelling index and so increase the coefficient of swelling. The fabric of the samples is far different from that assumed in the double-layer theory, which can qualitatively predict the physico-chemical forces involved in swelling. Dead volume, in which the double-layer force cannot operate, is shown to be large. The results of tests using n-decane as pore fluid to suppress osmotic swelling indicates that mechanical swelling is more than 50 to 60 per cent of total swelling in the samples. Both mechanical and total swelling indices are linearly correlated with liquid limit among remoulded samples. except for the Fuller's Earth clay which contains at least 65 per cent smectite (expandable clay).

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CHAPTER 1 INTRODUCTION

Mudrocks or argillaceous rocks, including heavily-overconsolidated clays, claystones, siltstones and shales, are the predominant sedimentary rocks in the earth's crust, constituting some 45 to 55 per cent of sedimentary rock sequences (Tucker, 1981). It is not surprising, therefore, that they are so frequently encountered in various engineering projects, *e.g.* foundations, natural or man-made slopes, underground works, and as construction materials (Taylor & Spears, 1981).

In this chapter a general review of mudrock behaviour is carried out with special reference to their swelling characteristics.

1-1 General Characteristics of Mudrocks

In general, mudrocks have the following characteristics:

(a) high clay contents,

(b) high overconsolidation ratios,

(c) diagenetic effects of various degrees, and

(d) discontinuities, *e.g.* bedding planes, slickensides, joints and irregular fractures, of various scales.

Mudrocks usually contain more than 50 per cent of clay minerals and, together with quartz, more than 80 per cent on a world-wide basis, as shown in Table 1-1. The highest clay mineral content, 70 per cent, is from the average U.K. mudrocks, which has been distorted by the inclusion of Fuller's Earths in the data of Smith (1978). Other components are in total no more than 20 per cent. Due to their affinity for water, clay minerals are responsible for the volume change with pressure variation in clays and mudrocks. Normally consolidated clays, which have experienced pressures no more than their existing overburden pressures, swell when pressure is reduced.

Table 1-1 Average mineral composition of mudrocks (world-wide)

	Yaalon (1962)	Shaw & Weaver (1965)	Pettijohn (1975)	Smith (1978) U.K.	Smith (1978) U.S.A.
Clay minerals	59	66.9	58	70	61
Quartz	20	36.8	28	29	36
Feldspar	8	4.5	6	1	3
Carbonates	7	3.6	5	4	3
Iron oxide	3	0.5	2	3	1
Organic carbon	-	1.0	-	1	1
Miscellaneous	-	0.2	-	-	-

The swelling amount is dependent upon their plasticity. A high content of clay minerals, which usually means high plasticity, endows mudrocks with as great a swelling 'potential' as normally-consolidated clays have. However, mudrocks have been subjected to great pressure. The pressure history is usually expressed as overconsolidation ratio (OCR), which is the ratio of the pre-consolidation pressure (P_c) to the present overburden pressure (P_o). At depth mudrocks have been strengthened to various degrees by diagenetic processes, *e.g.* mineral transformation, change of pore water composition, cementation, *etc*. It is the variation in OCR and diagenetic effects that make mudrocks behave differently. Swelling of mudrocks is usually a function of time, due not only to low permeability as normally consolidated clays have, but also to a progressive decay of diagenetic bonds and release of inbuilt strain energy by weathering or other agents. Mudrocks almost always have various scales of discontinuities and their over-all behaviours could be very different from the intact parts. Greater strains have been found normal to bedding in black shale cores and ascribed to greater permeability along bedding planes (Harper *et al*., 1978). Certainly this kind of preferential swelling and the resultant non-uniform softening have been deciphered as one of the reasons for the progressive nature of mudrocks by researchers (for example, Mesri *et al*., 1978).

Some mudrocks have been classified as 'problem rocks', having the property of extensive swelling. Amongst the problem mudrocks cited by Legget and Karrow (1983) are the Bearpaw Shale (containing smectite) of the mid-west of North America and the Lake Erie Shale (which contains pyrite) of Cleveland. Both are well-known since the former swells because of intrinsic clay mineral behaviour, whilst the latter can heave due to pyrite oxidation and subsequent sulphate formation.

Clay soils susceptible to significant volume change underlie about 20 per cent of the U.S.A. and the annual damage to property, regarded by some as being of natural disaster proportions, is estimated by Holtz (1983) to be about $6 billion per annum at 1982 prices. The scale of the problem is considered less in the U.K. because of the mild, damp climate (Driscoll, 1983). Nevertheless, the shrinkage of heavy clays (from Lias to London Clay) in East and Southeast England is particularly severe in drought years. Reece (1980) estimated the damage cost between 1971-80 to dwellings resulting from those clays to be about £250 million. Most of this cost can be ascribed to the drought of 1975-6. Construction difficulties associated with swelling have commonly been encountered in foundations on clay shales, especially in some dam projects in North America, *e.g.* Saskatchewan, Oahe and Fort Peck (Peterson & Peters, 1963; Knight, 1963; Underwood *et al.*, 1964). Anchoring had to be adopted to guard against prolonged heaving after excavation. Phenomena of volume change, due to: (a) chemical processes, *e.g.* pyrite oxidation, precipitation or decomposition of soluble minerals by ground water (Taylor & Cripps, 1984). (b) pore water pressure change, affecting effective stresses in foundations (for example, Penman, 1978), (c) frost and permafrost in cold regions (Andersland & Anderson, 1978), are not considered in this study.

The stability of mudrocks in slopes has long been a major problem in geotechnical engineering. The progressive development of sliding in the Cucaracha and Culebra Shales along the Panama Canal is one of the best known examples in the international literature (Lutton & Banks, 1970; Banks *et al.*, 1975). Progressive failure, which is a function of the brittleness of the material (Bishop. 1966), is a post-peak shear strength reduction phenomenon incorporating comminution and softening of the material. Pore water pressure responses to shear strain can influence the rate at which the movements develop. In these circumstances the process can be said to be progressive in both space and time. A pertinent review of this topic is given by Bjerrum (1967) in his Terzaghi Lecture; see also Chandler and Skempton (1974), Simons and Menzies (1978).

Swelling and deterioration are common problems in tunnelling through mudrocks. A typical example is a 150 m long horseshoe tunnel through shales, constructed in association with Tittesworth Dam (Wood, 1975). Swelling occurred at a faster rate than could be tolerated by the traditional tunnel supports of light arches and bars, because of inadequate regard for the effects of swelling ground. Qu *et al.* (1981) also presented a good case history of swelling damage caused by a smectite-containing rock layer in an underground excavation in China, which was enhanced by the dehydration of clay minerals during drying in air.

In drilling industry, water-sensitive mudrocks, known as mud-making, caving or sloughing shales, cause wellbore instability. Inhibited, potassium-based drilling fluids have frequently been used to minimize the swelling/dispersion behaviour of the included clay minerals (O'Brien & Chenevert, 1973; Streiger, 1982).

1-2 Classification of Mudrocks

With regard to the classification of fine-grained inorganic sedimentary materials, there has been no generally-accepted system. The engineering classification of fine-grained soils and rocks has been a subject of considerable debate.

Pettijohn (1975) defined shale as a laminated or fissile rock and suggested that the term 'mudstone' might be applied to those which were neither fissile nor laminated but were blocky or massive.

Tucker (1981) considered that 'mudrock' was useful as a general term for claystone, siltstone and shale. This viewpoint was also adopted by Stow (1981) and Taylor and Spears (1981), and is followed in this study. However, Potter *et al.* (1980) used the term 'shale' as the major class name for fine-grained terrigenous rocks, based on historical arguments and 'common usage'. The special term 'clay shale' has contributed to confusion, although its use in practice generally has been beneficial because it is associated with a characteristic complex of problems, which draws special attention to its peculiar behaviour. According to Ries and Watson (1947), clay shale is the intermediate form between shale and clay *per se*, the latter being used as a rock term. The general suspicion is that the term gained favour in the U.S.A. because of the wide spatial distribution of smectite-rich mudrocks of Upper Cretaceous and Tertiary age which have posed problems on engineering sites.

Stow (1981) offered a relatively simple geological classification, based mainly on partical size (Table 1-2). Potter *et al.* (1980) included the state of induration in their system, in addition to those used by Stow (1981). The boundaries between non-indurated, indurated and incipient metamorphic materials are important because of the sensitivity of the geotechnical properties to the nature and degree of induration as materials range from an active soil to an inactive rock. For soils the Atterberg limits have generally been accepted as the criterion of classification in the Casagrande plasticity chart and the unified soil classification system (Lambe & Whitman, 1969). For durable rocks, rock mass classification systems mainly considering discontinuities can be used (Hoek & Brown, 1980). Existing between normal soils and rocks, mudrocks have variable durability and swelling potential, so additional criteria are needed to resolve the problem types.

Table 1-2 Stow's (1981) mudrock terminology

Mudrock (>50% silciclastic, >50% less than 63 μm)			
Basic terms			
Unlithified	*Lithified/non-fissile*	*Lithified/fissile*	*Approx. proportions/grain-size*
Silt	Siltstone	Silt-shale	>$\frac{2}{3}$ silt-sized (4–63 μm)
Mud	Mudstone	Mud-shale	silt and clay mixture (<63 μm)
Clay	Claystone	Clay-shale	>$\frac{2}{3}$ clay-sized (<4 μm)
Metamorphic terms			
Argillite	slightly metamorphosed/non-fissile		silt and clay mixture
Slate	metamorphosed/fissile		silt and clay mixture
Textural descriptors	*Approx. proportions*		
Silty	>10% silt-size		
Muddy	>10% silt- or clay-size (applied to non-mudrock sediments)		
Clayey	>10% clay size		
Sandy, pebbly, etc	>10% sand-size, pebble-size, etc.		
Compositional descriptors	*Approx. proportions*		
Calcareous	> 10% $CaCO_3$ (foraminiferal, nannofossil, etc)		
Siliceous	> 10% SiO_2 (diatomaceous, radiolarian, etc)		
Carbonaceous	> 1% Organic carbon		
Pyritiferous Ferruginous Micaceous and others	Commonly used for contents greater than about 1–5%		

Underwood (1962) divided mudrocks into two broad groups: (a) Soil-like (or compacted), and (b) rock-like (or cemented), as proposed by Mead (1936). He also related significant physical properties of mudrocks to probable *in situ* behaviour on construction sites (Table 1-3). Principally Table 1-3 is based on the parameters of strength, swelling, mineralogy, activity ratio and slaking, most of which are closely interdependent to some extent. Morgenstern and Eigenbrod (1974) differentiated soils from rocks, based on the idea that a soil would disintegrate when exposed in an unconfined manner to water, but a rock would not unless slightly dried or mechanically disturbed. They used the parameters of strength softening, slaking and also slaking rate. Slaking test has also been recommended for the classification purpose by the International Society for Rock Mechanics (1979). In 1981 Taylor and Spears suggested Gamble's (1971) durability-plasticity classification for less indurated types and Olivier's (1976) uniaxial strength - swelling coefficient relationship for moderately strong to very strong mudrocks (Fig. 1-1). In conclusion, swelling and slaking are usually necessary in classifying the mudrocks with a strength between soils and durable rocks.

1-3 Clay Mineralogy

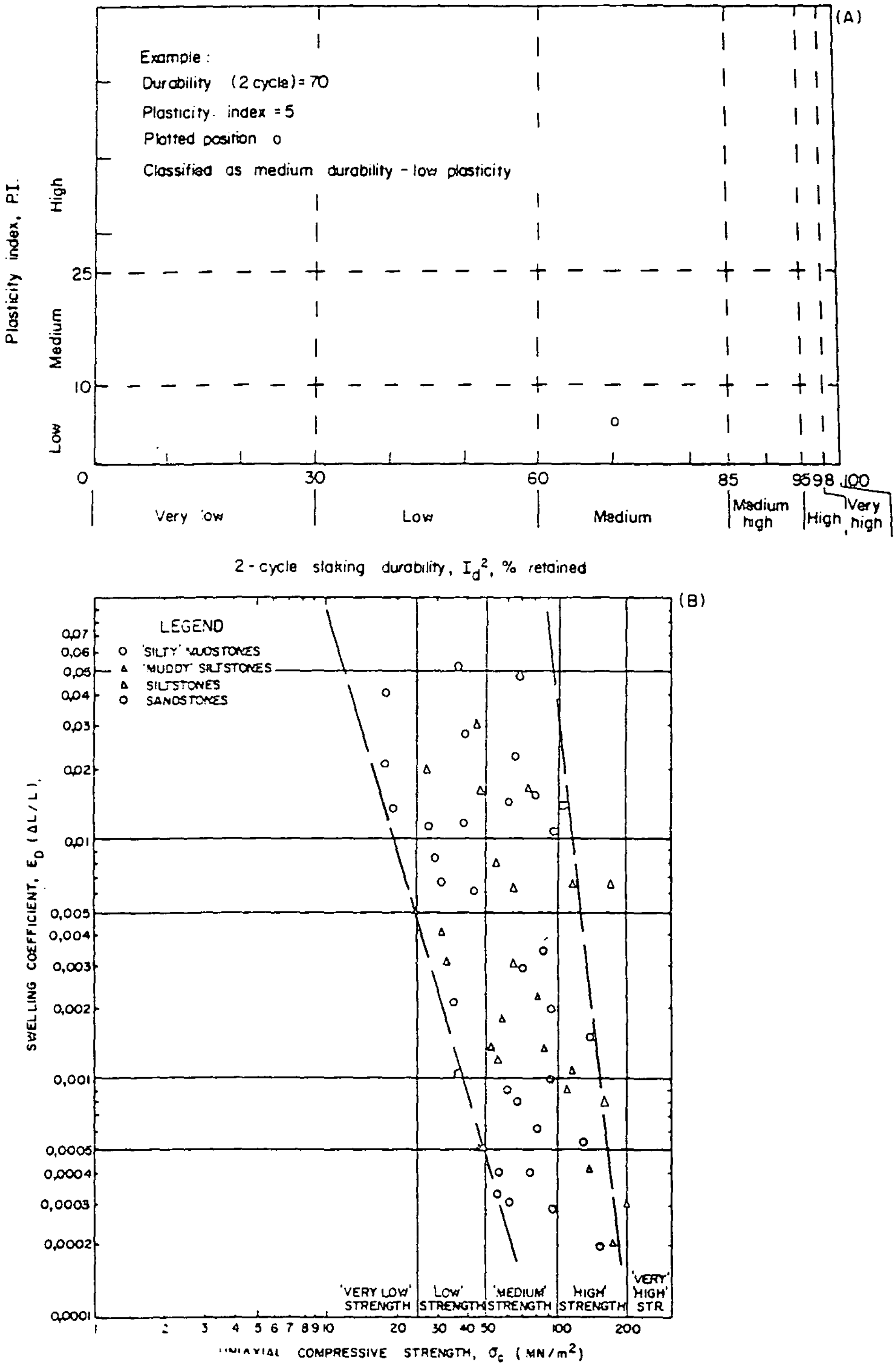
The importance of clay minerals with reference to the behaviour of mudrocks has been mentioned in Section 1-1. To gain an understanding of the properties of mudrocks, thereby, it is necessary to examine the essential features of the crystal structures of clay minerals, since their distinguished behaviours mainly come from the hydrous layer silicate structure.

Clay minerals are hydrous layer silicates, part of the larger family of phyllosilicates. The layer silicates contain continuous

Table 1-3 Underwood's (1967) engineering evaluation of mudrocks

Physical properties			*Probable in situ behaviour*						
Laboratory tests and in situ *observations*	*Average range of values*		*High pore pressure*	*Low bearing capacity*	*Tendency to rebound*	*Slope stability problems*	*Rapid slaking*	*Rapid erosion*	*Tunnel support problems*
	Unfavourable	*Favourable*							
Compressive strength, lbf in^{-2} (x 6.895 kN m^{-2})	50–300		yes	yes					
		300 5000							
Modulus of elasticity, lbf in^{-2} (x 6.895 kN m^{-2})	20.000 - 200.000			yes					yes
		2 x 10^5 - 2 x 10^6							
Cohesive strength, lbf in^{-2} (x 6.895 kN m^{-2})	5 100				yes	yes			yes
		100–>1500							
Angle of internal friction, degrees	10 20				yes	yes			yes
		20 65							
Dry density, lb ft^{-3} (x 0.016 Mg m^{-3})	70–110		yes					yes?	
		110 160							
Potential swell, percentage	3 15				yes	yes		yes	yes
		1 3							
Natural moisture content, percentage	20 35		yes			yes			
		5 15							
Coefficient of permeability m s^{-1}	10^{-7} – 10^{-12}		yes			yes	yes		
		$>10^{-7}$							
Predominant clay minerals	Montmorillonite or illite		yes			yes			
		Kaolinite or chlorite							
Activity ratio = $\frac{\text{plasticity index}}{\text{clay content}}$	0.75–>2.0					yes			
		0.35 0.75							
Wetting and drying cycles	Reduces to grain sizes						yes	yes	
		Reduces to flakes							
Spacing of rock defects	Closely spaced			yes		yes		yes?	yes
		Widely spaced							
Orientation of rock defects	Adversely orientated			yes		yes			yes
		Favourably orientated							
State of stress	Greater than existing overburden				yes	yes			yes
		About equal to existing overburden							

Fig. 1-1 (a) Gamble's (1971) durability-plasticity classification
(b) Olivier's (1971) uniaxial strength -- swelling coefficient relationship



two-dimensional tetrahedral sheets of SiO_5 and octahedral sheets of $Al_2(OH)_6$ (called gibbsite structure) or $Mg_3(OH)_6$ (called brucite structure) (Fig. 1-2). On the basis of layer types, which are made up of the two sheets, clay minerals can be classified into 1:1, 2:1, 2:1:1 and mixed-layer (or interstratified) types.

Far away from the ideal structures, much of clay mineral material in natural clays and mudrocks has appreciable structural disorder and many illites, for instance, are highly disordered (or poorly crystallized). Also involved in the order-disorder question is isomorphous substitution; Al^{3+} or Fe^{3+} for Si^{4+} in tetrahedral sheets and Fe^{2+}, Fe^{3+}, Mg^{2+} or Al^{3+} for Mg^{2+} or Al^{3+} in octahedral sheets. Isomorphous substitution is probably the most important factor leading to a negative charge in clay minerals. In addition, broken bonds, the dissociation of hydroxyl ions on the crystal surface, the absence of cations in the crystal lattice and the presence of organic matter and amorphous allophane also determine the size of the negative charge. Owing to this negative charge, clay minerals have the ability of adsorbing polar water molecules and cations to form a hydration shell. Those cations are exchangeable and their replacing ability can be arranged in an order of:

$$Li^+ < Na^+ < H^+ < K^+ < NH_4^{2+} \ll Mg^{2+} < Ca^{2+} < Ba^{2+} \ll Al^{3+}$$

The cation exchange capacity (CEC) is used to evaluate the basic property of charge deficiency of clay minerals. Table 1-4 shows some typical CEC values of clay minerals and also allophane and organic matter. It has generally been considered (Grim, 1968) that the cation exchange capacity increases with decreasing particle size for minerals such as kaolinite, in which the charge deficiency is due primarily to broken bonds, but remains unchanged in the case of expanding lattice minerals such as smectite, where most of the exchangeable sites are on accessible basal plane surfaces. Disorder

Fig. 1-2 Basic structure of clay minerals (after Taylor and Cripps, 1984)

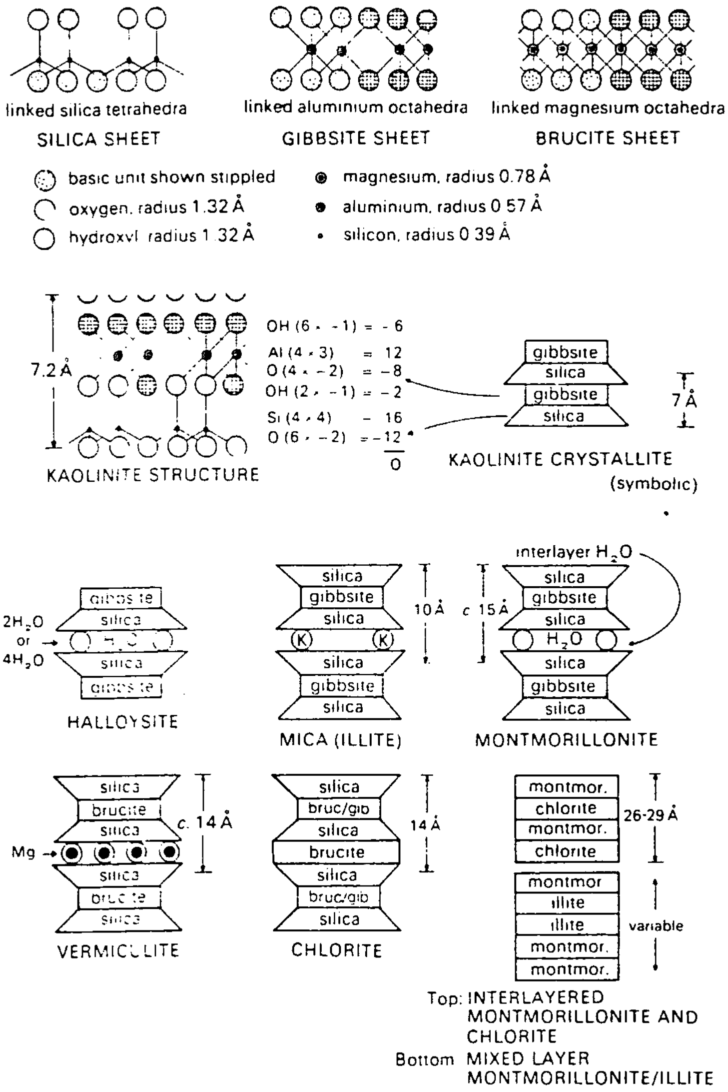


Table 1-4 Cation exchange capacity, surface area and plasticity of clay minerals and other components in sediments (after Grim, 1968 and Lambe & Whitman, 1969)

Material	CEC (meq/100g)	A_s (m^2/g)	P.L.	L.L.	P.I.
0.1 mm sand		0.03			
Kaolinite	3-15	10-20	27-37	38-59	11-23
Illite	10-40	80-100	45-60	79-120	33-67
Smectite	80-150	800	75 81 54	290(Fe) 510(Ca) 710(Na)	215(Fe) 429(Ca) 656(Na)
Chlorite	10-40	5-50			
Allophane	25-70	47-800*			
Organic matter					
in recent sediments	150-500				
in Oligocene clays	3.4-10				
in Carboniferous mudrocks	0.5-1.5				

* After Xidakis (1979).

in the crystal structure also increases the CEC values of clay minerals. For instance, a high CEC value of 22.3 has been found for a highly disordered kaolinite (Worrall, 1958), compared with a normal range of 3 to 15. Another important basic property of clay minerals is the surface area (A_s). Clay minerals usually exist in nature as fine, platy particles (less than 2 μm), because of the weak force between basal planes, and so they have a great specific surface area. Some typical values are shown in Table 1-4. Also included is the A_s value, 0.03 m^2/g, of 0.1 mm sand for comparison. Apart from the size of particles, also important is the intracrystalline space in expandable minerals. For instance, the theoretical surface area of smectite is 800 m^2/g, but the external area is only about one or two tenths, depending upon the particle size again. Table 1-4 also displays some values of the index parameters of plasticity. The close relationships among CEC, A_s and plasticity are noteworthy. The influence of cation types on the plasticity of smectite is also prominent.

In the following discussion on each species, only those clay minerals relevant to this study will be reviewed, mainly after Grim (1968) and Brindley and Brown (1980).

Kaolinite: This is of the 1:1 type (Fig. 1-2), having a tetrahedral sheet and an octahedral sheet in each layer. Rare isomorphous substitution (probably iron and/or titanium for aluminum) exists in kaolinites so that they carry only a small negative charge (Table 1-4). But disordered or degraded kaolinites are not uncommon in sediments and, as already mentioned, they can have a larger CEC value. The layers in kaolinites are bound together by relatively strong hydrogen- or hydroxyl-type bonds and thereby they exhibit no interlayer (or intracrystalline) swelling.

Smectite: This group of clay minerals belongs to the 2:1 type.

consisting of an octahedral sheet between two tetrahedral sheets (Fig. 1-2). The most common member of the smectite group is montmorillonite. Because of a low charge density on the basal plane surface, the strength of the interlayer bonds is weak and, therefore, varying amounts of water molecules and hydrated cations can penetrate into layers, causing the lattice to expand in the direction perpendicular to layers (Fig. 1-2). This kind of intracrystalline expansion is not unlimited in smectites with exchangeable cations other than Na and Li. For instance, Ca-smectite only expands up to about 9 Å, equivalent to three layers of water molecules (Blackmore & Miller, 1961). For a dry Na-smectite, however, the basal spacing first increases in steps, corresponding to various organized layers of water molecules until 40 Å is reached, and then it increases steadily. In natural deposits, Wyoming Bentonite is known as a Na-smectite and used as a drilling fluid to prevent from wall collapsing; whilst the Fuller's Earth in the U.K., a Ca-smectite, cannot be adopted for the same purpose before treatment because of that limited expansion capability. Due to the capability of swelling a small amount of smectite commonly has a disproportionate effect on the properties of mudrocks. According to MacEwan and Wilson (1980), it has become evident that the charge distribution and swelling behaviour of smectites can be highly inhomogeneous from layer to layer. In the sense that layers are unequally hydrated, smectite can be regarded as having mixed-layering; that is, random interstratification of two (or more) successive hydrates. All smectites lose interlayer water in the temperature range 100 to 200° C, giving a collapsed structure with a 10 Å d-spacing.

Illite: These minerals are the most common of the clay minerals in sediments. The name illite does not refer to a single mineral species, but rather to a group of essential non-expandable clays, the most common representative of which is a potassium-rich 2:1 layer type (Fig. 1-2), together with small amounts of interstratified smectite layers. The charge deficiency in the illite lattice is balanced partly by interlayer potassium ions, which are nonexchangeable. Since the size of the potassium ion is such that it fits snugly into the holes formed by the bases of the silica tetrahedra, it provides a very strong bond between layers. In this respect potassium is held with a greater bonding energy than other exchangeable cations and is effective in reducing differential swelling. For this reason it is used in XC-polymer/ KCl-based drilling fluids (O'Brien & Chenevert, 1973; Streiger, 1982). The structure of illites is commonly described as 1Md, implying a disordered stacking with one layer per monoclinic unit cell. Weaver's (1984) X-ray analyses indicate that illites commonly contain 10 to 30 per cent expandable layers, but deeply buried Paleozoic and Pre-Cambrian illites have no expandable layers. These diagenetic illites recrystallize towards a highly ordered 2M muscovite. It is noteworthy that 'Weaver's illites' might not be called illites. which contain no more than 5 per cent of smectite layers, according to Reynolds' (1980) definition. It indicates that there has not been a universally accepted definition of illite.

Chlorite: This is of the 2:1:1 type, containing a brucite-type sheet between parallel 2:1-type layers (Fig. 1-2), and basically has no intracrystalline expansion. Nevertheless, swelling chlorites have been reported; they expand slightly following the glycol treatment. Swelling chlorites are common in the Keuper Marl of the U.K. and continental Europe (Honeybourne, 1951; Jeans, 1978). Smith (1978) found 6 per cent in a sample from Cardiff Docks and this would seem to be the general order of abundance. As will be shown in the next chapter, only small amounts of chlorites are identified in the samples. In practice, however, it assumes importance in the more deeply buried mudrocks (as a neoformed species) in a transition towards the green schist facies of metamorphism.

Mixed-layer clay minerals: Because layer silicates have very similar structures, regular or random interstratification of kaolinite, illite, chlorite or smectite-type layers can occur (Fig. 1-2). According to Weaver and Pollard (1973), random mixed-layer clays are second only to illites in abundance in nature. The most common one is composed of expandable, water-bearing smectite layers and contracted non-water-bearing illite layers. With increasing illite layers, the potassium content of illite-smectite mixed-layer clays increases. Any kind of combination of expandable and non-expandable layers can exist, and also more than one kind of mixed-layering can be in one sample. This has usually made the mineralogical analysis, qualitative or quantitative, very difficult, sometimes impossible. There is no sharp boundary between illite and mixed-layer clays or smectite and mixed-layer clays, either.

1-4 Diagenesis of Mudrocks

After deposition sediments experience many kinds of change, including mineralogy, geochemistry and fabric in geological time. Those changes are generally called diagenesis. Influential factors include temperature, pressure and time and also biological and geochemical activities. During diagenesis sediments take on different properties; as a result, a general review on diagenesis is apposite.

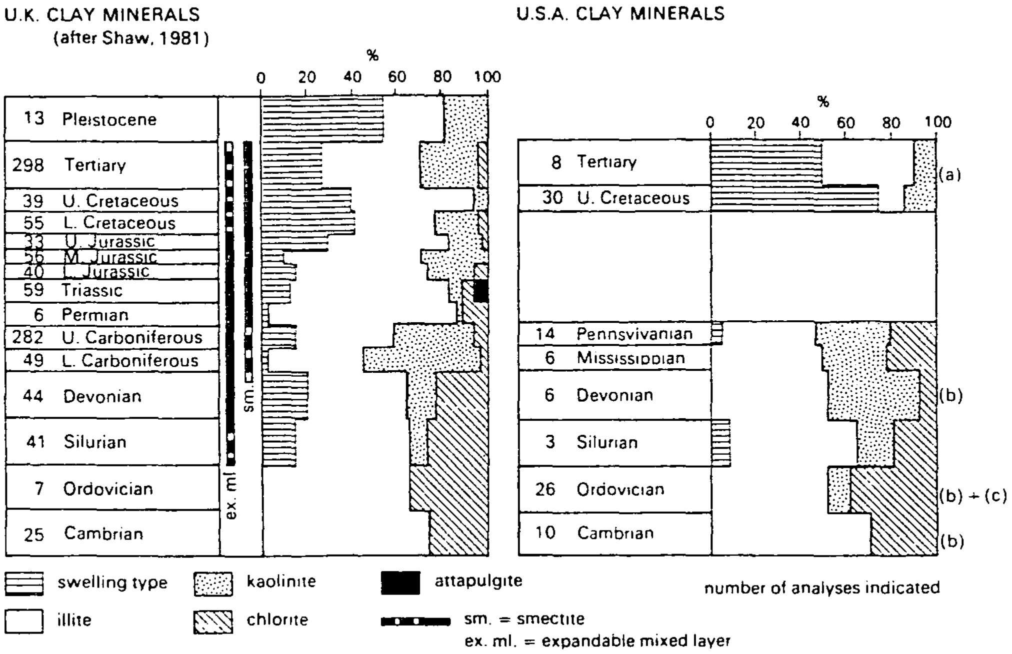
1-4-1 Mineral Diagenesis

As already mentioned in Section 1-1, mudrocks contain more than 80 per cent of clay minerals and quartz. In the environment of diagenesis, quartz remains inert, whereas most of clay minerals are altered in response to the changes of temperature, pressure and geochemical conditions. Figure 1-3 shows the changes of clay mineral contents with geological age as found in the U.K. and the U.S.A. It indicates an increase in illite and chlorite downwards at the expense of kaolinite and expandable clays (smectite and mixed-layer types) over geological time. Because of a complicated combination of influential factors, no definite depth and temperature can be assigned for the boundaries where changes occur. Generally the decrease in smectite starts at 70 to 95°C and at a depth of 1,000 to 2,500 m (Dunoyer De Segouzac, 1970) or possibly no more than 500 m (Muller, 1967). Kaolinite and expandable clays do not persist beyond about 5,000 m (Muller, 1967). The transition between diagenesis and metamorphism occurs at 300°C, independent of pressure (Winkler, 1965, quoted by Singer & Muller, 1983). At a normal geothermal gradient (30°C/km), a depth of *c*. 10,000 m might be expected for this transition. In mountain belts (regional metamorphism), additional thermal energy is produced so that the depth might be reduced to about 6,000 m. The most deeply buried one, Flockton mudstone, of the samples studied has experienced a maximum depth no more than 4,000 m, still far above the transition.

A brief description of mineral diagenesis is made in the following, based on the review of Dunoyer De Segouzac (1970) and the work of Weaver and Beck (1971).

The instability of kaolinite during burial is determined partly by geochemical factors, since it becomes unstable in alkaline conditions. In the transitional zone to metamorphism, however, the increase in temperature by burial causes the destruction of kaolinite. The dramatic decrease in kaolinite in ancient sediments is indicated in Fig. 1-3, which in itself provides quantitative proof

Fig. 1-3 Variations of clay minerals with geological age in the U.K. and U.S.A. (after Taylor and Cripps, 1984)



of its instability. Burial diagenesis causes a rapid but progressive transformation of smectite. Dehydration, adsorption of alkali ions and a rearrangement within the lattice occur. This transformation generally produces mixed-layers of the illite-smectite or the chlorite-smectite types. The chemical composition of the interstitial solutions is an important factor in this transformation. The universal occurrence of Mg, Na and K ions in the interstitial solutions during diagenesis induces adsorption between layers and so creates random mixed-layering. Based on the studies of the boreholes of the Gulf Coast, Burst (1969) distinguished the following three stages in dehydration during the transformation (smectite -- mixed-layers (illite-smectite) -- illite):

First stage: Pore water and excess (more than two layers) clay-water interlayers were removed in response to overburden pressure. In the first few thousand feet (>500 m) of burial, the water content was reduced down to about 30 per cent.

Second stage: Between 2,500 and 4,500 m deep, the temperature rise was sufficient to mobilize the penultimate water interlayer. The amount of water removed was 10-15 per cent of the compacted bulk volume.

Third stage: The final stage, which extracted the last remaining water monolayer from clay lattices, was extremely slow, in the order of tens or hundreds of millions of years.

Mixed-layer clays (mostly of illite-smectite type) undergo progressive illitization (or chloritization) by a decrease in the percentage of expandable layers; in the Gulf Coast their ability to expand decreases gradually until below 4,500 m, where they have almost disappeared (Burst, 1959). Illites are of diverse origin and show little by way of change during diagenesis. In deeper burial, however, the sharpness of the 10 Å peak, conventionally a measure of 'crystallinity', increases, indicating a higher level of diagenesis. Chlorite tends to be one of the least studied clay minerals in investigations of diagenesis, although large (detrital) grains are readily identified under the microscope, even when the mineral is only present in very small quantities. It can be equally as large as, or larger than, kaolinite (Reeves, 1971). In addition to clay minerals, organic matter undergoes excessive thermal decomposition during diagenesis to yield petroleum hydrocarbons and becomes inactive. As shown in Table 1-4, the CEC values of organic matter decrease very quickly with increasing age.

Cementation is widespread although it is not a prerequisite to the diagenesis of mudrocks. Calcite is by far the most important pore cement, quartz the second (except detrital quartz) and sometimes amorphous matter (Singer & Muller, 1983). At last, there is a noteworthy mineral, pyrite, which is quantitatively the most important diagenetic sulphide. During the activity of sulphate-reducing bacteria, H_2S is produced, which in the presence of dissolved iron or Fe-hydroxides is transformed into black hydrotroilite ($FeS.nH_2O$), and afterwards the stable sulphide, pyrite, is formed from the unstable hydrotroilite (Singer & Muller, 1983).

1-4-2 Evolution of Pore Water Chemistry

Subsurface brines are normally more concentrated than sea water (35,000 ppm), ranging between 50,000 ppm and 200,000 ppm (Dickey, 1969). Chamberlain and Glover (1976) even observed that in the deepest exploration levels of the Yorkshire, East Midlands and Kent coalfields, salt concentrations were approaching saturation (*i.e.* 360,000 mg/l as NaCl). The salinity of pore water usually increases linearly with depth at rates of increase varying between 10,000 ppm and 100,000 ppm per thousand feet (50 to 300 mg/l/m) (Dickey, 1969).

Brines are basically Na, Ca and Mg chlorides, deficient in Mg^{2+} and SO_4^{2-} and with excess Ca^{2+} and HCO_3^-, relative to sea water (Kramer, 1969). In the marine environment, clay minerals adsorb Mg and K ions and release exchangeable Ca ions. This process starts once clays are transported to the sea and continues after deposition and even lasts to the later stage, associated with the transformation of expandable clay minerals. It has usually been found (Singer & Muller, 1983) that the sulphate content and also the sulphate/ chloride ratio decrease with increasing depth. The decrease in sulphate content is brought about by sulphate-reducing bacteria in anaerobic environments, the same mechanism as for the formation of pyrite. Studies in this area, however, have not been conclusive. Schmidt (1973) showed that the shale pore water (obtained by leaching) generally had a concentration order of $SO_4^{2-} > HCO_3^- > Cl^-$, whereas the sandstone pore water gave a reversed concentration order. More conclusive is the behaviour of the Ca/Cl ratio which increases with depth and also with increasing overall ionic concentration. The Ca/Na ratio also increases with depth or at least remains constant (Kharaka & Berry, 1973; Weaver & Beck, 1971).

In order to explain the above-mentioned phenomena, it has long been suggested that shales and compacted clays behave as semi-permeable membranes to retard the passage of charged ionic species (especially divalent cations, relative to monovalent ones), while allowing a relatively free movement of water *per se* (Bredehoeft *et al.*, 1963; Kharaka & Berry, 1973). The membrane properties of mudrocks result from the cation exchange capacity of clay minerals. Hence, the membrane efficiency increases with the increasing cation exchange capacity. Laboratory evidence shows (Kharaka & Berry, 1973) that a ratio of input to effluent solution concentration as high as 5 may be achieved in subsurface conditions through a bentonite bed at a depth of 3,000 m. However, Edmunds (1975) proposes that for the brines of NE England, filtration analogous to reverse osmosis has occurred in response to differential hydrostatic pressures during compaction and lithification.

1-4-3 Compression

Compression has long been of major interest to geologists and geotechnical engineers. A sediment may be considered to be a skeleton of solid grains enclosing voids which are filled with water under a completely saturated condition (Taylor, 1948). Under the load usually encountered in sediments, the solid grains and the pore water, being relatively incompressible, do not undergo appreciable volume change. For this reason it is sufficiently accurate to consider the decrease in volume of a sediment as due entirely to an escape of water from the voids. As compression occurs, the rate of water escape depends upon the permeability of the sediment. Sediments with low permeability require a long time for the compression to take place. This process is well-known as consolidation.

As shown in Figs. 1-4 and 1-5, void ratios (or water contents) of sediments and pure clays decrease with increasing effective pressures in the field and under laboratory conditions. All the curves are usually assumed to be linear on the semi-logarithmic plot, at least for some part of pressure range. The slope of the compression curve, its absolute value being expressed as the compression index, C_c, is related to the plasticity of a sediment. Highly plastic sediments, *e.g.* liquid limit (L.L.) greater than 90 in Fig. 1-4, have a high compressibility, that is, a high compression index. Geogia kaolinite has a low C_c value of 0.157, compared with 0.488 and 0.275 for Wyoming Bentonite saturated with distilled and sea water, respectively (Fig. 1-5). The effect of pore fluid

Fig. 1-4 Skempton's (1970) sedimentation compression curves for normally-consolidated sediments

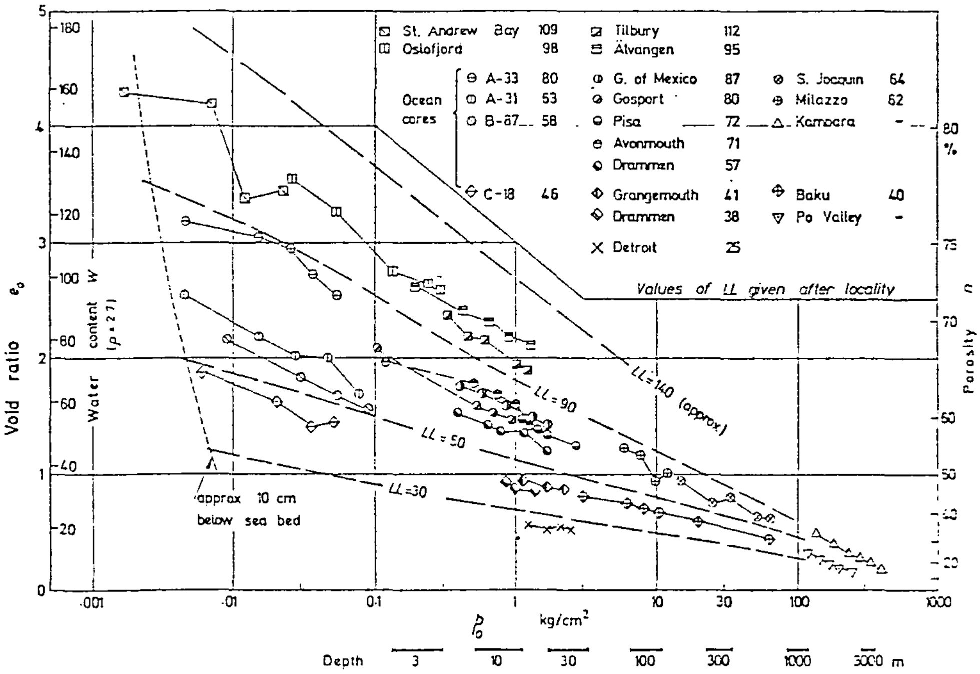
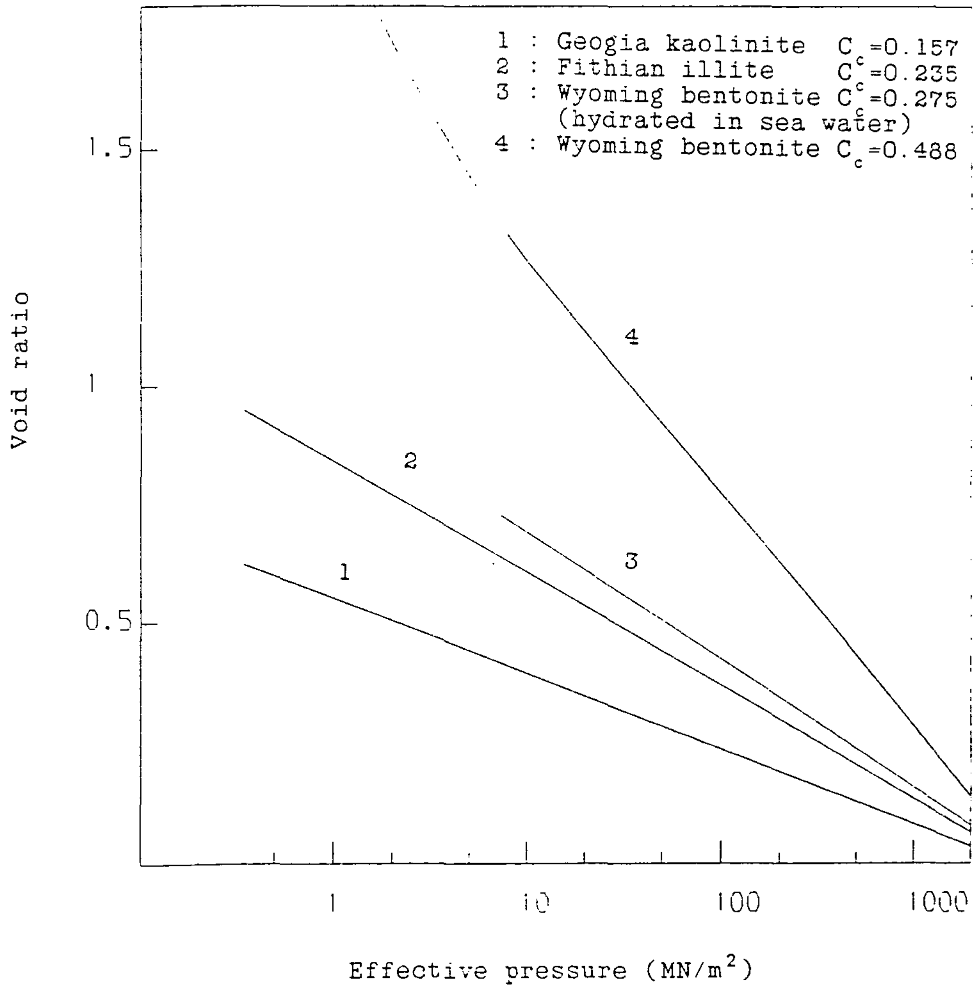


Fig. 1-5 Laboratory compression curves of pure clays (modified from Singer & Muller, 1983)



chemistry will be discussed later.

It has been demonstrated (Skempton, 1944 & 1953a) that the laboratory compression curves of remoulded sediments usually fall below the field ones if the pressure is less than about 10 MN/m^2; the reverse is shown to be the case if the pressure is greater than 10 MN/m^2. The laboratory compression curves for undisturbed samples lie between the field curves and those for remoulded samples. Terzaghi (1941) also differentiated the actual sedimentation compression curve from the artificial one. It was suggested that, due to the very slowly increasing pressure during sedimentation and geological compression, natural sediments will have an extremely open structure and much larger moisture contents than those simulated in the laboratory. The latter would consolidate under a rapid loading rate probably many hundred or even thousand times faster than in nature. Terzaghi ascribed this difference to the rigid, solid bonds of adsorbed water layers on clay particles, and suggested that high loading rates collapsed the structure and broke the bonds, so producing smaller void ratios.

Laboratory tests by Fleming *et al.* (1970) on mudrocks (clay shales) consistently indicated a greater pre-consolidation pressure than did the geological evidence. In these laboratories tests by Smith (1978) also suggest a similar trend for both U.K. and North American mudrocks. It was suggested (Leonards & Ramiah, 1960; Bjerrum, 1967) that this was the effect due to diagenesis (Fig. 1-7A) or rigid bonding of the adsorbed water layers.

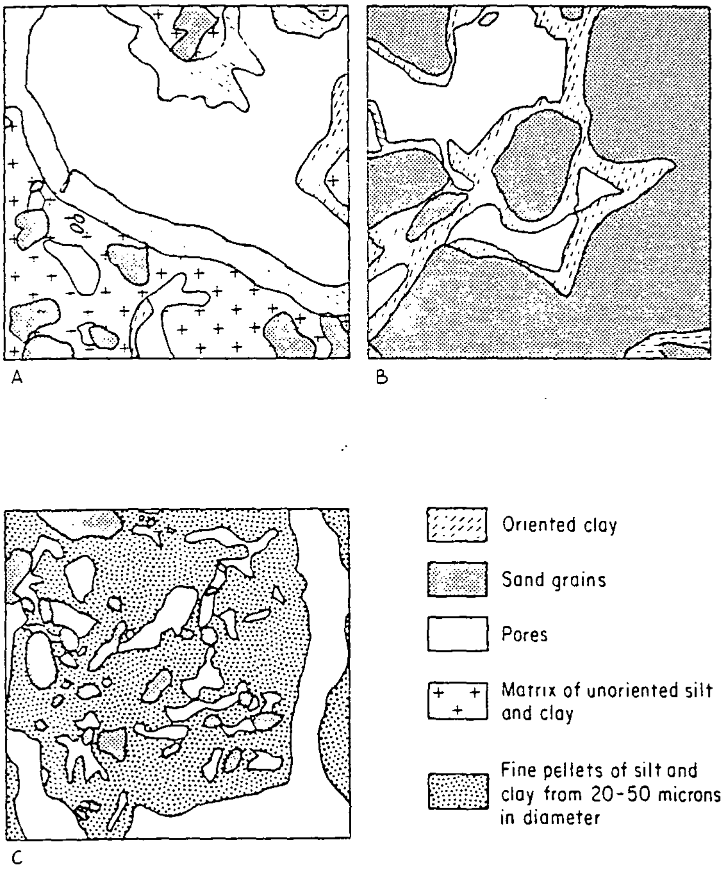
1-4-4 Evolution of Fabrics

Lambe (1958) first envisaged three main modes of clay fabric, salt-flocculated, non-salt-flocculated and dispersed, which were related to the salt concentrations during deposition. In 1960

Aylmore and Quirk introduced the concept that compacted clays were composed of 'domains' or turbostratic groups (also called tactoids) of oriented packets of clay flakes. It appears indisputable now (Moon, 1972) that domains form with increasing pressure and more particles or platelets are incorporated into domains. What is also quite certain is that with compression there is an increase in particle orientation or, more properly, in domain orientation (Moon, 1972). Generally speaking, larger particles, *e.g.* kaolinite and illite, develop a preferred orientation much more easily than smaller particles of smectite (Meade, 1964). Another important phenomenon, frequently attributed to particle or domain orientation, is the fissility of shales. Fissility has been found to be associated with a well-developed preferred particle orientation (O'Brien, 1970), probably due to the organic content as a dispersing agent, or simply because of a low electrolyte content in the deposition environment which also causes a dispersed fabric. Nevertheless, no relationship between fissility and depth of burial has been found to be the common case (for example, White, 1961). Moon (1972) suggested that it might be explained by a consideration of the chemistry of the depositional medium.

Most sediments have a range of grain sizes and include non-clay particles. As sketched in Fig. 1-6, the fabric of natural sediments is made up of an arrangement of sand or silt grains with oriented or random clay domains or particles. Two kinds of pore spaces can readily be identified. The pore spaces between fabric units (for example, domains and aggregates) are larger than those between particles within fabric units. Yong and Warkentin (1975) define the former as macro-pores and the latter as micro-pores. The importance of this differentiation may be appreciated if connected to some characteristics of sediments. For instance, unequal pore sizes were

Fig. 1-6 Thin-section drawings of soils showing particle arrangement (after U.S. Department of Agriculture. 1960; reprinted in Yong & Warkentin. 1975)



found to be the most possible reason for the discrepancies between the measured and the predicted flow rates in clays (Olson, 1962). Delage and Lefebvre (1984) showed that the compressibility of the Champlain Clay, a sensitive clay, was governed by macro-pore collapses, but the micro-pores remained unchanged. So far, very rare information is available on the pore sizes in mudrocks. A good example is the work of Heling (1970) on the Tertiary shales in Rhinegraben in SW Germany. Heling found that the most frequent pore radii in the shales decreased with increasing overburden and the reduction of pore size seemed to be more advanced in the older than in the younger shales (a function of diagenetic duration). It was also demonstrated that the surface areas of the shales remained unchanged until 1,000 m and then reduced, which coincided with the transformation of expandable clays to illites.

1-5 Geotechnical Viewpoints of Diagenesis in Mudrocks

The engineering behaviour of mudrocks in their present field conditions is certainly a reflection of their stress history in depth and it is usually referred to as stress-path-dependent. Having reviewed the diagenesis of mudrocks, it seems to be relevant to consider the stress-strain characteristics of mudrocks during the diagenetic process.

1-5-1 Recoverable Strain Energy and Diagenetic Bonding

In his Terzaghi Lecture Bjerrum (1967) used the concept of recoverable strain energy and diagenetic bonds to interpret the progressive failure of slopes in mudrocks. Diagenesis was deemed to be the process causing physical and chemical alterations of sediments due to great overburden pressure, higher geothermal temperature, geological time and other agents. The resultant effect on the sediments was considered by Bjerrum to be the development of 'diagenetic bonds'. The bonds could result from particle adhesion, particle recrystallization and cementation. With the development of bonds the sediment structure, therefore, would become stronger and more brittle without further volume change.

Recoverable strain energy is referred to as the recoverable part of compression process. Bjerrum (*op. cit.*) considered that the amount of recoverable strain energy depended on the consolidation pressure and the properties of the sediment. In general, the more plastic the sediment, the greater the recoverable strain energy (Brooker, 1967). He also thought that the recoverable strain energy was primarily due to the recovery of flexible flake-shaped clay particles which had deformed around equant habit minerals such as quartz grains during compression process (see Fig. 1-6). This mainly follows Terzaghi's (1931) concept on swelling. Great decrease in macro-pore volume with increasing compression effort has been found (for example, Sridharan *et al.*, 1971), and this can be related to the unrecovered strain in the consolidation-swelling process (Delage & Lefebvre, 1984).

Using the concept of recoverable strain energy and diagenetic bonds, Bjerrum (1967) was able to postulate the geological history of a mudrock (Fig. 1-7A,D). After normal consolidation (the compression curve of which is called the virgin compression curve) and diagenesis mudrocks would unload as erosion removes some part of the overburden. Due to the presence of recoverable strain energy the mudrock has a tendency to swell and increase in water content. However, a mudrock with strong bonds would swell from (c') to (e) in Fig. 1-7A, less than that with weak bonds from (c) to (d), and has a higher shear strength (Fig. 1-7B). For high degrees of unloading the bonds are further stressed and fail in increasing numbers. Therefore the water content increases to a greater degree towards the ground surface. The final water content depends on the recoverable strain energy and also on the strength of the bonds and the degree of their destruction. As the bonds are gradually destroyed by weathering or other agents (Chandler, 1972), the locked-in recoverable strain energy would be liberated, causing mudrocks to swell. In Bjerrum's view strong and brittle mudrocks are unreliable, since strain energy may only be released slowly over a long period of time. A good example, documented by Bjerrum (*op. cit.*), is shown in Fig. 1-8. The Bearpaw Clay Shale has well-developed diagenetic bonds. Its water contents highly increase from the hard, unweathered rock to the soft, weathered zone, towards the water contents derived from the remoulded sample in the laboratory.

Bjerrum's concept of diagenetic bonding and locked-in recoverable strain energy has been adopted widely in geotechnical engineering. Working on remoulded mudrocks, Brooker (1967) demonstrated that the ratio, K_o, of horizontal to vertical stresses at rest (in a condition of one-dimensional consolidation-swelling) was a function of recoverable strain energy at a given overconsolidation ratio. He also concluded that the degree of disintegration of overconsolidated sediments during a slaking test was related to that energy. Mineralogy and the capacity of sediments to adsorb strain energy were concluded to be related. Those sediments with high smectite contents absorbed more strain energy during consolidation. However, diagenetic bonds should not exist in remoulded sediments. Schmertmann (1969) used Bjerrum's concept to explain why some undisturbed clays had a much smaller swelling index than the equivalent remoulded ones, which lost most of the bonds. Tchalenko (1968) also reached a similar conclusion for London Clay.

Fig. 1-7 Schematic geological history of overconsolidated clay (after Cripps and Taylor, 1981)

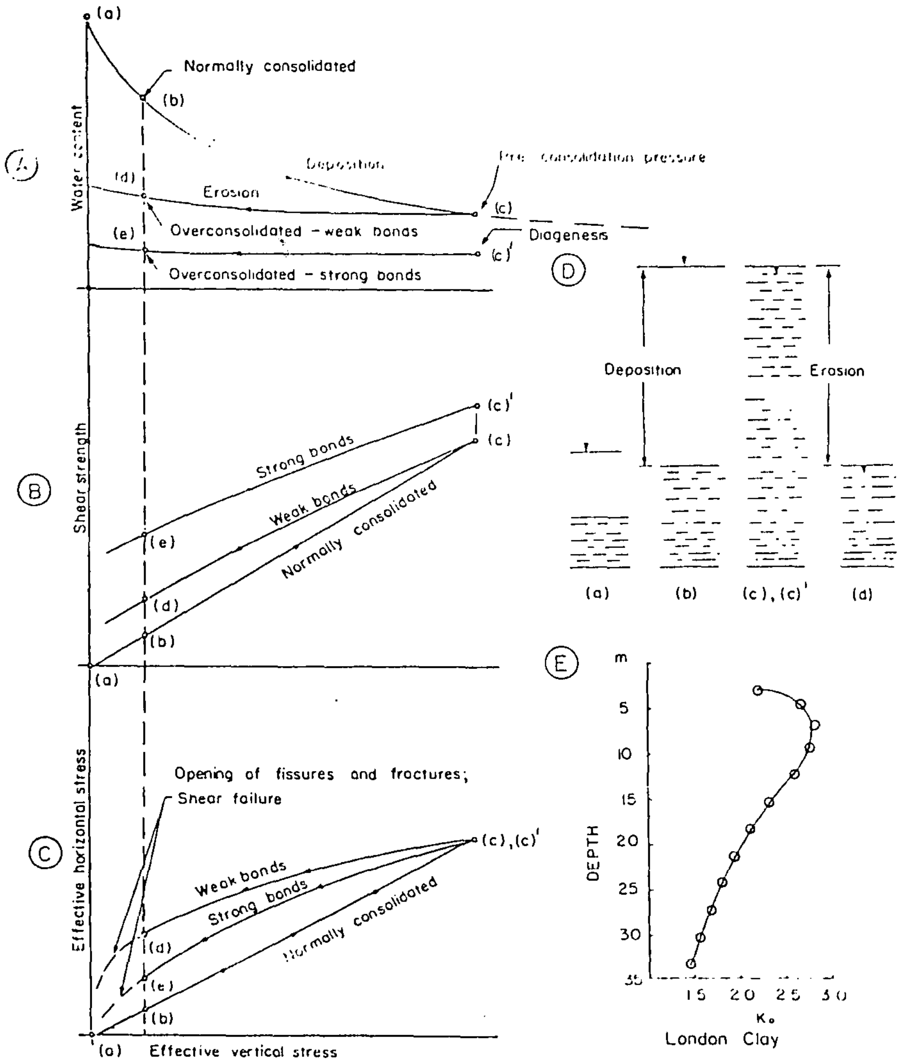
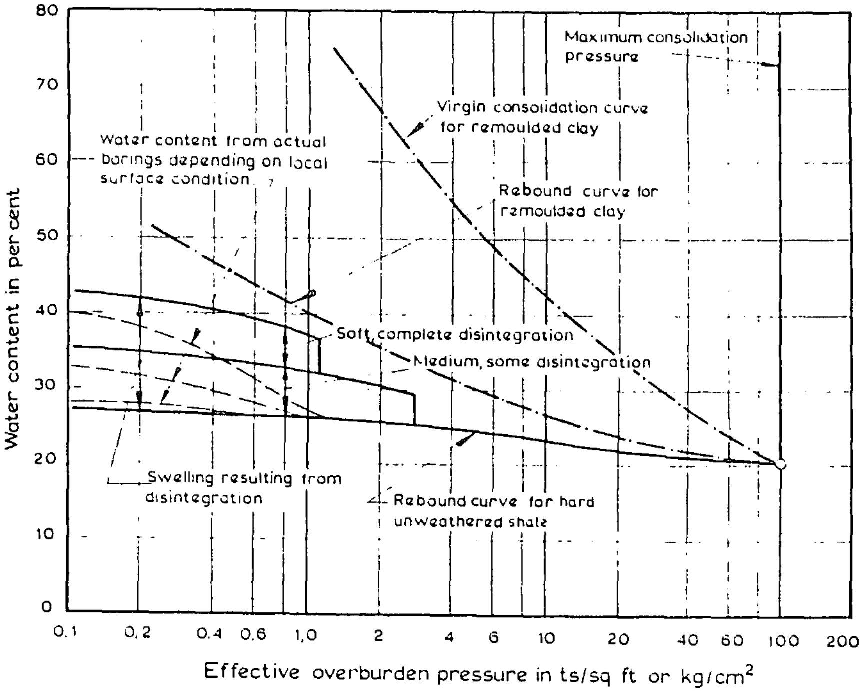


Fig. 1-8 Geological history of Bearpaw Shale (after Bjerrum, 1967)



1-5-2 High Horizontal Stresses (K_o) and Shear Failure

During one-dimensional compression the K_o value is less than unity and remains constant, as shown in Fig. 1-7(C). In unloading, however, K_o values increase with increasing overconsolidation ratios and become greater than unity, because the ground is free to swell vertically but not horizontally. In other words, horizontal stresses are greater than vertical stresses during unloading. Figure 1-7E shows an example of high K_o values in the London Clay near the ground surface. Mudrocks with weak bonds can develop higher K_o values than those with strong bonds, because bonding tends to cause a greater reduction of the horizontal stress by retaining a greater amount of strain energy (Bjerrum, 1967). Kavazanjan and Mitchell (1984) have suspected that K_o values are time-dependent, approaching a value of unity over geological time. For normally consolidated clays K_o increases with time during secondary consolidation (Akai & Sano, 1984); whereas for overconsolidated clays with K_o greater than unity, K_o could decrease with time.

It has been suggested (Skempton, 1961; Terzaghi, 1961; Yudhbir, 1969) that during unloading mudrocks would experience a passive shear failure. Shear planes or slickensided zones in mudrocks near ground surface have been ascribed to this kind of failure. The reason for this is demonstrated by Skempton (1961), who showed that in the London Clay at Bradwell the value of K_o increased upwards from about 1.5 at 30 m to about 2.8 at 7-9 m (Fig. 1-7E). A K_o value of 2.8 is of the same order as the coefficient of passive earth pressure at failure, K_p. Singh *et al.* (1973), working on a remoulded Bearpaw Shale, were able to demonstrate that when the overconsolidation ratio was high enough, one-dimensional swelling became much larger such that equilibrium was not attained in a definable time period. Moreover their stress path analysis also indicated that during unloading the passive failure line was reached, *i.e.* failure occurred. The laboratory evidence that failure might occur as a consequence of high horizontal stresses being developed near the ground surface has also been provided by Mesri *et al.* (1978). They found that on unloading the negative pore pressures dissipated very rapidly and eventually the pressure became positive in the one-dimensional swelling test on remoulded Cucaracha and Bearpaw Shales. It was interpreted as direct evidence that positive shear-induced pore pressures were superimposed on the excess negative pore pressures, although it was not clear how the samples continued to swell after the pore pressure became positive. They acknowledged, however, that additional evidence of failure was required, for instance, from observed shear failure surfaces.

1-6 Mechanisms of Swelling

Swelling is defined as the expansion related to a change of water content (Yong & Warkentin, 1975). Exception has been found by Lo *et al.* (1978) who showed that no water uptake occurred during swelling in shaly rocks. There are basically two models to interpret the swelling behaviour; (a) mechanical, and (b) physico-chemical.

The mechanical model, based on Terzaghi's (1931) theory of swelling, considers that the process of swelling merely represents an elastic expansion of 'scale shaped' mineral particles, caused by a pore pressure deficiency. Terzaghi thought that physico-chemical reactions were held to influence swelling only inasmuch as they changed the elastic properties of the system by altering the coefficient of surface friction of particles, the adhesion at the points of contact or stiffness of molecular links, or by generating an additional tension in the liquid phase by an osmotic pressure effect. This model is little different from Terzaghi's model of consolidation. Terzaghi (1931) mentioned, however, that 'as we proceed from coarse to fine dispersed systems, the relative importance of physico-chemical factors increase, due to their dependence on specific surface, while purely mechanical factors, such as elasticity and porosity, remained as effective as before'.

The physico-chemical model is based on the Gouy-Chapman double-layer theory (see, for example, Sridharan & Jayadeva, 1982). Charge deficiency and large surface area enable a clay platelet to adsorb water molecules and hydrated cations to form a diffuse ion double layer around the platelet, as shown in Fig. 1-9. The cation concentration decreases with increasing distance away from the platelet surface. If a load is applied to parallel clay platelets, their double layers come closer and interfere, having a long-range electrical repulsive force equivalent to the external load (Fig. 1-9). The system can be regarded as an osmometer. The factors involved in the double-layer theory are:

(a) clay properties, represented by cation exchange capacity and surface area, and

(b) fluid properties, *i.e.* ion concentration, cation valency, dielectric constant and temperature.

Hydrated ion size and anion adsorption which influence the behaviour of clays, are not considered in the theory. The attractive force between platelets is also neglected. This is not a major factor since in unloading the particles are moving apart such that the van der Waals' and other attractive forces are much more unlikely to be operative at spacings of more than 15 Å or so. One of the main assumptions in the double-layer theory is the 'parallel' condition between clay platelets, which normally departs away from the real fabric in natural mudrocks (see Section 1-4-4). Lower swelling pressures are generated with a randomly oriented fabric (Yong &

Warkentin, 1975).

Figure 1-10 shows a theoretical analysis on the double-layer theory by Sridharan and Jayadeva (1982). The relationship between the half distance (d) of platelets and the logarithm of effective pressure is independent of clay type, since clay properties can be represented by the ratio of CEC to A_s, which has a small range (0.1 to 0.4) in common clay minerals. The effect of clay properties, however, is evident in the void ratio (e) - pressure relationship of Fig. 1-10. Also shown in this figure is the effect of cation concentration. As cation concentration increases, swelling pressure decreases because the double layer is compressed. The effect of concentration on both d and e is greater in the low pressure range. Cation valency is directly related to d and e and has an important effect on swelling; monovalent cations result in greater swelling than divalent ones because of the expanded double layer. This is of course demonstrated by the greater free swelling of Na-smectites as compared with Ca-smectites (see Table 1-5). In most cases water is the pore fluid and so the dielectric constant is not important. If water is replaced by a non-polar liquid with a low dielectric constant, no double layer can develop. Temperature usually has a negligible effect, although it is a variable in swelling phenomena. Sherif *et al.* (1982) showed, however, that for Wyoming Bentonite and sand mixtures, temperature increased the amount of swelling by 17 to 28 per cent over the range 24 to 66°C.

Although mechanical and physico-chemical effects must sensibly occur simultaneously in all clays, the experiments by Olson and Mesri (1970) and Sridharan and Venkatappa Rao (1973) indicate that one or the other usually dominates. In suspensions, physico-chemical effects dominate because of the large spacing between particles. As physico-chemical effects influence the original clay fabric, they

Fig. 1-9 Schematic hydration and swelling of two clay platelets (after Taylor and Cripps, 1984)

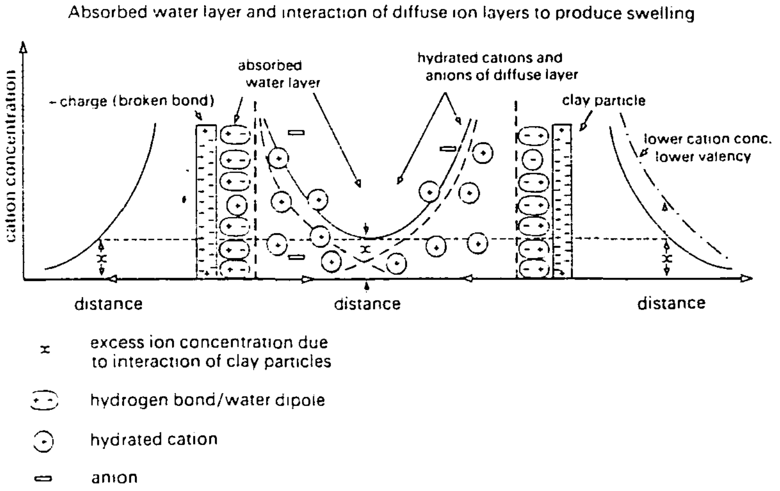


Fig. 1-10 Theoretical relationships between particle spacing (d) void ratio (e) and effective pressure (P) for various clay types and pore fluid concentrations (after Sridharan & Jayadeva, 1982)

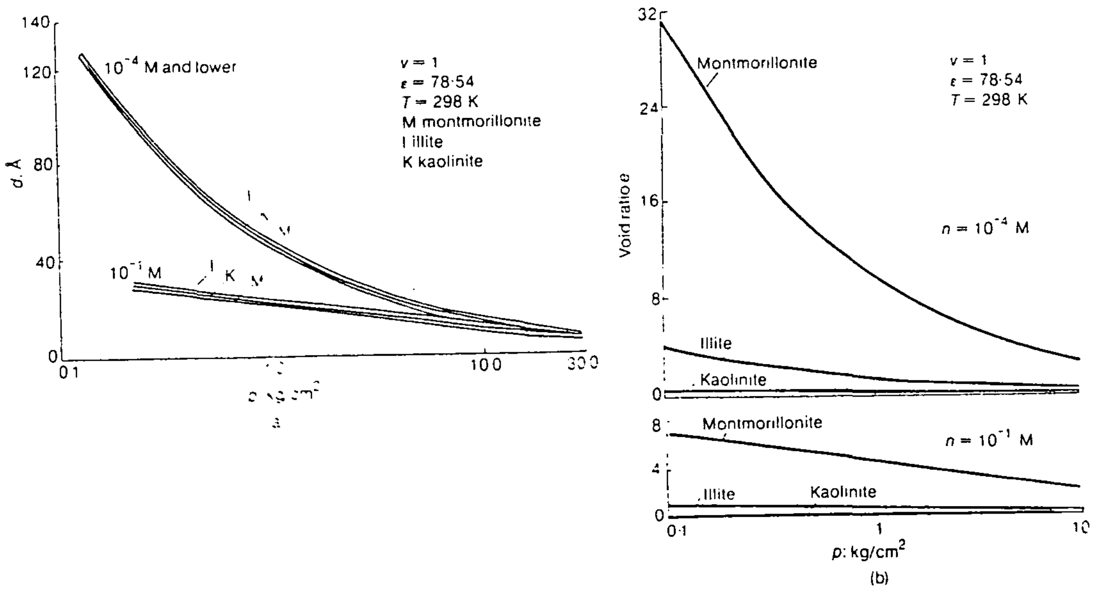


Table 1-5 Clay mineral swelling
(after Shamburger *et al.*, 1975)

Clay	Average free-swell (%)	Range (%)
Na-smectite	1500	1400-1600
Ca-smectite	102	65-145
Illite	89	60-120
Kaolinite	28	5-60

exert an indirect influence on virgin compressibility for all clays. Once the original fabric is established, it seems that the swelling of kaolinite is governed by the mechanical model, whereas physico-chemical effects play an important role in that of smectite. Illite seems to occupy an intermediate position with both mechanical and physico-chemical effects evident during swelling. Mitchell (1973) came to a similar conclusion that the double-layer theory had application only in systems of very small clay particles (less than a few tenths of micrometre) if dead volume in tactoids was taken into account. Among others, however, Madsen (1979) and Morgenstern and Balasubramonian (1980) produced very convincing evidence in favour of the physico-chemical model in mudrocks. Madsen used the external surface areas (derived by the nitrogen adsorption analysis) in the calculation of the swelling pressures of mudrocks and found a reasonably good correlation between the measured and the calculated swelling pressures. Morgenstern and Balasubramonian (*op. cit.*) compared the theoretical swelling pressure with the measured one at the same void ratio for two undisturbed clay shales. They found that the physico-chemical forces could be predicted by the double-layer theory during the swelling of clay shales. In his Terzaghi Lecture Mitchell (1986) presented a good example of the physico-chemical effect that the remoulded shear strength of quick clays increased significantly with time after sampling, due to the increase in pore water salinity and divalent cations.

There are other physico-chemical forces involved in the swelling of clay minerals, including surface and cation hydration. It is believed, however, that forces of hydration are satisfied after adsorption of the first few water layers (Mitchell, 1973). Natural water contents in the field are probably high enough so that these forces are of minor importance in most swelling phenomena (Harper *et* *al.*, 1979). During diagenesis in depth, expandable clay minerals encounter structural transformation and lose their ability of intracrystalline swelling. They could become reactive through weathering agents near ground surface, but not in the laboratory condition.

1-7 Rate of Swelling

Relative to consolidation, the rate of swelling of mudrocks has not attracted many researchers. Karl Terzaghi was probably the first person again to investigate the time factor in the swelling of clays. In 1931, he already observed that the swelling of gelatin agreed in a remarkable manner with his theory of consolidation. In the summary he concluded that 'the time rate of swelling of gelatin followed almost exactly the laws which held for coarse disperse two-phase systems'. He also used the time rate of swelling to calculate the coefficient of permeability.

Terzaghi's theory of swelling (or consolidation) was used to compute the pore pressure equalization in some slopes along the Panama Canal (Lutton & Banks, 1970). The field piezometric levels were generally below the water level in the Canal, indicating that the pore pressures had not yet reached equilibrium and that softening was still proceeding. The laboratory test results demonstrated that for a clay shale, 6 m in thickness, the pore pressures reached about 85 per cent equalization some 60 years after construction and this was in reasonable agreement with the field observation. The delayed failure of slopes cut in overconsolidated fissured clays has also been suspected by Vaughan and Walbancke (1973) and Skempton (1977) to be controlled mainly by the slow rate of excess negative pore pressure dissipation. As shown in the laboratory testing results of Mesri *et al.* (1978), the rate of swelling is even slower than that of pore pressure increase. Vaughan and Walbancke (1973) suggested that further examination of the swelling process seemed to be desirable.

There is some information in the recent literature on the swelling rate of remoulded mudrocks. At the eighth International Conference on Soil Mechanics and Foundation Engineering Singh *et al.* (1973), for instance, presented some data on the swelling rate of a remoulded Bearpaw Shale. It was shown that volumetric strain and excess negative pressure dissipation appeared to follow the Terzaghi theory prior to passive failure, but when the passive failure condition was reached (see Section 1-5-2), the swelling continued at a significant rate after the excess negative pore pressures dissipated completely. In their tests, the final unloading was maintained for 200 days with continued swelling, giving no indication of equilibrium (sample thickness *c.* 10 mm). Mesri *et al.* (1978) investigated the time-rate of one-dimensional and isotropic swelling of four remoulded mudrocks in North America. It was shown that Terzaghi's theory of swelling correctly predicted the shape of the percentage swelling - logarithm of time curves up to about 60 per cent primary swelling, and beyond 60 per cent the shape of the swelling rate curves was a function of the ratio of secondary swelling index, $C_{\alpha s}$, to swelling index, C_s, and also the pressure decrement ratio. Secondary swelling could be very significant and the ratio, $C_{\alpha s}/ C_s$, could be as high as 0.4, which contrasted with the maximum observed ratio, 0.1, of secondary consolidation index to compression index. In addition, the $C_{\alpha s}/C_s$ values were not a constant but increased with the overconsolidation ratio. In favour of Terzaghi's theory Sherif *et al.* (1982) showed that the swelling of Wyoming Bentonite (a Na-smectite) and sand mixtures appeared to be almost the exact opposite of consolidation. They found that there was a unique linear relationship between the time and the square of sample thickness, which conformed with what the theory of consolidation predicted. In order to predict the rate of swelling, they also adopted the square root of time fitting method, normally used to evaluate the rate of consolidation.

The secondary swelling rate was used by Lo *et al.* (1978) as a parameter of swelling potential for some shales and shaly rocks. They found the secondary swelling rate was stress-dependent and the swelling potential of shales might be correlated with the calcite content, indicating the degree of cementation, of the rock (for a rock having more than 15 per cent of calcite, the swelling potential was essentially zero).

1-8 Aims of the Project

The preceding review in this chapter on the swelling characteristics of mudrocks and their clay mineral constituents, demonstrates how little has been done in terms of undisturbed mudrock *per se*. Most of the research into swelling mechanisms relates to single species clay minerals and their response when compacted. Investigations of 'real' clays and mudrocks are invariably carried out on remoulded materials in which diagenetic bonds and long-term fabrics have been destroyed. Commonly there has been little control on porewater compositions and in many projects the porewater composition is unknown. In fact, there is not much data on the basic behaviour of undisturbed mudrocks, such as free swelling percentage or likely uplift pressures. What information exists is difficult to interpret (Taylor & Cripps, 1984).

One of the problems in these studies of swelling behaviour is that the research has been directed largely to the understanding of: (a) clay minerals and pore fluids, or (b) consolidation theories, which have a direct application to ground engineering. There is little by way of an interplay between the two approaches, which might be construed as an 'engineering geology' approach. This may be because engineering geology has not yet taken an analytical role, being largely directed towards classification systems and observational geology. There are, of course, exceptions and this work was largely motivated by two pieces of previous research on real mudrocks, Morgenstern and Balasubramonian (1980) and Madsen (1979).

The samples chosen in this study cover a wide range of mineralogical composition and engineering properties. They range from what may be deemed overconsolidated clays to indurated mudrocks, *i.e.* from Eocene clay to Carboniferous mudrock. The samples are listed in Table 2-1.

For the purpose of this investigation particular emphasis is placed on the following aspects in an attempt to improve the understanding of the swelling behaviour of argillaceous rocks:

(a) influence of mineralogy and pore fluids,
(b) influence of fabric,
(c) physico-chemical behaviour,
(d) diagenetic bonds, and
(e) rate of swelling.

Both undisturbed and remoulded samples (which must contain few by way of diagenetic bonds) have been investigated. Special consolidation and swell cells have been designed by the writer and fabricated in stainless steel to reduce contamination to a minimum. For similar reasons a high pressure squeezer has been designed and manufactured in the Engineering Geology Laboratories at Durham University. Constant monitoring of long-term consolidation and swelling tests has been adopted whenever feasible using L.V.D.T. transducers and the laboratory datalogging system.

CHAPTER 2 MINERALOGY AND GEOCHEMISTRY

As reviewed in the previous chapter, clay minerals dominate the deformational behaviour of mudrocks; therefore, their identification is important in this study. Two approaches have been made, (a) X-ray diffractometry, and (b) geochemical analysis. The quantitative analysis of clay minerals in natural sediments is not easy. Special attention has been paid to expandable clays since they usually play a disproportionately important role in the swelling of mudrocks. Clay mineral properties also depend upon the environmental conditions, so the analyses of exchangeable cations and pore fluid composition have also been conducted. The determination of cation exchange capacity is also helpful for the evaluation of expandable clay minerals. A special effort has been made to refine the more commonly available analytical methods used in the determination of exchangeable cations.

Basic information on the samples studied and their plasticity and specific gravity are presented in the first part of this chapter, and then mineralogical and geochemical analyses of the solids and the fluids follow consecutively. These basic data, together with those on fabrics in the next chapter, form a basis for the discussion of the swelling characteristics of the mudrock samples.

2-1 General Information on the Samples

Details on the samples studied of geological age, locality, depth of sampling and source are given in Table 2-1 in an order of age. The samples span a wide stratigraphic spectrum in the United Kingdom, ranging from Carboniferous up to Eocene. Carboniferous Coal Measures mudrocks are known to have been deposited in fresh or brackish water, whereas all the others were laid down under marine conditions. They were recovered from very different depths, from near surface down to about 500 m deep. All the samples have been protected carefully after field sampling from the loss of moisture and any mechanical disturbance. Either core tubes or wax and Sellotape were used for this purpose.

There are two London Clay samples from two different locations and depths. Both of them are stiff and fissured, with a relatively homogeneous structure. The sample from the City of London, a typical London Clay, was recovered in a U100 aluminium tube. The other core sample from Warden Bay, 76 mm in diameter, has an irregular outer surface, showing some disturbance during coring. Two lumps (500 x 300 x 200 mm) of Fuller's Earth were taken from a spoil tip of freshly extracted deposit. They appear to be stiff and have a soapy texture. They also show some weathering character on a few fracture planes, marked by brown iron oxide and black stainings, the latter being described by the site manager as resembling algal growth. The two Oxford Clay samples were recovered from the same borehole in U100 stainless steel tubes. They contain some shell fragments and pyritic nodules, which were avoided in the preparation of the samples for analysis. Both of them are very stiff and also fissured. The Lias Clay sample, 76 mm in core diameter, is strong, brittle and horizontally fissile. During the slaking process (see Appendix C-1-2 (b)), some white growth material appeared and was identified by X-ray diffractometry as rozenite ($FeSO_4:4H_2O$), a product of pyrite oxidation, possibly indicating a high content of disseminated pyrite. This was also found by Simonds (1984). The Flockton mudstone sample has an almost horizontal, well-developed fissility on a microscopic scale and appears very brittle. Both the Lias Clay and Flockton mudstone samples are highly indurated and required a longer period of time (about one month) to be disintegrated. They were also difficult to handle in the preparation process for the consolidation-swelling

Table 2-1 General information on the samples

Sample	Geologic Age	Locality	Depth (m)	Source
London Clay (LC)	Eocene	City of London	19.5	Wimpey Laboratories Ltd.
London Clay (LCW)	Eocene	Warden Bay, Sheppy, Kent	59	Dr. E.Bromhead, Kingston Polytechnic
Fuller's Earth (FE)	Lower Cretaceous	Woburn, Bedfordshire	c. 5	Steetley Minerals Ltd.
Oxford Clay (OX10 & 19)	Upper Jurassic	Gloucester Green, Oxford City	10 & 19	Soil Mechanics Ltd. (Doncaster)
Lias Clay (LI)	Lower Jurassic	Nr. Minehead, Somerset	62.7	Holst Soil Engineering (Leeds)
Flockton mudstone (FM)	Carboniferous	Nun Monkton, Nr. York City (Selby coalfield)	492	National Coal Board

Table 2-2 Plasticity and Specific Gravity (G_s) of the samples

Sample	*in situ* moisture content (%)	P.L.	L.L.	P.I.	Plasticity classification *	G_s
London Clay (LC)	25	32	75	43	CV	2.77
London Clay (LCW)	27	36	93	57	CE	2.74
Fuller's Earth (FE)	86	71	131	60	CE	2.79
Oxford Clay (OX10)	19	19	68	49	CH	2.64
Oxford Clay (OX19)	21	23	66	43	CH	2.66
Lias Clay (LI)	12	24	37	13	CI-MI	2.67
Flockton mudstone(FM)	3.6	25	42	17	CI	2.75

* Based on Anon (1972)

tests (Appendix C-1-2) because of their very brittle character.

2-2 Atterberg Limits and Specific Gravity

The Atterberg limits collectively reflect the general properties of clay minerals, as shown by the close relationships among the limits, surface area and cation exchange capacity (see Section 1-3). Limits are universally used as an important criterion in the classification of soils. In this study the liquid and plastic limits are also applied as major parameters in the consolidation-swelling behaviour of the samples, although other criteria are needed to accommodate diagenetic bonding effects.

The tests for liquid limit (L.L.), plastic limit (P.L.) and specific gravity (G_s) were conducted as specified in BS 1377 (1975), except for the slaking process in the preparation of the samples, which is described in Appendix C-1-2(b). Liquid limit usually increases and plastic limit decreases if slaking is carried out on samples, instead of the mechanical disintegration method in BS 1377. As suggested by Smith (1978), those limits obtained after slaking are more representative of the properties of mudrocks since they probably reflect the behaviour of individual particles rather than aggregated rock.

The liquid and plastic limits and the plasticity indices (P.I.) of the samples all cover a wide range, as shown in Table 2-2, with the Fuller's Earth being at the top and the Lias Clay and Flockton mudstone at the bottom. The liquid limit of the Fuller's Earth is lower than that of smectite quoted in Table 1-4, probably due to the aggregation in natural sediments. The plastic limits are little different among the Oxford and Lias Clays and Flockton mudstone. The limits plot above the A-line of the Casagrande plasticity chart, indicating a relatively high plasticity in a remoulded state, except for the Lias Clay, which lies on the boundary. The Casagrande classification of plasticity of the samples shows (Table 2-2) that the samples range from CE (extremely high plasticity) to CI (medium plasticity), covering a whole range of inorganic, plastic soils. According to their L.L. and P.I. values, the samples can be placed in an order of:

Fuller's Earth ⩾ London Clays ⩾ Oxford Clays ⩾ Lias Clay &
Flockton mudstone

However, the London Clay sample (LCW) from Warden Bay has a higher plasticity than the other one (LC).

The *in situ* moisture contents, also presented in Table 2-2, of the samples range from 3.6 to 86 per cent and are about 0 to 20 percentage points below their plastic limits, except that of the Fuller's Earth, which has a moisture content 15 per cent above its plastic limit. This indicates a high degree of compaction state in most samples.

The values of specific gravity for the samples, presented in Table 2-2, range from 2.64 to 2.79. These values were used in the calculation of the void ratios in the consolidation-swelling tests (Chapter 4) and the derivation of the cumulative curves of pore size distribution (Section 3-3).

2-3 Mineralogy

2-3-1 Method of Analysis

The mineralogical compositions of the samples were first determined using a Philips PW1130 X-ray diffractometer (XRD) with iron-filtered cobalt K_α radiation. First of all a qualitative examination was made on the samples to identify the mineral components present. Then a quantitative analysis was attempted using a combination of methods by Griffin (1954) and Shultz (1960), as shown in Appendix A-1. Griffin's method has been modified and applied in these laboratories for years and results have usually been acceptable (Taylor, 1971; Smith, 1978). X-ray intensities reflected by components in mixtures are related to the proportions of the components and the quantitative analysis is made on this basis. Using boehmite as the internal standard, the amounts of clay minerals, quartz, carbonate minerals, pyrite and other accessary minerals are determined. For clay minerals, based on the first order basal reflections, calibration curves have been produced in these Laboratories (Smith, 1978), using the conventional reference minerals with varied crystallinities. Crystallinity affects the diffracted intensity to a great extent. So the crystallinity of each clay mineral type in the samples must be determined prior to a quantitative estimation. The determination of illite and smectite amounts is based on the diffracted intensities after glycolation. The mixed-layer clay amount is derived from the difference of the intensities of the 10 Å reflection and its low 2θ angle tail before and after glycolation. The tail splits and expands to a higher angstrom value on glycolation. However, no reference mixed-layer clay has been used, although most reference illites contain substantial amounts of smectite layers (*e.g.* Fithian and Morris illites, Grim, 1968).

Following a number of trials Shultz's (1960) method was used eventually in this study to estimate the amounts of mixed-layer clays in the samples. Smectite and mixed-layer clay minerals of illite-smectite type collapse at 300°C to give a 10 Å peak. This 10 Å peak has an approximately equal area to the 10 Å peak of illite. Shultz (1960) gives the ratio of the kaolinite 7 Å peak area to the 10 Å one, which depends on the crystallinity of kaolinite. Since kaolinite, illite and smectite can be quantified by means of Griffin's (1954) method, the amount of mixed-layer clays of illite-smectite type can then be obtained by subtracting the illite and smectite amounts from the total 10 Å peak area.

Strictly speaking, the XRD analysis is only semi-quantitative. There are several reasons for this. Importantly the variability of clay minerals, chemically and structurally, not only affects the intensities diffracted by the components but also makes the selection of reference minerals very difficult. Particle size is another factor. Brindley (1980) proposed that the particle size should be of the order of 1 µm in a quantitative analysis of clay minerals. Prolonged grinding is usually needed to reach that proposal, but this could seriously disorder the structure of the material and reduce the reflected X-ray intensity. In this project only gentle grinding was applied. Particle orientation is also important. The platy characteristic of most clay mineral particles tends to give some degree of preferred orientation of the particles, particularly in the thin surface layer of the diffraction specimen. Basal plane diffraction intensities are thereby enhanced. Because consistent preparation techniques were used, however, it is assumed that the influence of orientation on the intensities is kept constant. When distilled water was used as the liquid medium in the preparation of the slides, the intensity diffracted by each clay mineral was greater than in the case of acetone (see Appendix A-1), indicating a greater preferred orientation with distilled water.

The crystallinity indices of clay minerals and the mineralogical compositions of the samples by XRD analysis are given in Tables 2-3 and 2-4. All the uncorrected total mineral contents lay between 92 and 97 per cent, except for the Fuller's Earth. For the purpose of the following discussion, the results have been normalised to 100 per cent, except for the Fuller's Earth. The X-ray traces of the oriented samples (using distilled water) before any treatment are also presented in Fig. 2-1.

2-3-2 Clay Minerals

Kaolinite: This mineral is identified by its 001 reflection which occurs at 7 Å. Griffin (1954) used a shape factor, which was defined as the ratio of the width at the half peak height of the mineral to that of boehmite, as a measure of the crystallinity state, with lower values representing higher degrees of crystallinity. The shape factors of the kaolinites in the samples are in a small range, 2.50 to 2.75 (Table 2-3). The kaolinite contents range between 20.1 and 28.5 per cent in five of the samples. It is only 7.5 per cent in the Lias Clay, whilst it is zero in the Fuller's Earth.

When chlorite is present, its 002 reflection coincides with the 7 Å reflection of kaolinite, thus increasing the area of the kaolinite peak. To subtract the chlorite contribution from the total 7 Å peak area, Smith (1978) found a ratio of 2.35 between the 7 and 14 Å peaks of chlorite. This ratio was used in this project when chlorite was present in a significant amount.

As pointed out by Murray and Lyons (1956), ordered kaolinites usually have a 4.12-4.17 Å doublet and two triplets, 2.55-2.52-2.49 Å and 2.37-2.33-2.28 Å, and disordered types only show non-resolved peaks at those d-spacings. In the present samples only broad bands have been observed, suggesting that the kaolinites are of a disordered form.

Illite: All illites have a basal reflection at 10 Å, usually with a tail on the low 2θ angle side because of an expandable mixed-layer component. Since no definite boundary between illite and mixed-layer clays can be given, the illite contents were based arbitrarily on the 10 Å peak after glycolation, which normally makes the 10 Å tail

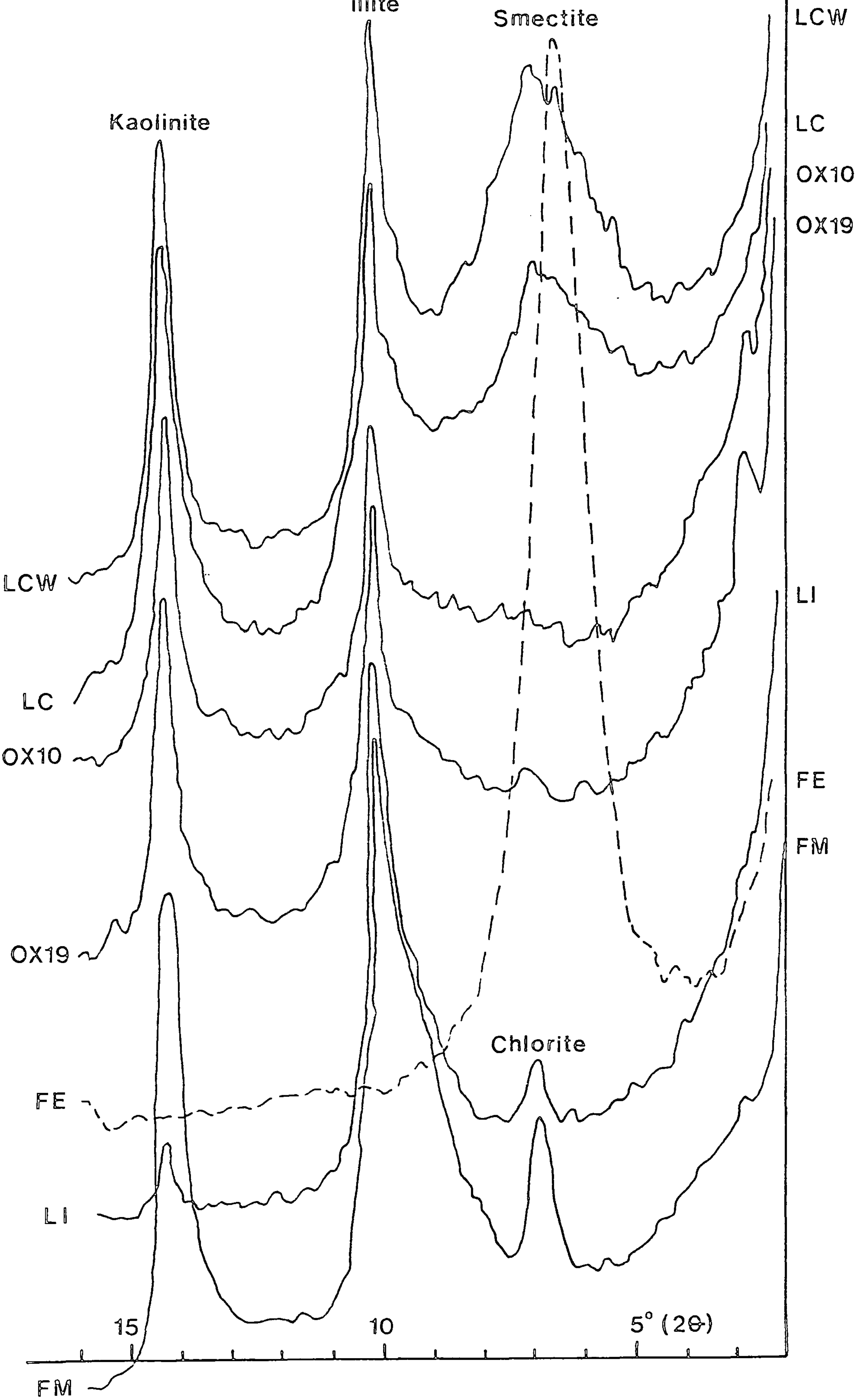


Fig. 2-1 The X-ray traces of the oriented samples

Table 2-3 Crystallinity indices of clay minerals of the samples

Sample	Kaolinite*	Illite*	Illite**	Smectite*
London Clay(LC)	2.52	2.0	0.056	12.5
London Clay(LCW)	2.75	3.5	0.069	8.5
Fuller's Earth(FE)	--	--	--	6.0
Oxford Clay(OX10)	2.55	4.5	0.11	--
Oxford Clay(OX19)	2.50	3.5	0.088	--
Lias Clay(LI)	2.62	5.0	0.13	--
Flockton (FM) mudstone	2.50	4.5	0.043	--
Reference minerals***				
Kaolinite				
Cornish	1.4			
South Carolina	1.6			
Crushed S. Carolina	1.95			
Disordered	4.5			
Illites				
Le-Puy-en-Valey		3.2-4.5	0.13	
Fithian		8.2-10.9	0.35	
Morris		15.0-18.1	0.59	

* Griffin's (1954) index.

** Taylor's (1971) index.

*** after Smith (1978).

Table 2-4 Mineralogical compositions (in percentage by weight) of the samples

Sample	K	I	ML*	S	Ch	Q	Fel	Cal	Dol/ Ank	Sid	Py	C **
LC	28	14	3	15	tr	31	3	1.7	2.6	--	0.6	1.3
LCW	25	15	6	18	tr	28	3	--	3.4	--	0.7	0.6
FE	--	--	--	65	--	tr	3	--	--	7.2	--	1.1
OX10	22	10	28	tr	tr	33	tr	4.1	--	--	1.8	1.2
OX19	25	11	28	tr	tr	28	tr	3.5	--	--	2.4	1.7
LI	8	43	7	--	5	23	5	--	4.2	--	3.9	0.7
FM	20	32	8	--	8	25	5	--	--	2.0	tr	0.4

	Total clay minerals	Clay size particles
LC	60	57
LCW	64	60
FE	65	70
OX10	60	55
OX19	64	54
LI	63	51
FM	68	49

K: kaolinite I: illite ML: mixed-layer clays S: smectite

Ch: chlorite Q: quartz Fel: feldspar Cal: calcite

Dol/Ank: dolomite/ankerite Sid: siderite Py: pyrite

C : organic carbon

* only including those mixed-layer clays contracted to 10 Å d-spacing after 300°C heating.

** based on the result of chemical analysis (Table 2-6).

either disappear or become smaller by expansion and splitting. The shape of the 10 Å reflection is an indication of the degree of crystallinity of illite and varies much in different types of illites. In addition to Griffin (1954), Taylor (1971) expressed the shape factor as the ratio of the 10 Å peak height to its width at the half height. The reference illites used by Smith (1978) in the determination of the calibration curves cover a wide range of shape factor, 3.2 to 18.1 after Griffin and 0.13 to 0.59 after Taylor (Table 2-3). The shape factors of the illites in the present samples, however, lie in a small range, 2.0 to 5.0 and 0.04 to 0.13, respectively. They are more like the French Le-Puy-en-Valey illite. Heating at 300°C increases slightly the degree of crystallinity of the illites. The illite of the Flockton mudstone has the highest crystallinity, probably indicating the greatest degree of diagenesis in the samples, whereas those of the London Clays are relatively more disordered.

Illites occur in all the samples, except for the Fuller's Earth, and vary widely in amount between 10.2 and 43.6 per cent. They are the dominant mineral, exceeding quartz, in the Lias Clay and Flockton mudstone.

Smectite: Smectites are identified by their 001 basal reflection which occurs at 12.5-15 Å, depending upon the state of hydration and the type of exchangeable cations. In the ambient condition, Na-smectite usually contain one layer of water molecules, giving a basal d-spacing of about 12.5 Å, whilst Ca-smectites have two layers and a d-spacing of 14.5-15.5 Å. The exchangeable cation determination shown in Table 2-8 has revealed that all the smectites in the samples have Ca as the dominant exchangeable cation. The 001 reflection of smectite is very strong in intensity and so a trace amount can easily be recognized by XRD. After glycolation the 001 d-spacing is expanded up to 17 Å and the intensity is reduced by about one third. Smectite structures are collapsed after being heated at 300°C, giving a 10 Å peak with about one fifth the glycolated peak area. Vermiculite also has a peak around 14 Å. Unlike that of smectites, however, this peak normally does not shift to 17 Å after glycolation. The estimation of the smectite content was made on the area of the glycolated peak, which is more regular and stable than the untreated one. Clearly, mixed-layer clays with a high content of smectite layers are not distinguishable from smectites and are probably included in this estimation.

Smectites are present in four of the samples and absent in the two oldest mudrocks, the Lias Clay and the Flockton mudstone. The two Oxford Clay samples contain only trace amounts of smectite which were not quantified. The two London Clay samples have considerable amounts of smectite. Burnett and Fookes (1974) showed a general trend in the London Clay of smectite contents (about 10-35 per cent) steadily increasing eastwards and also with depth. The Warden Bay London clay (LCW) with a higher smectite content was taken at a greater depth. Moreover, its location is to the southeast of the City of London where the other one (LC) was recovered (Section 2-1). It thus agrees with the general trend. Smectite is a major component of the Fuller's Earth and makes up 65 per cent. Where the 060 reflection was distinguished it was close to 1.495-1.5 Å, indicating that the species present are dioctahedral. Geochemical evidence (Section 2-4) tentatively suggests that the smectite of the Woburn Fuller's Earth is a montmorillonite. Amorphous material is possibly present, particularly in the Fuller's Earth which is of a volcanic origin (Kerr, 1932: Weaver & Pollard, 1973). However, no attempt was made to identify and quantify it.

Mixed-layer clays: When different types of layers occur in random intergrowth, the (001) series of reflections are not an integral (or rational) sequence. The (001) values of mixed-layer clays are average values resulting from the simultaneous scattering by different types of layers (Weaver, 1956). Their qualitative identification and quantitative estimation are probably the most difficult and least precise (Section 1-3). In this study Shultz's (1960) method was attempted to quantify them. According to the intermediate degree of crystallinity of the kaolinites, as shown in Table 2-3, the ratio of the kaolinite 7 Å peak area to the 10 Å one after being heated at 300°C was assigned as 1.2, based on Shultz's (1960) data.

Except for the Fuller's Earth, mixed-layer clays are present in all the other samples, varying in amount between 2.9 and 28.1 per cent. Their contents exceed those of other clay minerals in the two Oxford Clays. The compositions of the mixed-layer clays were not examined because of their broad X-ray reflections. However, some regular mixed-layer clays probably exist because some peaks occur at the low 2θ angle region (2.8-6.0° of 2θ, equivalent to 37-17 Å d-spacing) (Fig. 2-1). Particularly in the Oxford Clays a well-shaped peak occur at 36 Å, which disappears after being heated at 300 and 550°C. Probably it belongs to a regular mixed-layer clay of illite-smectite type. However, it has been pointed out (Weaver, 1956) that a large d-spacing (24-30 Å) is, in itself, not proof of regular mixed-layering. After being heated at 300°C, most mixed-layer clays collapsed to 10 Å, although some persisted in trace amounts in all the samples which contained mixed-layer clays. It implies that most of the mixed-layer clays in the samples are of the illite-smectite type. Those which did not contract to 10 Å after being treated would contain chlorite layers and were not included in the total mineral contents in Table 2-4.

Chlorite: Chlorite is identified by its 001 basal reflection which occurs at 14.3 Å. To distinguish chlorite from vermiculite and mixed -layer clays, the samples were heated at 550°C for an hour. At this temperature the peaks of vermiculite and mixed-layer clays containing smectite and/or illite layers would be changed but the chlorite peak would remain unaltered. Even though most samples contain a considerable amount of mixed-layer clays interfering with the identification of chlorite, the existence of chlorite was recognized on the oriented slides of most samples (except for the Fuller's Earth). However, only two samples, the Lias Clay and the Flockton mudstone, contain a significant amount of chlorite, 4.6 and 7.9 per cent, respectively.

2-3-3 Other Detrital Minerals

Quartz: This omni-present mineral is quantified by means of its 101 reflection at 4.26 Å. Except as a trace mineral in the Fuller's Earth, quartz is present in a substantial quantity in all the other samples, varying from 23.4 to 33.1 per cent.

Feldspar: This group of minerals was identified by a series of peaks between 3.23 and 3.18 Å. No attempt was made to elucidate the species. Feldspar occurs in an amount of 3.0 to 5.2 per cent in five samples and as a trace mineral in the Oxford Clays.

2-3-4 Non-detrital Minerals

Carbonate minerals: Calcite, dolomite (and/or ankerite) and siderite were identified in the samples, based on their diagnostic peaks at 3.03, 2.88-2.90 and 2.79 Å, respectively. Two kinds of carbonate minerals exist in one of the London Clays (LC); whilst in other samples, only one species is present. The carbonate contents in Table 2-4 are based on the results of chemical analysis in Table 2-6.

The carbon dioxide content of the London Clay sample with two carbonate minerals was allocated according to the ratio determined by XRD. The carbonate content varies in amount from 3.4 to 6.2 per cent. Analysis was also made on the Oxford Clays including shell fragments and their carbonate contents are as high as 20-30 per cent. Because shell fragments were not included in the specimens for the consolidation-swelling tests, the carbonate contents in Table 2-4 are more representative. In other samples, carbonates probably act as cementing material.

Pyrite: Pyrite is identified by its 2.71 Å reflection in six samples and verified by chemical analysis. The pyrite amounts are also based on the sulphur contents in Table 2-6. Pyrite is absent in the Fuller's Earth and is present in a trace amount in the Flockton mudstone; in other samples, its amount varies from 0.6 to 3.9 per cent. The highest percentage is for the Lias Clay, which has been recognized by a decomposition product, rozenite (Section 2-1). Gypsum was suspected as being present in the Oxford and Lias Clays, but the amounts must be only at a trace level.

2-3-5 Relation between Mineralogy and Plasticity

As shown in Table 2-4, the total clay contents of the samples lie within a small range, the difference between extremes being only 7.5 per cent. The relative amounts of the clay mineral components vary very much, especially the content of active, expandable clays comprising smectite and mixed-layer clays containing smectite layers. According to the content of active clay minerals the samples can be classified into 4 groups in the following order:

Fuller's Earth > London Clays (LCW > LC) > Oxford Clays > Lias Clay and Flockton mudstone

This order is exactly the same as that based on the index parameters of plasticity (Section 2-2).

Skempton (1953b) defined the following ratio which he defined as 'activity' to reflect the influence of clay mineralogy on the plasticity of soils:

Activity = P.I./percentage by weight of clay size particles 2-1

As shown in Fig. 2-2, smectite, illite and kaolinite have very different activity values, represented by the gradients of those lines. In other words, smectite adsorbs the greatest amount of water and is the most active; whilst kaolinite is the least active. Illite is situated between smectite and kaolinite, and mixed-layer clays of smectite-illite type probably have activity values between illite and smectite. The particle size analysis was conducted using the pipette method in BS1377 (British Standard Institution, 1975). The particle size distributions of the samples are shown in Fig. A-2. The clay size fractions of the samples are given in Table 2-4 and the activities in Table 2-5. In general the clay size fractions are very close to the total clay mineral contents in the samples. The ratios of plastic and liquid limits to total clay mineral content are also shown in Table 2-5. From those values in Table 2-5, it appears that the plastic limits of the samples are affected only by the smectite contents; that is, the higher the smectite content, the greater the plastic limit. Meanwhile, the liquid limits depend not only on the smectite content but also that of mixed-layer clays. This shows up in the relatively high ratios of liquid limit to total clay content in the Oxford Clay samples which contain a high proportion of mixed-layer clay minerals but only traces of smectite. The clay size fractions are plotted against plasticity index in Fig. 2-2. It is apparent that the Fuller's Earth has a much lower activity than Skempton's values. This is probably due to the cementing effect of carbonates or larger particle size in this sample, as also found in

Fig. 2-2 Relation between plasticity index and clay content (after Skempton, 1953b)

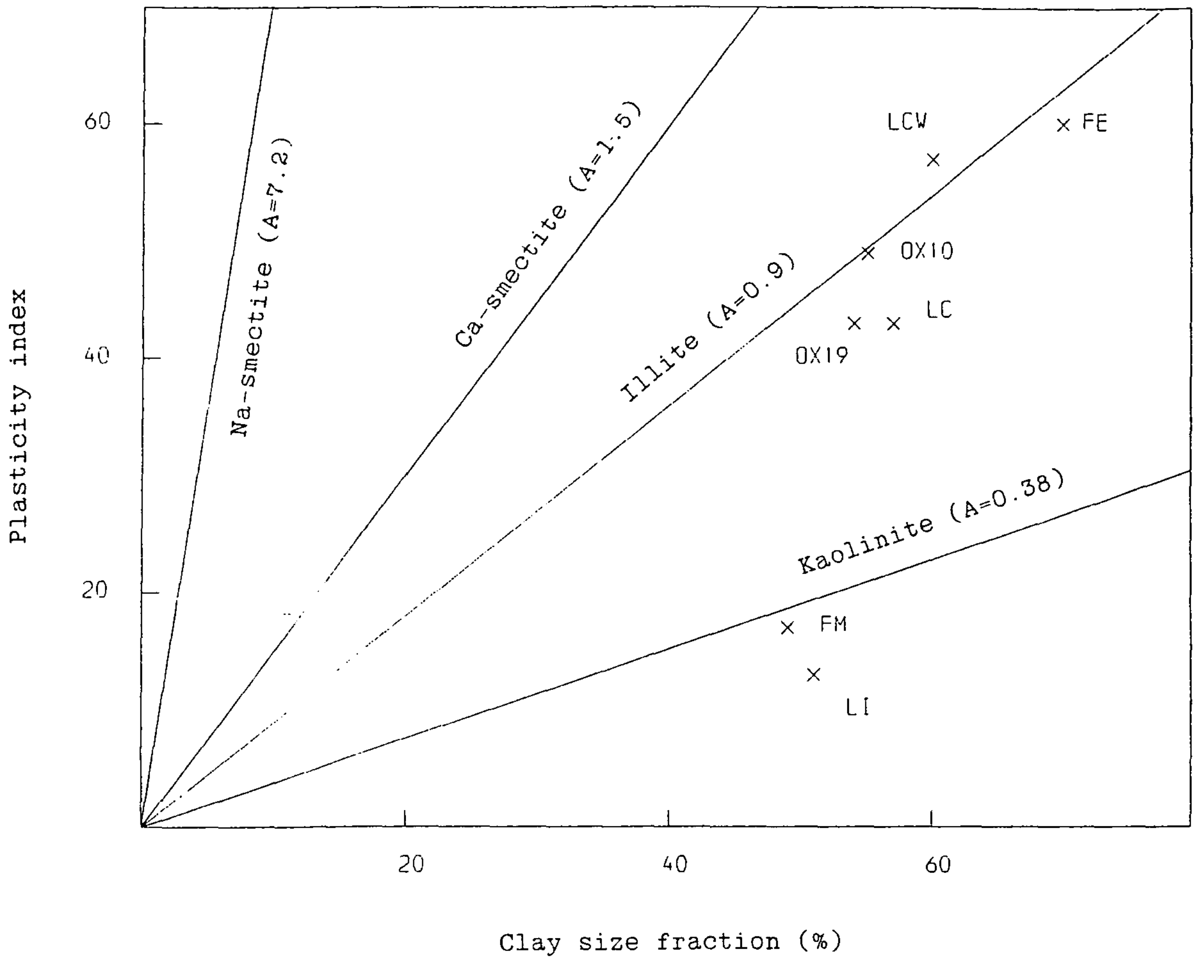


Table 2-5 Ratios of Atterberg limits to total clay mineral (TC) and activities of the samples

Sample	P.L./TC	L.L./TC	Activity
London Clay (LC)	0.53	1.25	0.75
London Clay (LCW)	0.56	1.45	0.95
Fuller's Earth (FE)	1.09	2.02	0.88
Oxford Clay (OX10)	0.32	1.14	0.89
Oxford Clay (OX19)	0.36	1.03	0.80
Lias Clay (LI)	0.38	0.59	0.25
Flockton (FM) mudstone	0.37	0.62	0.35

other Fuller's Earths (Smith, 1978), or to the suspected amorphous material (Section 2-4-2). According to Fig. 2-2, the over-all activities of London and Oxford Clays and Fuller's Earth are similar to that of illite, and the Lias Clay and Flockton mudstone have similar activities to kaolinite.

2-4 Whole-rock Geochemistry

2-4-1 Method of Analysis

Geochemical analysis of the whole rock samples was conducted with a Philips PW1212 Automatic Sequential X-ray Fluorescence (XRF) Analyser. Eleven major elements (as elements or element oxides), Si, Ti, total Fe, Mg, Ca, Mn, Na, K, P and S, were analysed, using pressed powders. Their oxide contents (except S) are expressed as percentages of the sample weight. Carbon dioxide was determined by decomposition with orthophosphoric acid and adsorption by sofnalite. Moisture, organic carbon and lattice water contents were obtained by thermal treatment. The normalized results are listed in Table 2-6. To aid the geochemical analysis and to confirm the clay mineralogy of the samples, Table 2-7 was derived by subtracting quartz, feldspar (as a K-form), carbonate, pyrite and organic carbon from the total composition in Table 2-6 and also excluding the minor amounts of TiO_2, MnO, and P_2O_5 and the water contents.

2-4-2 Relation between Geochemistry and Mineralogy

The total silica content comprises free silica (quartz) and combined silica. Combined silica, along with alumina, occur as a major constituent of silicates. Except where feldspar is present, these two oxides are dominantly represented by clay minerals. The total silica contents of the samples range between 51.13 and 59.12 per cent, showing little variation. When only the combined silica (

Table 2-6 Chemical compositions of the samples

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	MnO
London Clay(LC)	51.13	0.94	16.52	7.09	3.54	1.86	0.04
London Clay(LCW)	54.57	0.97	16.50	7.54	3.46	1.14	0.04
Fuller's Earth(FE)	55.28	0.49	10.84	10.45	3.09	1.40	0.01
Oxford Clay(OX10)	56.22	0.69	17.94	5.80	1.79	2.50	0.05
Oxford Clay(OX19)	53.50	0.72	18.40	5.45	1.66	2.26	0.03
Lias Clay(LI)	51.44	0.64	16.24	5.52	4.16	1.58	0.08
Flockton(FM) mudstone	59.12	0.79	21.07	3.76	1.83	0.22	0.03

Sample	Na_2O	K_2O	P_2O_5	S	CO_2	C	$H_2O(+)$	$H_2O(-)$
LC	0.30	3.42	0.16	0.34	1.98	1.33	5.95	5.39
LCW	0.60	3.36	0.15	0.39	1.62	0.59	5.25	3.81
FE	0.07	0.38	0.03	--	2.72	1.14	1.75	12.36
OX10	0.40	3.63	0.19	0.94	1.80	1.18	3.46	3.41
OX19	0.41	3.78	0.13	1.29	1.54	1.72	5.85	3.27
LI	0.84	5.53	0.05	2.07	1.98	0.70	5.57	3.59
FM	0.95	4.49	0.12	0.02	0.71	0.43	4.58	1.87

Table 2-7 Calculated chemical compositions of the clay mineral fractions in the samples

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O
London Clay(LC)	52.53	26.20	10.96	4.89	0.20	0.49	4.74
London Clay(LCW)	56.04	23.94	10.61	4.09	0.17	0.90	4.24
Fuller's Earth(FE)	72.31	13.95	7.56	4.19	1.90	0.09	--
Oxford Clay(OX10)	60.22	24.95	6.44	2.49	0.29	0.56	5.05
Oxford Clay(OX19)	57.42	27.59	5.77	2.49	0.45	0.61	5.67
Lias Clay(LI)	61.49	21.55	4.14	4.56	0.45	1.18	6.62
Flockton(FM) mudstone	59.96	27.63	3.35	2.51	0.30	1.30	4.94

Sample	$\frac{SiO_2}{Al_2O_3}$	$\frac{Fe_2O_3}{Al_2O_3}$	$\frac{MgO}{Al_2O_3}$	$\frac{CaO}{Al_2O_3}$	$\frac{Na_2O}{Al_2O_3}$	$\frac{K_2O}{Al_2O_3}$
London Clay(LC)	2.00	0.42	0.19	0.0	0.02	0.18
London Clay(LCW)	2.34	0.44	0.17	0.0	0.04	0.18
Fuller's Earth(FE)	5.18	0.54	0.30	0.14	0.0	--
Oxford Clay(OX10)	2.41	0.26	0.10	0.0	0.02	0.20
Oxford Clay(OX19)	2.08	0.21	0.09	0.02	0.02	0.21
Lias Clay(LI)	2.85	0.19	0.21	0.02	0.05	0.31
Flocton(FM) mudstone	2.17	0.12	0.09	0.0	0.05	0.18

excluding free silica and that in feldspar) are considered (Table 2-7), the variation becomes greater (72.31-52.53 per cent), indicating a difference in clay mineral suite.

For the examination of the influence of clay mineralogy on the chemical composition, it is more diagnostic to refer to the ratios of oxides to alumina (excluding the non-clay mineral fraction). These are shown in Table 2-7.

Typical combined silica to alumina ratios for clay minerals are as follows (after Weaver & Pollard, 1973; Smith, 1978; van Olphen & Fripiat, 1979):

Kaolinite -- 1.06-1.37 (1.18 for ideal kaolinite)
Illite -- 1.45-2.49 (2.02 for Fithian illite and 2.49 for Le-Puy-en-Valey illite)
Montmorillonite -- 2.14-3.45 (4.32 for Fuller's Earth)
Chlorite -- 1.02-2.06

Ratios with Al_2O_3 as denominator of other oxides are taken to indicate variation with total clay content and variation in relative amounts of the clay mineral species, as shown in Table 2-7.

The combined SiO_2/Al_2O_3 ratios of the London, and Oxford Clays and Flockton mudstone samples are 2.00 to 2.41 per cent, in the illite ratio range. The high value, 2.85, for the Lias Clay is certainly an indicator of its low kaolinite content (Table 2-4).

It was shown by Smith (1978) that the combined silica to alumina ratio in the British mudrocks had a positive correlation with the smectite content, indicating the dominance of Si over Al in the smectite lattice. The SiO_2/Al_2O_3 ratio of the Fuller's Earth is as high as 5.18, much greater than the possible values, perhaps indicating some amorphous silica (and/or alumina) present, in addition to a trace amount of quartz identified by XRD (Table 2-4). The total mineral content of the Fuller's Earth is only 76.3 per cent

(Table 2-4), thus strongly suggesting the existence of amorphous material. The smectite of the Fuller's Earth has been found by XRD to be dioctahedral, and with the high SiO_2/Al_2O_3 and CaO/Al_2O_3 and low Fe_2O_3/Al_2O_3 ratios, it is most probably a montmorillonite, according to the classification of Brindley (1980).

Iron and magnesium mainly substitute for aluminium in the octahedral layers of clay minerals. The Fe_2O_3 and MgO to Al_2O_3 ratios are higher in the London Clay samples and the Fuller's Earth, which all have significant amounts of smectite, showing a high degree of association between iron and magnesium and smectite contents. The Lias Clay is an exception, probably because the chlorite (4.6 per cent) could have a great influence (MgO/Al_2O_3= 0.11-2.28). The Flockton mudstone also contains chlorite, but its chlorite would have a lower magnesium content, according to the smaller MgO/Al_2O_3 ratio.

The CaO/Al_2O_3 ratios appear to vary little, except in the Fuller's Earth which would have Ca as the major interlayer cation (Table 2-8).

The K_2O contents and the K_2O/Al_2O_3 ratios are much greater than the Na_2O contents and the Na_2O/Al_2O_3 ratios, because potassium is fixed by the illites, except for the Fuller's Earth where no illite exists. The highest K_2O/Al_2O_3 value corresponds to the high illite content of the Lias Clay.

2-5 Exchangeable Cations and Cation Exchange Capacity

From the general considerations given in the first chapter, it is apparent that the type and the amount of different cations in a clay-water-electrolyte system have a major influence on the double-layer interaction or physico-chemical force. A clay mineral does not have a fixed value of cation exchange capacity (CEC), since CEC depends on various compositional and environmental factors, particularly pH value (Mitchell, 1976). However, the standard procedure used in the laboratory is commonly based on a pH value of 7. The equilibrium distribution of different cations in the double layer and the bulk solution has been explained by a number of theories, the double-layer theory being one of the most common (Sections 1-6 & 5-1). According to the double-layer theory, the ratio of divalent to monovalent cations is much higher in the double layers than in the bulk solution. For cations of the same valency, the double-layer theory predicts the same ratio (Mitchell, 1976). Because of differences in hydrated ion size and specific interaction energy, however, substantial deviation may exist, as shown by the order of replacing ability in Section 1-3. For assessing the proportions of monovalent and divalent ions, the Gapon equation is usually used. A practical form of the Gapon equation is (Mitchell, 1976):

$$(Na/(Ca+Mg))_e = K\ (Na/((Ca+Mg)/2)^{1/2})_s \quad \text{--------------------} \quad 2\text{-}2$$

where concentrations are in milliequivalents per litre (meq/l), the subscripts e and s refer to the exchangeable cations and the cations in the bulk solution, respectively, and K is the selectivity constant. The quantity in the right-hand side of Equation 2-2 can be expressed in terms of sodium adsorption ratio (SAR) as follows:

$$(Na/((Ca+Mg)/2)^{1/2})_s = SAR\ (meq/l)^{1/2} \quad \text{--------------------} \quad 2\text{-}3$$

The proportion of sodium in the adsorbed layer has an important bearing on the structural status of a material and is often described in terms of the exchangeable sodium percentage, ESP, defined as:

$$ESP = (Na/CEC) \times 100 \quad \text{------------------------------------} \quad 2\text{-}4$$

It has been indicated by Mitchell (1976) that the ESP and SAR values provide a good indication of the stability of clay soil structure to breakdown and particle dispersion.

2-5-1 Method of Analysis

The analysis of exchangeable cations in sediments of a high salt content is very difficult. Rinsing of samples with distilled water, or other agents, prior to the determination of exchangeable cations is usually an inevitable process to flush out interstitial electrolyte. Rinsing, (that is, dilution of the interstitial solution), leads to the selective uptake of cations of 'higher' valence relative to cations of lower valence. This can be described by the Donnan equilibrium concept or double-layer theory. Sayles and Mangelsdorf (1977) showed that rinsing with distilled water dramatically increased the amounts of exchangeable Ca and Mg and decreased those of exchangeable Na and K in the sediments saturated with sea water. However, CEC values *per se* are unlikely to be changed by rinsing.

Most sediments contain various amounts of carbonate minerals, which to a certain extent release in most exchange solutions the cations (commomly Ca and/or Mg) present in the carbonates (Holmes, 1980). For example, one of the most common replacing agents, ammonium acetate, dissolves carbonate minerals. Smith (1978) used methylene blue as a replacing agent to correct for the exchangeable Ca values obtained by means of ammonium acetate. Methylene blue molecules are however too big to enter the intracrystalline space of expandable minerals. As a result, his data may underestimate the CEC values of the samples containing smectite and mixed-layer clays, which are important components of the present samples studied in the content of swelling behaviour.

In order to overcome the difficulties mentioned above, the method shown in Appendix A-2, modified from Richards (1954), was adopted. The amounts of exchangeable cations are the difference between those extracted using $BaCl_2$ and those extracted using H_2O. A similar procedure was employed by Sameshima and Way (1982), who used $LaCl_3$ instead. The replacing cation, barium, has a high replacing ability (see Section 1-3). Barium has been used in the determination of exchangeable cations by Weaver and Beck (1971) and by other laboratories (van Olphen & Fripiat, 1979). The resultant cation ratios, however, still represent those in the relevant dilution ratios only. The resultant amounts of exchangeable Na, K, Ca and Mg cations are listed in Table 2-8. Also given are the CEC values, calculated as the sum of the four exchangeable cations, and the ESP values. All the amounts are expressed in milliequivalent per 100 grams of dry sample (at 105°C).

2-5-2 Exchangeable Cations

Calcium seems to be the major exchangeable cation from the values on Table 2-8, with less Mg, Na and K. Potasium is absent in the Fuller's Earth. Since considerable amounts of carbonate minerals are present in all the samples, a small dissolution of the carbonates (Section 2-6) would increase the concentrations of divalent cations in the solutions and thus also the amounts of exchangeable cations. The dilution introduced by rinsing would also be in favour of divalent cations, as already discussed at the beginning of Section 2-5. Therefore, the ESP values in Table 2-8 would tend to be lower than the actual ones. Nevertheless, the ESP values of London and Lias Clays and Flockton mudstone are already more than 2 per cent, above which soils are susceptible to spontaneous dispersion in water (Mitchell, 1976). In particular the Flockton mudstone has an ESP value as high as 18. This might be one of the reasons for the efficient slaking noted in the disintegration method used (Appendix C-1-2(b)). Although the ESP values of the Oxford Clay samples are not high, the Na contents in soluble salts are relatively much

Table 2-8 Exchangeable cations and cation exchange capacity of the samples (content in meq/100 g sample)

Sample	Exchangeable cations Na	K	Ca	Mg	CEC	Calculated CEC	ESP
London Clay(LC)	1.30	0.19	14.49	5.56	21.54	19.7	6.02
London Clay(LCW)	0.94	2.03	20.35	6.51	29.83	25.1	3.17
Fuller's Earth(FE)	0.54	---	60.27	14.31	75.12	65.0	1.71
Oxford Clay(OX10)	0.28	0.30	13.96	4.94	19.48	19.3	1.42
Oxford Clay(OX19)	0.07	0.03	13.80	4.63	18.53	19.4	0.39
Lias Clay(LI)	0.52	0.76	6.36	4.38	12.02	11.7	4.31
Flockton(FM) mudstone	1.80	1.47	5.17	1.46	9.90	10.9	18.21

higher, as indicated by their SAR values in Table 2-10. This probably suggests higher ESP values in the Oxford Clay samples than indicated by the measured ones.

2-5-3 Cation Exchange Capacity

Cation exchange capacity depends upon clay mineral types and amounts in soils. As shown in Table 1-4, smectites have a much higher CEC value than other clay minerals. Mixed-layer clays with smectite layers would also have relatively high CEC values. This would depend on the percentage of smectite layers. The CEC values of the samples range widely from 9.90 to 75.12 meq/100 g, in an order commensurate with that based on the content of smectite and mixed-layer clays (Section 2-3-5). The CEC value of Fuller's Earth is at the lower end of the range quoted in Table 1-4, probably because clay minerals in the natural material are usually present as cemented aggregates; thus, some of the exchangeable sites become inaccessible (Sansom and White, 1971).

If arbitrary CEC values are chosen from Table 1-4 the following order may be chosen for clay minerals:

Kaolinite -- 4 (meq/100 g sample)
Illite -- 15
Mixed-layer clays -- 60
Smectite -- 100
Chlorite -- 10

CEC can therefore be calculated from the mineralogical composition (Table 2-4) according to the following equation:

$$\mathrm{CEC} = 4\,K + 15\,I + 60\,ML + 100\,S + 10\,Ch \qquad \text{------------------} \qquad 2\text{-}5$$

where K= kaolinite. I= illite, ML= mixed-layer clays of illite-smectite type, S= smectite and Ch= chlorite, expressed as proportions between 0 and 1. The results are comparable with the measured values, as shown in Table 2-8. Organic matter has been ignored because the organic matter in these old mudrocks would not be active and have a significant CEC (Table 1-4). Additionally, the organic carbon contents of the samples are small, being less than 2 per cent (Table 2-4).

The CEC values are also in a good agreement with liquid limit, L.L., as shown in Fig. 2-3. A linear relationship between CEC and L.L. has generally been found (for instance, Farrar & Coleman, 1967), because the water adsorption ability of clays results from the charge deficiency in their crystal structures, which is quantified as CEC (Section 1-3). Farrar and Coleman (*op. cit.*) expressed this relationship as:

$$L.L. = 1.80\ CEC + 22 \quad \text{------------------------------------} \quad 2\text{-}6$$

Their data do not include those of Fuller's Earth. According to the data here, that linear relationship might be best expressed as:

$$L.L. = 1.34\ CEC + 38 \quad \text{------------------------------------} \quad 2\text{-}7$$

which has a coefficient of correlation of 0.95. When the Fuller's Earth is excluded, the coefficient of correlation is improved to 0.98 and the relationship becomes as:

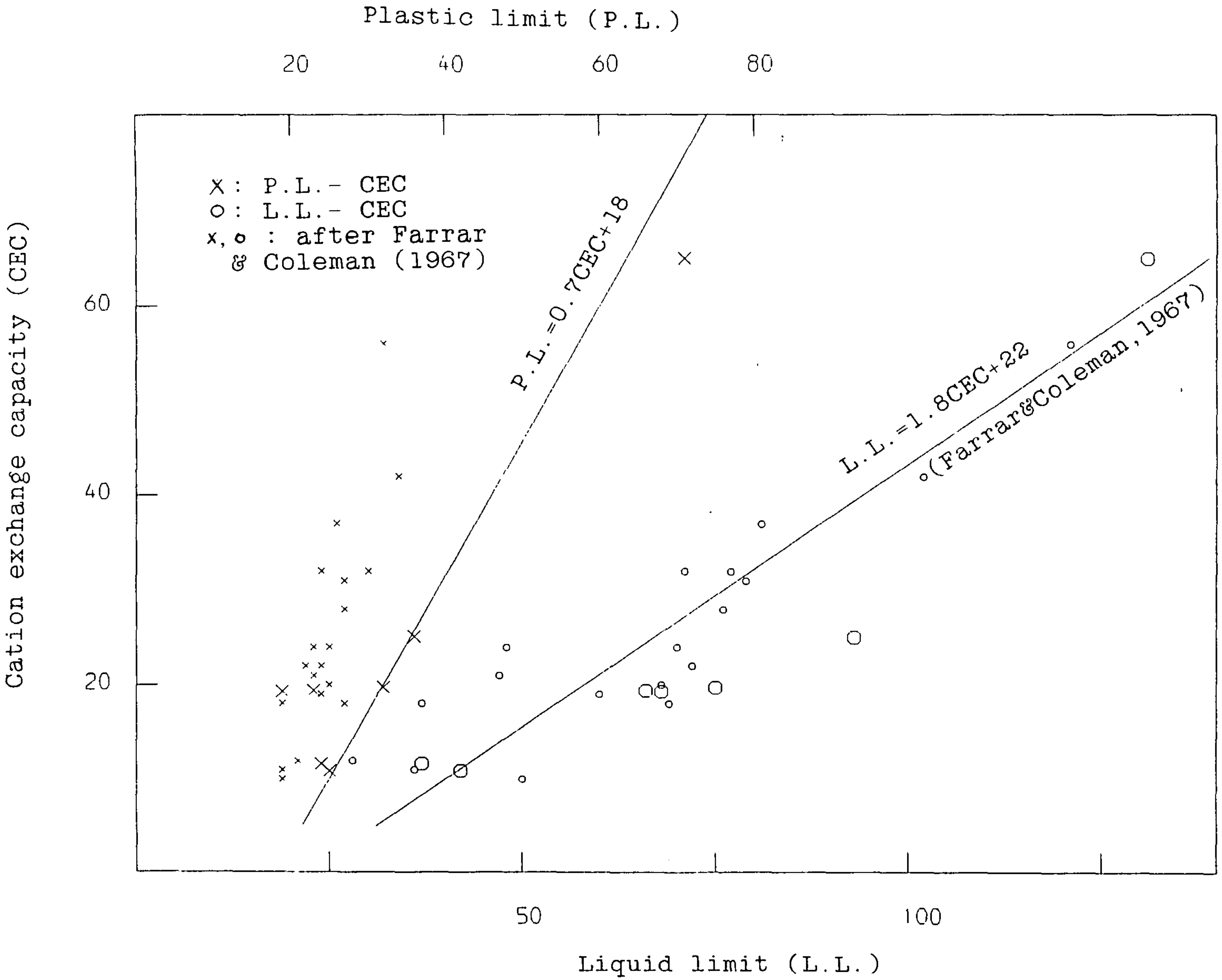
$$L.L. = 2.87\ CEC + 10 \quad \text{------------------------------------} \quad 2\text{-}8$$

Compared with those values Farrar and Coleman (1967) obtained using the ammonium acetate method, the CEC values of the samples obtained in this study tend to be lower at the same L.L. values. A linear relationship with a coefficient of correlation of 0.97 is also found between plastic limit, P.L., and CEC, as shown in Fig. 2-3; but the correlation of plasticity index, P.I., and CEC falls below any significant level.

2-6 Pore Fluid Geochemistry

2-6-1 Pore Fluid Extraction

Fig. 2-3 Relationship between plastic and liquid limits and cation exchange capacity in the samples



A number of methods have been employed for extracting pore fluid from sediments, including leaching, centrifugation, immiscible liquid/gas displacement and low-pressure mechanical squeezing (Rieke & Chilingarian, 1974). Except for leaching, these methods are best used with recent sediments or relatively unconsolidated soils. A major disavantage of leaching, which many investigators have used especially for ancient mudrocks (for example, Spears, 1974), is that the soluble salts concentration increases as the water content increases (Richards, 1954; Bower *et al.*, 1952; Reitemeier, 1946). This method gives a non-representative pore fluid chemistry.

In the initial stage in this project, centrifugation was applied, but, apart from the Fuller's Earth, the method failed to extract any fluid from a glacial laminated clay from Co. Durham with a much higher moisture content than the other samples studied. Eventually a simplified squeezer of the Kriukov type, described in detail by Manheim (1966), was manufactured (as shown in Fig. A-1) and used to extract the pore fluids. The Flockton mudstone and Lias Clay samples have moisture contents less than 12 per cent, which is lower than the moisture contents of other samples even after they were squeezed. Hence, no attempt was made to extract pore fluid from those two samples. Instead, a saturation extract was derived by making slurries beyond the liquid limit and then squeezing them. The extraction procedure is given in Appendix A-3 and the chemical compositions of the pore fluids are presented in Table 2-9.

2-6-2 Influence of Squeezing Pressure

It has long been appreciated that the squeezing pressure might influence the composition of the pore fluid extracted from sediments (for example, Manheim, 1966). The reason is probably that clay minerals act as semi-permeable membrane and their efficiency becomes

Table 2-9 Pore fluid compositions (concentration in ppm) of the samples

Sample	Pressure (MN/m^2)	Na	K	Ca	Mg	Total cations	Cl	SO_4
London Clay (LC)	18.1	199	39.4	447	210	895.4	1030	480
	SS	1180	2790	7620	2000	13590	1790	1420
London Clay (LCW)	14.2	1170	73.3	128	55.4	1426.7	1780	520
	24.3	1180	68.8	128	56.3	1433.1	1800	493
	24.3*	1240	76.2	107	79.1	1502.3	1910	605
	34.3	869	54.2	129	59.6	1111.8	1380	471
	72.0*	502	39.1	110	57.9	709	790	407
	SS	5280	1970	96.9	30	7647.9	2140	3080
Fuller's Earth (FE)	10.2	28.1	1.20	34.9	10.6	74.8	40	n.d.
	14.2	21.6	0.93	31.6	8.98	63.1	34	n.d.
	18.1	10.0	0.45	22.5	3.61	36.6	19	n.d.
	18.1*	12.1	0.55	28.6	4.52	45.8	25	n.d.
	72.0*	4.26	0.26	19.5	5.03	29.1	17	n.d.
	SS	216	565	14.4	19.2	814.6	62	18
Oxford Clay (OX10)	18.1*	1110	103	700	237	2150	1840	1030
	24.3*	1120	93.0	732	230	2175	1730	1210
	45.0*	435	97.2	605	233	1370.2	980	915
	72.0*	257	63.5	674	212	1206.5	951	724
	SS	2000	1580	11800	1420	16800	20 0	1520
Oxford Clay (OX19)	18.1	2310	78.0	812	208	3408	3920	951
	SS	7070	3230	15900	1900	28100	4670	3070
Lias Clay (LI)	SE	8710	1090	2170	895	12865	9650	2310
	SS	16900	5660	8860	3610	35000	12200	14100
Flockton mudstone(FM)	SE	14500	1410	--	35.0	15945	9750	4500
	SS	39000	8760	--	113	47873	17300	15700

SS: Calculated composition from the content of soluble salts (see Appendix A-2).

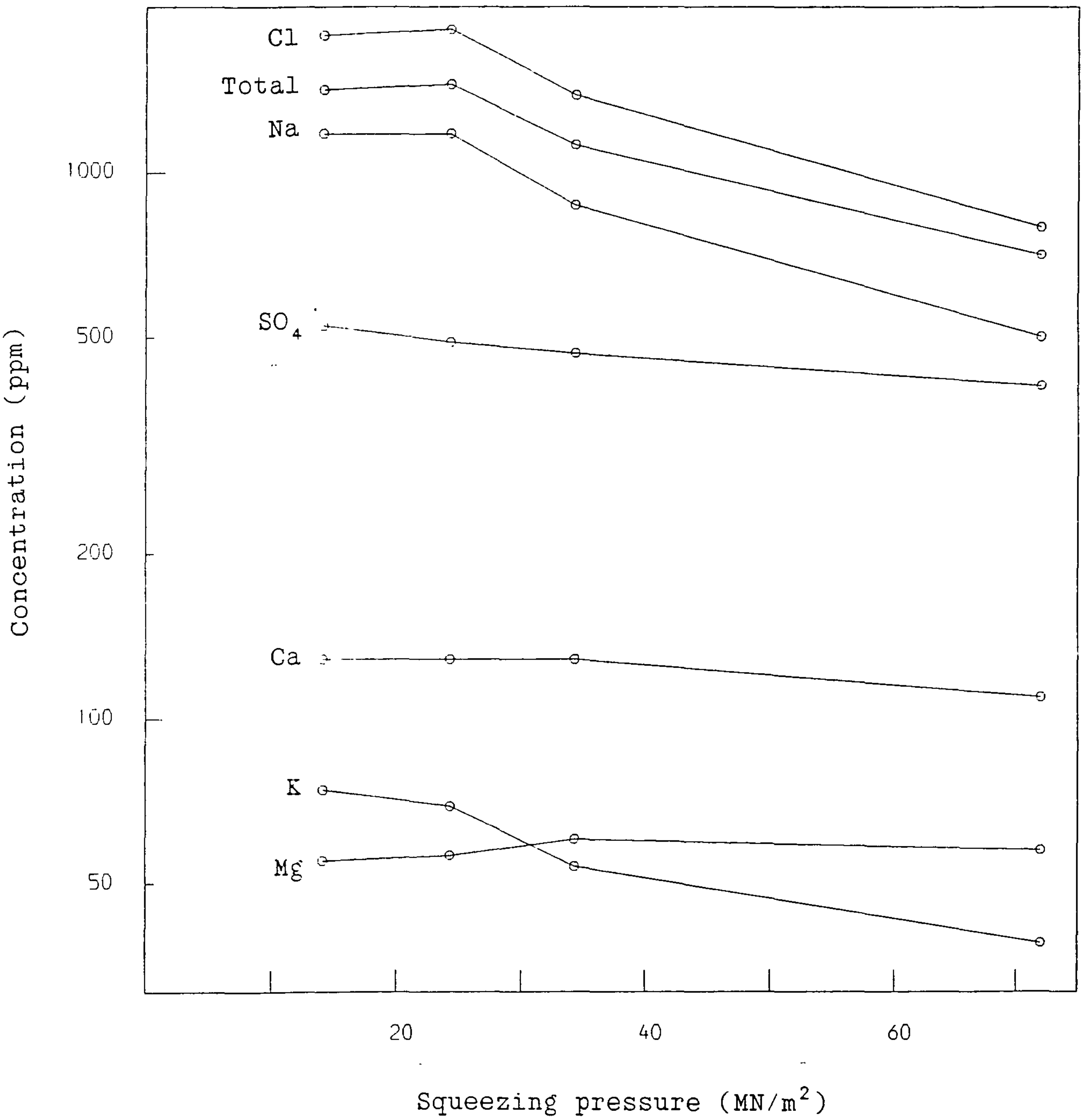
SE: By means of saturation extract.

n.d.: not detectable.

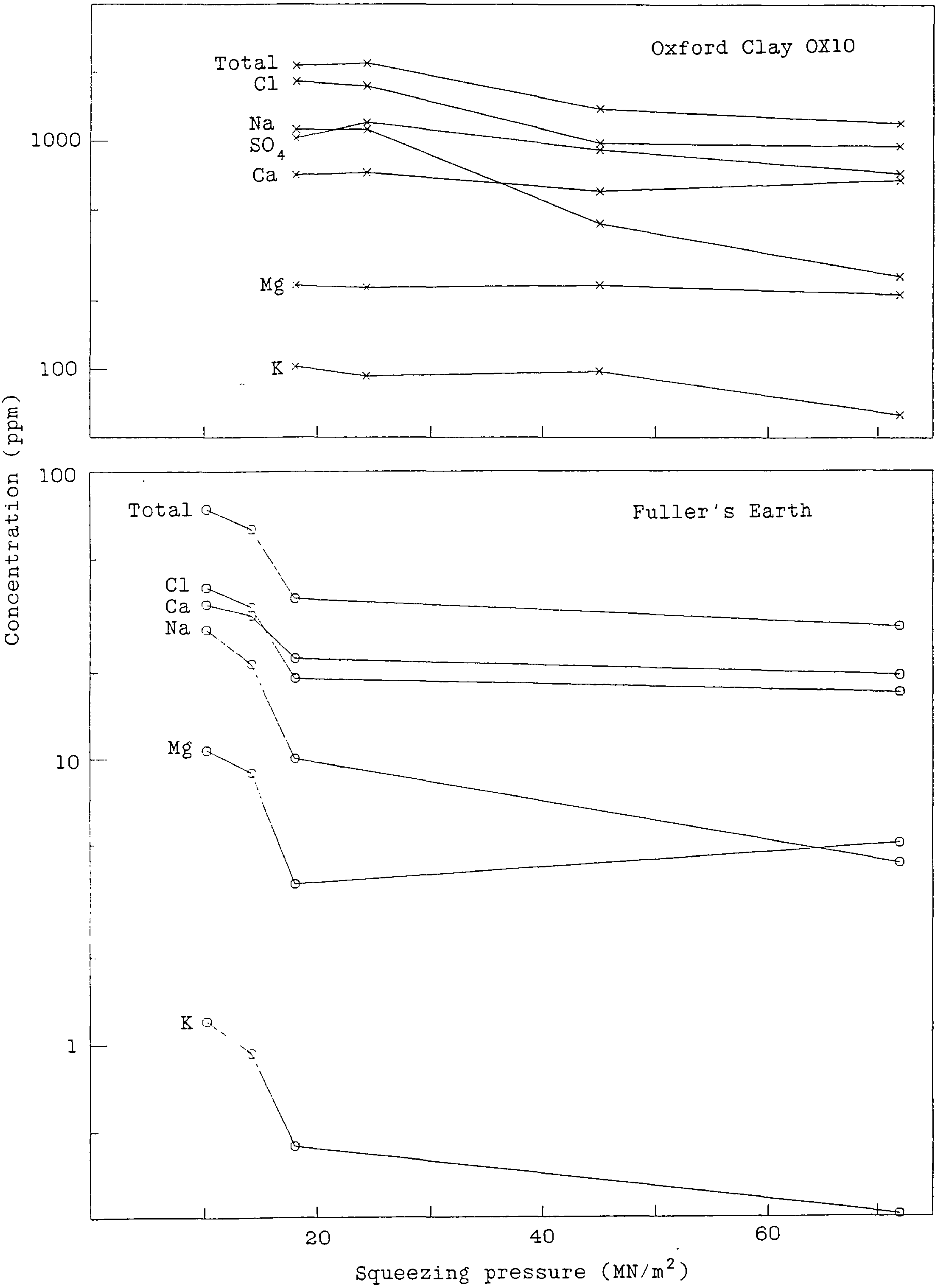
greater at higher pressures. Three sets of tests were carried out to check the extent of this influence. From the results, shown in Figs. 2-4-1 to -3, it is clear that for different samples, the resultant concentrations of total cations are affected to varying degrees by the applied squeezing pressure. The cation concentrations of the pore fluids from the Fuller's Earth are very sensitive to the squeezing pressures. The total cation concentrations are reduced to more than half in the pressure range of 10.2 to 18.1 MN/m^2. For the London (LCW) and Oxford (OX10) Clays, the squeezing pressures have little influence on the concentrations until they reach about 24 MN/m^2, respectively. This conforms with what Kharaka and Berry (1973) found, that the membrane efficiency is the highest in clays with the highest cation exchange capacity (see the CEC values in Table 2-8). Morgenstern and Balasubramonian (1980) also found a pressure threshold which influenced the compositions of the extracted pore fluids. In order to obtain a sufficient amount of pore fluid for chemical analysis within a reasonable period of time, a pressure of 18.1 MN/m^2 was used for other samples. This is much higher than the pressure, 4.83 MN/m^2, used for the Bearpaw and Morden Shales of Morgenstern and Balasubramonian (1980), which contain a high percentage of smectite and mixed-layer clays. Nevertheless it is still less than their threshold pressure of 20.7 MN/m^2.

The relative concentrations of cations are also influenced by squeezing pressure. It appears that the squeezing pressure has a greater effect on Na and K and is less effective for divalent cations, as shown in Figs. 2-4-1 to -3. The Ca and Mg concentrations remain almost constant in the pore fluids from the London (LCW) and Oxford (OX10) Clays. This is contrary to the double-layer theory, which is used to explain the role of clay minerals as a semi-permeable membrane. According to the theory, divalent cations are

Fig. 2-4-1 Influence of squeezing pressure on pore fluid chemistry in the London Clay (LCW)



Figs. 2-4-2 (bottom) and 2-4-3 (top) Influence of squeezing pressure on pore fluid chemistry in the Fuller's Earth and Oxford Clay



held preferentially because of their higher charge. As pointed out by Kharaka and Berry (1973), however, the higher hydraulic pressure gradients in the laboratory result in high flow velocities and also in greater water drag force, which has less effect on the divalent cations with 'smaller' hydrated radii. The Cl ion concentration appears to follow the decreasing pattern of the Na concentration; whilst the SO_4 ion concentration is less affected by squeezing pressure.

2-6-3 Influence of Sample Thickness

In the initial stage of the pore fluid extraction experiments, a sample thickness of c. 50 mm was adopted, using a static loading system. Because clay minerals are semi-permeable membranes, sample thickness could influence the pore fluid composition. Another loading system was adopted allowing the sample thickness to be reduced down to about 7 mm. This loading system entailed hydraulic force from an Avery-Denison machine. As shown for pairs of results at the same pressures (Table 2-9, LCW & FE), the sample thickness affects the total cation concentrations of the London Clay (LCW) and Fuller's Earth by 5 and 25 per cent, respectively, and the chloride ion concentrations are reduced in the thicker specimens by 6 and 32 per cent. The great reduction of ion concentrations in the thicker Fuller's Earth specimen could also be ascribed to its high cation exchange capacity, the same reason as for the influence of squeezing pressure.

2-6-4 Pore Fluid Composition

The extracted pore fluids have a wide range of concentrations, with the near-surface Fuller's Earth being the most dilute and the Oxford Clays the most concentrated, as shown in Table 2-9. The

Table 2-10 Cation ratios and SAR values in the pore waters of the samples

Sample	Pressure (MN/m^2)	Na/K	Na/Ca	Na/Mg	Ca/Mg	SAR
London Clay	18.1	5.05	0.45	0.95	2.13	1.95
(LC)	SS	0.42	0.15	0.59	3.81	3.11
London clay	14.2	16.0	9.14	21.1	2.31	21.8
(LCW)	24.3	17.2	9.22	21.0	2.27	22.0
	24.3*	16.3	11.6	15.7	1.35	22.2
	34.3	16.0	6.74	14.6	2.16	15.9
	72.0*	12.8	4.56	8.67	1.90	13.6
	SS	2.68	54.5	17.5	0.32	59.7
Fuller's Earth	10.2	23.4	0.81	2.65	3.29	1.07
(FE)	14.2	23.2	0.68	2.41	3.52	0.87
	18.1	22.2	0.44	2.77	6.23	0.52
	18.1*	22.0	0.42	2.68	6.33	0.55
	72.0*	16.4	0.22	0.85	3.88	0.22
	SS	0.38	15.0	11.3	0.75	8.77
Oxford Clay	18.1*	10.8	1.59	4.68	2.95	9.25
(OX10)	24.3*	12.0	1.53	4.87	3.18	9.25
	45.0*	4.48	0.72	1.87	2.60	3.81
	72.0*	4.05	0.38	1.21	3.18	2.21
	SS	1.27	0.17	1.41	8.31	4.63
Oxford Clay	18.1	29.6	2.84	11.1	3.90	18.7
(OX19)	SS	2.19	0.44	3.72	8.37	14.1
Lias Clay	SE	7.99	4.0	9.73	2.42	39.7
(LI)	SS	2.99	1.91	4.68	2.45	38.2
Flockton mudstone	SE	10.3	--	414	0	526
(FM)	SS	4.45	--	345	0	787

SE: Saturation extract.

SS: Calculated compositiom from the content of soluble salts (see Appendix A-2)

* Thin specimen.

saturation-extract result, also shown in Table 2-9, indicates that highly concentrated pore fluids probably exist in the Lias Clay and Flockton mudstone. Also included in this Table is the calculated pore fluid composition, based on soluble salts contents (see the calculation in Appendix A-2). These results show that the calculated pore fluid concentrations from the soluble salts contents are 5 to 15 times as high as the concentrations of the squeezed pore fluids. The pore fluid compositions calculated from the soluble salts contents have a lower Na/K ratio in all the samples than from squeezed pore fluids, as shown in Table 2-10. The Na/Ca ratio is higher in the London Clay (LCW) and Fuller's Earth and lower in the London (LC), Oxford and Lias Clays. The Na/Mg ratio is higher in the Fuller's Earth than in other samples, and the Ca/Mg ratio is higher in the London (LC) and Oxford Clays and lower in the London Clay (LCW) and Fuller's Earth. The dissolution of calcite would be partly responsible for the lower Na/Ca and higher Ca/Mg ratios in the London (LC) and Oxford Clays, in which calcite is the major carbonate mineral. The higher Na/Ca ratios in the London Clay (LCW) and Fuller's Earth coincide with the higher smectite contents (Table 2-4), indicating the function of cation exchange process in these two samples. In addition to the dissolution of calcite and cation exchange, another possible process that is responsible for the changes in the relative and total amounts of soluble ions which occur with increasing water content could be the dissolution of clay minerals, regarded as a kind of hydrolysis by Yariv and Cross (1979). Some values for the solubility of standard clay minerals were offered by Huang and Keller (1973), as shown in Table 2-11. Low Na/K ratios could be due to the preferential release of K from illite and Ca-smectite by dissolution in water, according to the data in Table 2-11. The same reason might apply to the lower Na/Mg ratios in most

Table 2-11 Dissolution of clay minerals in distilled water (recalculated from Huang & Keller's (1973) data) (concentration in ppm)

Cation species	Geogia kaolinite	Fithian illite	Wyoming * bentonite	Arizona ** montmorillonite
Na	--	0.20	39.1	0.35
K	--	1.41	0.66	0.78
Ca	--	1.56	0.33	2.38
Mg	0.005	0.53	0.96	0.40

* Na-smectite.

** Ca-smectite.

samples.

The relative abundance of Na in the cation suite has been postulated in terms of ESP values in Section 2-5-2. However, those ESP values are meaningful only in the relevant solutions (40 ml water). The SAR values for the squeezed pore fluids show that the London Clay (LC) and Fuller's Earth have relatively low SAR values, indicating low Na contents in their pore fluids. The expandable clay minerals in those two samples would not have intracrystalline swelling beyond 20 Å according to Mitchell (1976). The relatively high SAR values in the London (LCW), Oxford and Lias Clays probably indicate a demixing phenomenon in the interlayer exchange sites of the expandable clays (Mitchell, 1976); that is, the interlayer spacing with exchangeable divalent cations would be restricted to 20 Å. The extremely high SAR value for the Flockton mudstone is certainly an indication of the absence of Ca and the low Mg concentration in the pore fluid (Table 2-9).

2-7 Summary

1. Seven British mudrock samples were used in this study, which cover a wide range of geological age and depth. They range from heavily -overconsolidated clays to highly-indurated mudstones.
2. According to the conventional soil classification, the disintegrated (remoulded) samples also have a great range of plasticity, from extremely high to medium plasticity.
3. By X-ray diffraction analysis, clay mineral types and amounts were investigated, especially smectite and expandable mixed-layer clays. It was found that the smectite and expandable mixed-layer clay contents, 0 to 65 and 0 to 28 per cent, respectively, were closely related to the liquid limits of the samples.
4. Based on plasticity and the content of expandable clay minerals,

the samples can be arranged in an order of geotechnical sensitivity as follows:

Fuller's Earth > London Clays (LCW > LC) > Oxford Clays
> Lias Clay & Flockton mudstone

5. The whole-rock geochemical analysis showed ten major (>1%) oxides or elements, SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, K_2O, S, CO_2, C and H_2O. The calculated chemical composition of the clay mineral fraction has been used to check the variation of clay mineral suite, using the diagnostic ratios of oxides to alumina. The SiO_2/Al_2O_3 values indicate that amorphous material is present in a substantial amount in the Fuller's Earth, whilst other samples have illite as major clay mineral. The Fe_2O_3 and MgO to Al_2O_3 ratios are associated with the smectite contents. Both K_2O and K_2O/Al_2O_3 are the greatest in the Lias Clay, which contains the greatest amount of illite.
6. The CEC values of the samples range widely from 9.90 to 75.12 meq/100 g, in an order commensurate with that based on the content of smectite and mixed-layer clay minerals. CEC is linearly related to the liquid and plastic limits, but not to plasticity index. The cation exchange capacity can be estimated from the mineralogical composition.
7. Calcium is the major exchangeable cation with less Mg, Na and K in the samples according to the modified exchangeable cation analysis.
8. A pore fluid squeezer was used to obtain more representative pore fluid compositions from the samples. The influence of sample thickness and squeezing pressure on the resultant compositions was also investigated. It was found that monovalent ion concentrations were greatly affected by squeezing pressure and specimen thickness, especially in the Fuller's Earth which has a

high cation exchange capacity.

9. According to the chemical analyses of exchangeable cations and pore fluid, the Fuller's Earth has low ESP and SAR values; whilst the other samples have quite high values and are susceptible to spontaneous dispersion. These high SAR values also indicate that the expandable clay minerals in those samples would show some intracrystalline swelling. Although the Flockton mudstone has the highest SAR and ESP values, it contains only 7.5 per cent of expandable mixed-layer clay minerals.

CHAPTER 3 FABRIC ANALYSES

Fabric, defined as the geometrical arrangement of the constituent particles, including void spaces (Yong & Warkentin, 1975), is an integral and vital component of the properties of mudrocks or clays. Although it is usually difficult to quantify, an assessment of fabric is required for a proper understanding of the interaction of the individual microscopic constituent elements. With the aid of techniques of scanning electron microscopy, X-ray diffractometry and porosimetry, a greater understanding of the fabric and its response to stress is made possible.

An attempt has been made to investigate the fabrics of the present samples, particularly the difference in fabric between the samples, undisturbed and remoulded. The characterisation methods used include the surface area measurement by nitrogen adsorption, the pore size analysis by mercury porosimetry and the measurement of clay mineral orientation by X-ray diffractometry. All these three methods give a quantitative result. Scanning electron microscopy and X-ray radiography have been applied to examine microscopic and macroscopic features in the samples. These fabric analyses provide some important information which is useful in the investigation of swelling behaviour.

3-1 Sample Preparation

Most of the techniques for studies of clay fabric require dehydration of samples. The most common method, air- or oven-drying, is not suitable for samples of high moisture contents, because of the resultant shrinkage (Tovey *et al.*, 1973). Two other methods, critical-point-drying and freeze-drying, have given apparently identical and satisfactory results (Gillott, 1973; Tovey *et al.*, 1973

). The former applies high temperature and pressure to the samples and thus incorporates the attendant risks of affecting clay mineral structures. Freeze-drying is relatively simple and was adopted in this study. The details of the procedure are given in Appendix B-1. Although the best freezing agent seems to be Freon 22 cooled by liquid nitrogen to avoid air bubbles around samples (Delage & Lefebvre, 1984), the samples were directly immersed in liquid nitrogen in this project. Ahmed *et al.* (1974) used a similar method to pretreat compacted clays and obtained satisfactory results on the pore size distribution, which is one of the main purposes in this study. The resultant specimens were used in the analyses of surface area, pore size distribution and scanning electron microscopy.

3-2 Surface Area

3-2-1 Principle of Nitrogen Adsorption Measurement

There are a number of ways of estimating the surface area (van Olphen, 1970). Among them, nitrogen and glycerol adsorption methods seem to be two of the most common. The latter has been used to measure the total surface area of clay minerals (Madsen, 1977). Dye adsorption is also frequently used, possibly because its application is relatively quick and simple. In this study, the conventional nitrogen adsorption method was applied to measure the 'external' surface areas of the samples which were freeze-dried already. The procedure is described in Appendix B-2. Before the adsorption tests, the samples were de-aired at 300°C for two hours. Under this condition, the intracrystalline space of expandable clay minerals collapsed (see Section 2-3-2); thereby, only external surfaces were measured. Since only limited intracrystalline swelling is expected in the samples (Section 2-3-2) the measurement of external surface area is considered to be adequate.

The nitrogen adsorption results are traditionally interpreted by the BET (Brunauer, Emmett and Teller) equation as follows (Gregg & Sing, 1967):

$$\frac{1}{V\,(1 - P/P_o)} = \frac{1}{V_m\,C} + \frac{C - 1}{V_m\,C}\,\frac{P}{P_o} \qquad \text{3-1}$$

where V = volume adsorbed at P,

P = adsorbate (N_2) equilibrium pressure,

V_m = volume the adsorbate monolayer would occupy at S.T.P.,

P_o = adsorbate saturated equilibrium vapour pressure,

C = constant.

On the plot of $1/V(1-P/P_o)$ versus P/P_o (for example, Fig. B-1), Equation 3-1 appears to be a straight line. From the slope, $(C-1)/V_mC$, and the intercept, $1/V_mC$, of the straight line, the volume of the adsorbate monolayer can be derived and then the surface area of the sample is calculated as follows:

$$A_s = N\,A_a\,(V_m/V_o)\,/\,W \qquad \text{3-2}$$

in which A_s = surface area of the sample,

N = Avogadro's number, 6.02×10^{23},

A_a = cross-section area of the adsorbate molecule, 16.2 A^2 for nitrogen molecules.

V_o = volume of a mole of gas at S.T.P., 22,400 cm^3/mole,

W = weight of the sample used.

The BET equation in fact has become the standard one for practical surface area determinations. The linear region of a plot according to Equation 3-1 typically lies in a range of P/P_o values, 0.05 to 0.3. In this study, three P/P_o values, 0.1, 0.2 and 0.3, were used for each specimen. An example of the calculation is given in Appendix B-2-2.

Surface areas of the undisturbed samples before and after tests in the modified oedometers and the swell cell were measured, together with remoulded samples after consolidation-swelling tests. Twenty six measurements were carried out in total.

3-2-2 Experimental Result and Discussion

The surface areas of the undisturbed and remoulded samples presented in Table 3-1 range from 10 to 107 m^2/g. These external surface area values are representative of the particle sizes in the samples, controlled largely by clay minerals. The order of the samples in external surface area is as follows:

Fuller's Earth > London and Oxford Clays ≥ Lias Clay &
Flockton mudstone

The London Clay samples have the same range of external surface area as the Oxford Clay samples. This probably indicates that all four samples have similar particle size, although the two London Clay samples contain a significant amount of smectite; whilst the two Oxford Clay samples contain large amounts of mixed-layer clay minerals, instead (Section 2-3-2). The smectite particles of the Fuller's Earth are certainly of a very fine size, because of its large external surface area. The Lias Clay and Flockton mudstone have the smallest surface area.

The surface area values are plotted against liquid limit in Fig. 3-1, together with the data of Farrar and Coleman (1967). Also included is the linear relationship found between total surface area and liquid limit by Farrar and Coleman. All the surface area values are less than the Farrar and Coleman's equation predicts. Obviously this is because the surface area obtained by nitrogen adsorption represents external surfaces only. The vertical distance between the straight line and the range of external surfaces shown in Fig. 3-1 provides a rough estimate of the amount of internal surface area. The estimated total and internal surface areas are given in Table

Table 3-1 Surface Areas (m^2/g) of the samples

Sample		Surface area** E	T	I	Sample		Surface area** E	T	I
London	U *	58	100	42	Oxford	U	60	88	28
Clay	UF	54		|	Clay	UF	58		|
(LC)	U24	58		46	(OX10)	U34	53		35
	S24	56				S34	59		
	Average	57				Average	58		
London	U	48	132	69	Oxford	U	51	84	22
Clay	UF	49		|	Clay	UF	52		|
(LCW)	U24	63		83	(OX19)	U34	58		33
	S24	58				S34	62		
	Average	55				Average	56		
Fuller's	U	107	200	93	Lias	U	18	32	6
Earth	UF	105		|	Clay	U24	19		|
(FE)	U34	100		100	(LI)	S24	26		14
	S24	106				*** Average	19		
	Average	105							
					Flockton	U	12	41	16
					mudstone	U34	10		|
					(FM)	S34	25		31
						*** Average	11		

* U : Undisturbed sample.

UF: Undisturbed sample after testing in the swell cell (see Appendix C-2).

U24(34), S24(34): Undisturbed (U) and remoulded (S) samples after testing in the modified oedometers with a maximum pressure of 24 or 34 MN/m^2 (see Appendix C-1).

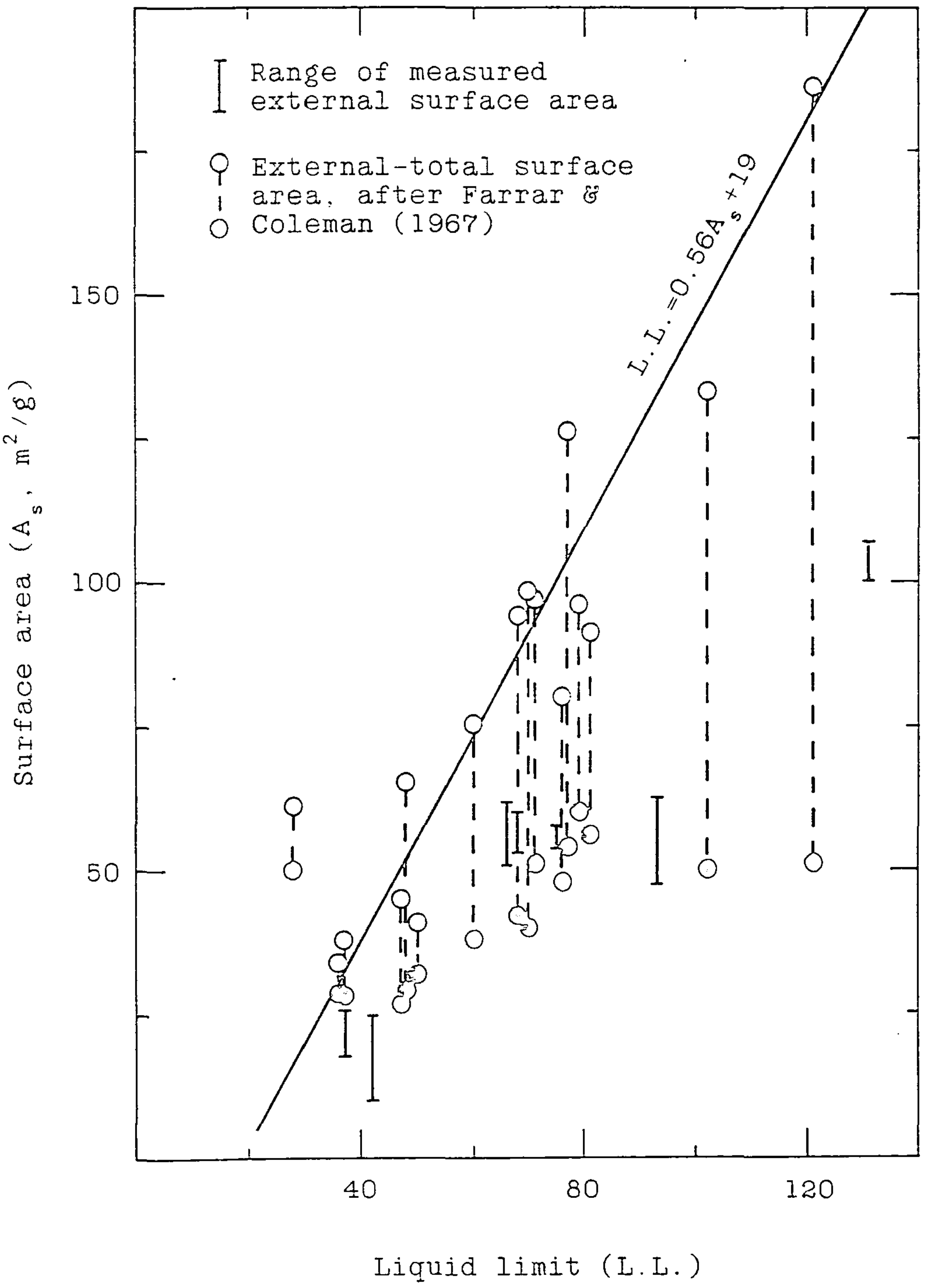
** E : External surface area measured.

T : Total surface area, calculated from $L.L.=0.56A_s+19$.

I : Internal surface area, the difference between T and E.

*** The average external surface areas of Lias Clay and Flockton mudstone only take account of the undisturbed samples.

Fig. 3-1 Relationship between surface area and liquid limit in the samples (The linear relationship is for total surface area after Farrar and Coleman, 1967)



3-1. It is clearly shown that the difference between the external and the total surface area is the greatest in Fuller's Earth and London Clay samples, because all of them contain substantial amounts of smectite and/or expandable mixed-layer clays (Table 2-4); the former has an enormous amount of internal space. The internal surface of the two Oxford Clay samples is less but is still significant. The Oxford Clay samples contain a substantial amount of expandable mixed-layer clay minerals (Table 2-4) which would have internal space inaccessible to nitrogen gas. The Lias Clay and Flockton mudstone have much less internal surface area, which has been revealed by their paucity in expandable clay minerals (Table 2-4).

The difference in external surface area between undisturbed and remoulded samples of the London Clay, Fuller's Earth and Oxford Clay is insignificant. This implies that the slaking process, used to make the remoulded samples, does not expose more external surface. In other words, it does not change the particle sizes. For the Flockton mudstone the remoulded sample has an external surface area about twice that of the undisturbed material. This might indicate quite a good efficiency in the slaking process adopted (Appendix C-1-2), because the Flockton mudstone has a high degree of induration, by which the particles are welded together. X-ray radiography, however, indicates (Fig. 3-5(h)) that the process is by no means perfect. There are numerous sand size particles as shown. The Lias Clay shows a smaller increase in external surface area after slaking.

3-3 Pore Size Distribution

3-3-1 Determination of Pore Size Distribution

The pore size distributions of the samples studied were determined by the method of mercury injection using equipment at Leeds University. This method is based on the principle that, if the angle of contact between a liquid and a solid exceeds 90°, then an excess pressure is required to force the liquid into a capillary within the solid, by a simple adoption of the Young-Laplace equation (Gregg & Sing, 1967):

$$P = -2\sigma\cos\theta/r \tag{3-3}$$

where P = injection pressure,

σ = surface tension of the liquid, 480 dyn./cm for mercury at 25°C,

θ = angle of contact, 141.3° for mercury on silicate minerals,

r = radius of the capillary, assumed cylindrical in form.

The values for mercury given above are suggested by Heling (1970) and are similar to those adopted by Delage and Lefebvre (1984). Using these values Equation 3-3 can be simplified as:

$$r = 75{,}000 / P \tag{3-4}$$

where the pore radius, r, is measured in Å and the injection pressure, P, in kg/cm^2. In this study a mercury porosimeter, which has a maximum pressure of 2,000 kg/cm^2, was used. According to Equation 3-4, at the maximum pressure all pores with radii greater than 37.5 Å would be penetrated by mercury.

In Equation 3-3 it is assumed that the pores are cylindrical in shape. This assumption introduces considerable uncertainty, which rarely corresponds to reality. From the scanning electron microscopic examination in Section 3-5, pores vary in shape and are usually irregular. Another unavoidable problem is the ink-bottle-neck effect (Diamond, 1970). Mercury cannot enter a capillary with a neck smaller than its body, until the pressure reaches high enough for mercury to pass the neck first. It is more appropriate, therefore, to define the pore radius as the 'pore entrance radius' (

Delage & Lefebvre, 1984).

The undisturbed samples before and after the consolidation-swelling tests and also after the free swelling tests and the remoulded samples after the consolidation-swelling tests were analysed using a Carlo Erba Strumentazione (Milan) porosimeter. The freeze-dried samples (Section 3-1) were used in the tests. The procedures for the determination of pore size distribution are given in Appendix B-3.

3-3-2 Experimental Result and Discussion

All the experimental results are displayed as the cumulative curves of pore size distribution in Figs. B-3-1 to -7. The difference between the total pore volume derived from the measured values of density and specific gravity and the pore volume injected by mercury is the volume of pores with radii smaller than 37.5 Å.

All the cumulative curves were analysed using R_{75}, R_{50} and R_{25} (the pore radii at 75, 50 and 25 per cent, respectively), the coefficients of sorting and skewness, same as applied in the analysis of particle size distribution (Pettijohn, 1975). The coefficients of sorting and skewness are based on a logarithmic scale. These parameters of the samples are given in Table 3-2. When plotted against liquid limit, the coefficient of sorting has a high correlation in the remoulded samples, as shown in Fig. 3-2. This means that the higher the plasiticity of a sample, the wider the pore size distribution. No significant correlation was found between other parameters and plasticity in the samples. The coefficients of skewness of the samples are always close to unity (Table 3-2). implying a symmetrical distribution. Because of the polymodal distribution, as discussed later, however, the coefficient of skewness may not give a clear indication of variations among the

Table 3-2 Parameters of pore size distributions in the samples

Sample		R_{75}	R_{50}	R_{25}	Coefficient of sorting *	Coefficient of skewness**
		(in Angstrom)				
London Clay	LC-U ***	89	215	620	1.20	1.00
	LC-UF	107	275	1900	1.27	1.12
	LC-U24	87	340	1500	1.28	0.96
	LC-S24	120	202	1850	1.25	1.28
London Clay	LCW-U	66	230	570	1.23	0.90
	LCW-UF	63	275	2200	1.36	1.01
	LCW-U24	120	475	4200	1.32	1.05
	LCW-S24	77	400	2600	1.35	0.95
Fuller's Earth	FE-U	67	230	4400	1.41	1.19
	FE-U34	80	200	2400	1.33	1.21
	FE-S24	44	185	4500	1.49	1.17
Oxford Clay	OX10-U	93	300	1350	1.26	1.00
	OX10-UF	85	212	5900	1.40	1.34
	OX10-U34	165	870	3850	1.27	0.92
	OX10-S34	125	530	8700	1.37	1.11
Oxford Clay	OX19-U	200	670	3150	1.23	1.01
	OX19-UF	118	560	4050	1.32	0.99
	OX19-U34	235	740	5100	1.25	1.07
	OX19-S34	185	880	4350	1.26	0.95
Lias Clay	LI-U	77	122	305	1.15	1.08
	LI-U24	58	140	620	1.26	1.07
	LI-S24	97	245	660	1.19	0.98
Flockton mudstone	FM-U	77	140	350	1.16	1.04
	FM-U34	85	155	490	1.18	1.06
	FM-S34	160	900	1800	1.22	0.82

* Coefficient of sorting, $S_o = LogR_{25}/LogR_{75}$.

** Coefficient of skewness, $S_k = LogR_{25}\ LogR_{75}/Log^2R_{50}$.

*** Sample designation same as in Table 3-1.

Fig. 3-2 Relationship between coefficient of sorting of pore size distribution and liquid limit in the remoulded samples

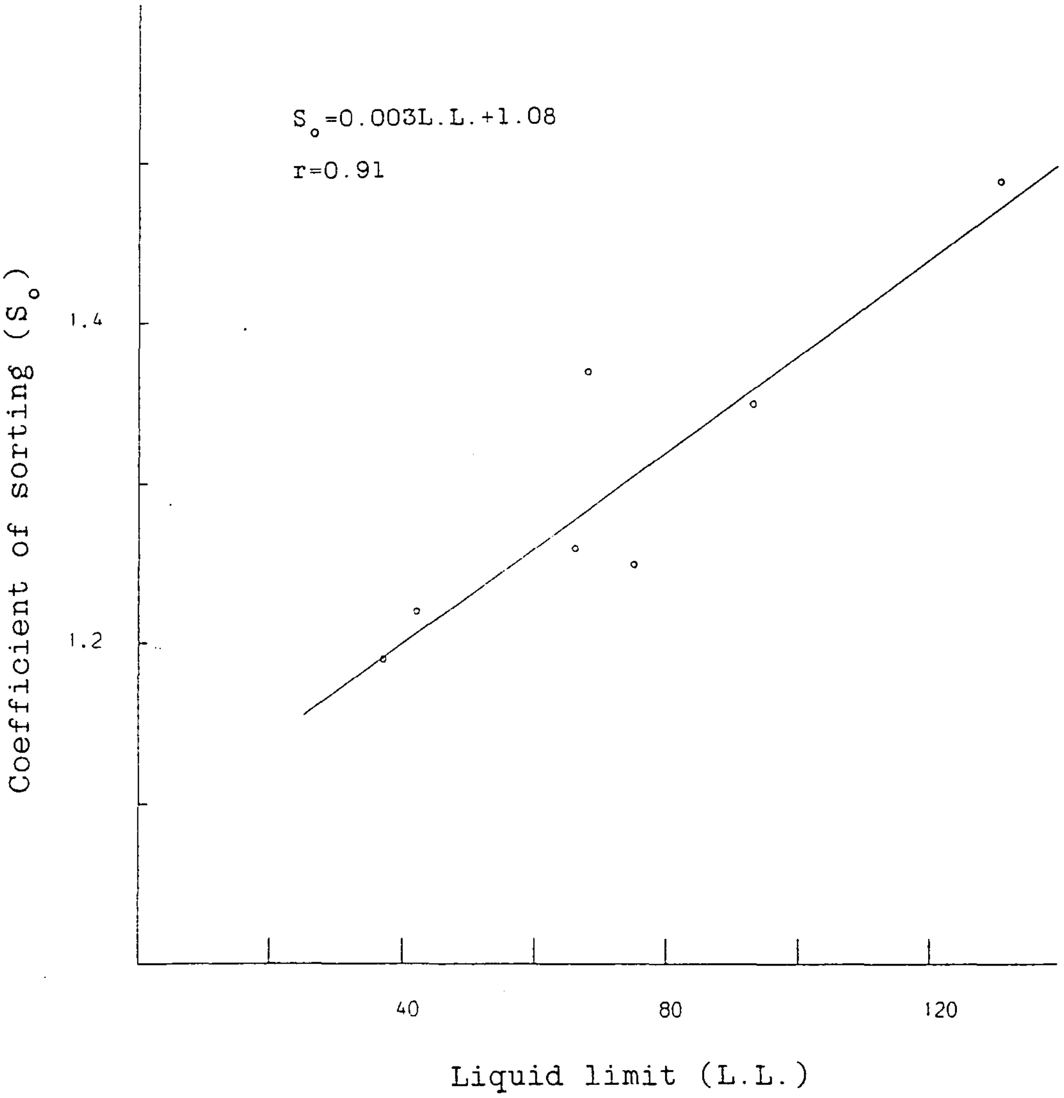


Table 3-3 Classification of pore sizes in mudrocks

Smart (1975)		This project	
Caverns			
	200 mm		
Gross-pores			
	6 mm		
Mini-pores			
	200 µm		
Macro-pores			
	6 µm		
Micro-pores		Macro-pores	> 1,000 Å (0.1 µm)
	0.2 µm		
Ultra-micro-pores		Medium-pores	200 - 1,000 Å
		Micro-pores	< 200 Å

samples.

By differentiating the cumulative pore size distribution curves, the pore volume increase at each pore radius is obtained and displayed in Figs. 3-3-1 to -7. The ordinate used is that customarily used by surface chemists (for example, Gregg & Sing, 1967), namely, change in volume per logarithmic change in radius. Generally speaking, the differentiated pore size distribution curves on a semi-log plot are uni-, bi- or polymodal. The bimodal pattern seems more common in the samples studied, particularly in the remoulded samples (for example, LC-S in Fig. 3-3-1). A bimodal pore size distribution was also found in remoulded silty clays by Garcia-Bengochea *et al.* (1979). This probably conforms with Yong and Warkentin's (1975) concept of intra- and inter-ped voids or macro- and micro-pores. The wide range of pore sizes measured supports Olson's (1962) postulation that the inadequacy of the Kozeny-Carman and Darcy equations for saturated clays can be ascribed to unequal pore sizes.

According to Smart's (1975) classification system (Table 3-3), the pores in the samples are classified into only two classes, micro- and ultra-micro-pores. The features of the pore size distribution curves become more distinct when the pore sizes are arbitrarily divided into macro- (>1,000 Å), medium- (200-1,000 Å) and micro-pore (<200 Å) regions. This classification will be used in the following discussion. Pores with radii greater than 10,000 Å appear to be insignificant in the two London Clays, Fuller's Earth, Lias Clay and Flockton mudstone (Figs. 3-3-1 to -3, -6 & -7), but seems to play a more important part in both the Oxford Clays (Figs. 3-3-4 & -5).

The undisturbed Lias Clay and Flockton mudstone have almost no macro-pores and many less medium-pores (LI-U & FM-U in Figs. 3-3-6 & -7). Their remoulded counterparts have distinct bimodal distribution curves with large pore volume in the macro- and medium-pore regions as in other remoulded samples. Since these two samples have experienced high degrees of diagenesis (Chapter 4), the large reduction of macro- and medium-pores can sensibly be ascribed to the diagenetic effects. The other undisturbed samples have different strength of diagenetic bonds (Chapter 4), but all of them show significant proportions of macro- and medium-pores (-U in Figs. 3-3-1 to -5). The bonds in the undisturbed Fuller's Earth are very strong, but of a cementing nature; its macro-pores are high in proportion (FE-U in Fig. 3-3-3), an indication of its very open fabric.

Four free swelling undisturbed samples (-UF) were available and their differentiated pore size distribution curves in Figs. 3-3-1, -2, -4 and -5 show that the undisturbed samples after free swelling have more macro-pores. This is also indicated by the greater R_{25} values and coefficients of sorting (Table 3-2). The micro-pores also increase in volume after free swelling, but to a less extent.

When compared with their remoulded counterparts, the undisturbed samples after consolidation-swelling tests appear to have a more uniform pore size distribution (-U24 or 34, -S24 or 34 in Figs. 3-3-1 to -7). The remoulded samples usually have more macro-pores than the undisturbed (for example, OX10-S34 & -U34 in Fig. 3-3-4), or more medium-pores in the Lias Clay and Flockton mudstone (LI-S24 & -U24, FM-U34 & -S34 in Figs. 3-3-6 & -7). Also, remoulded samples usually have more or similar macro-pores to the undisturbed samples, but medium-pores are less (for example, LC-S24 & -U24 in Fig. 3-3-1). The highly-indurated Lias Clay and Flockton mudstone (Figs. 3-3-6 & -7) are different. It seems that diagenesis exerts more influence in macro-pores and collapses them to the medium-pore region. The 19
undisturbed Fuller's Earth after the test shows a great reduction in macro- pore volume, but its medium- and micro-pores remain almost the

Figs. 3-3-1(Top) and 3-3-2(Bottom) Differentiated pore size distributions of the London Clay (Sample designation same as in Table 3-1)

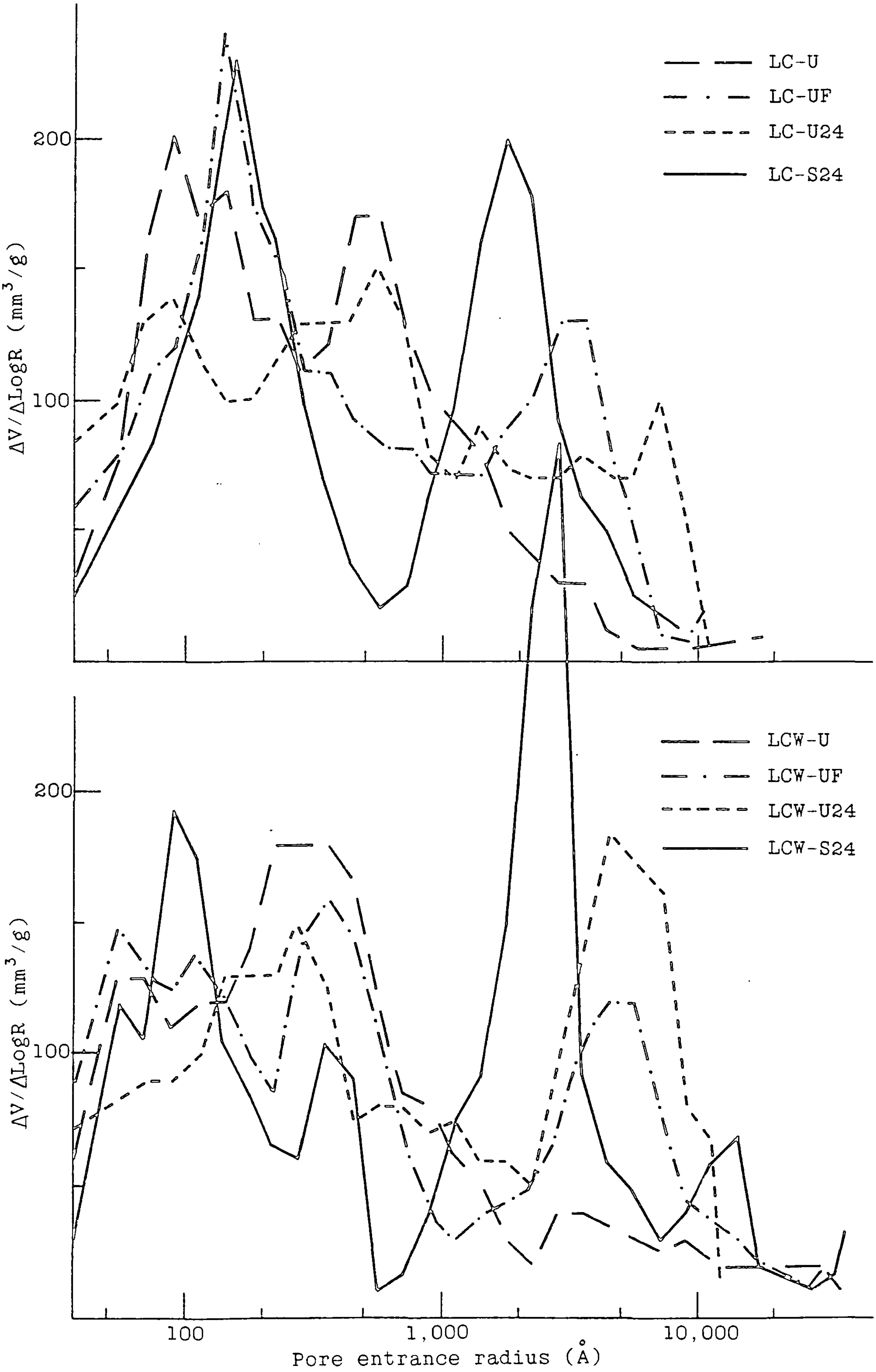
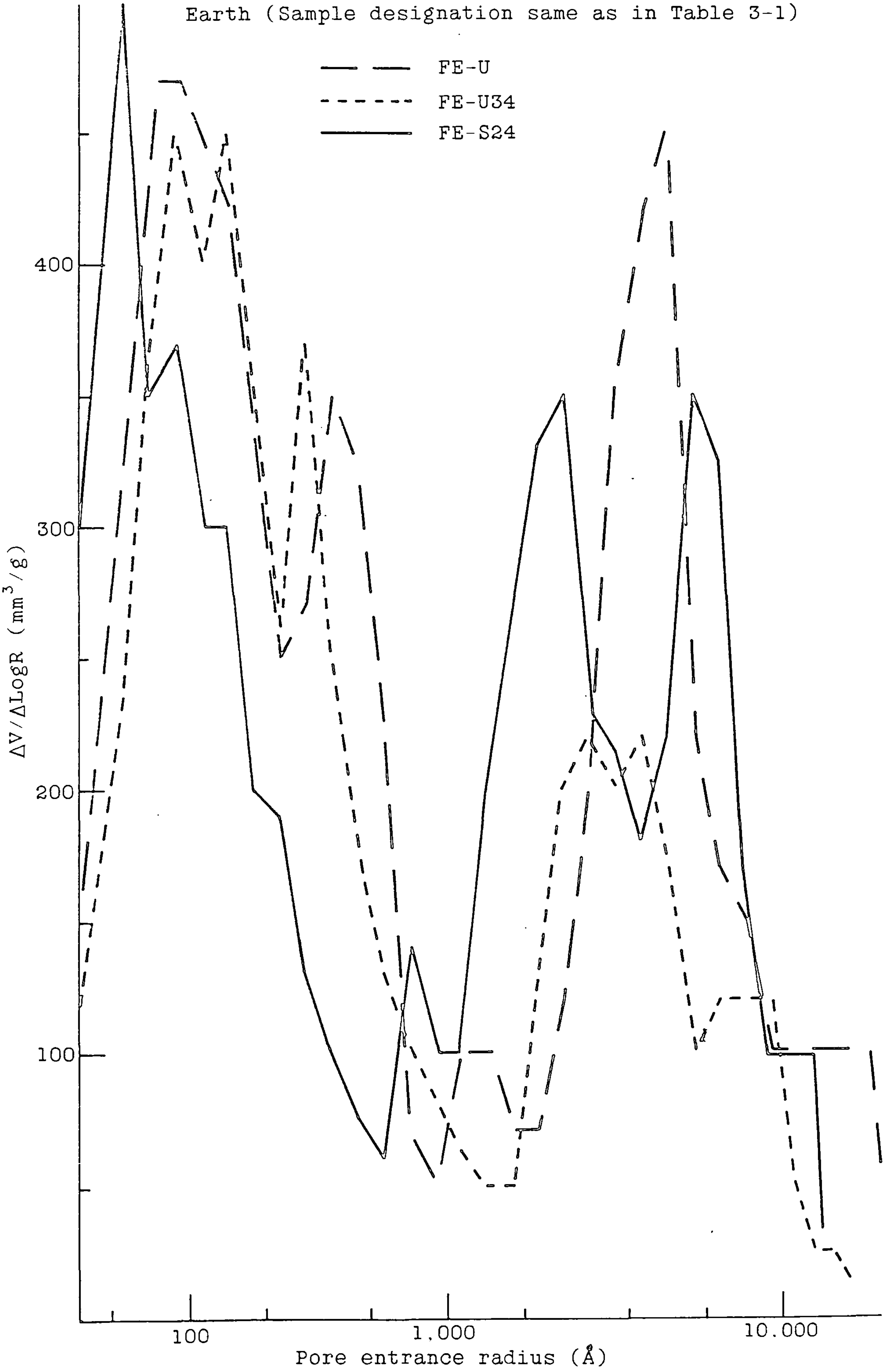
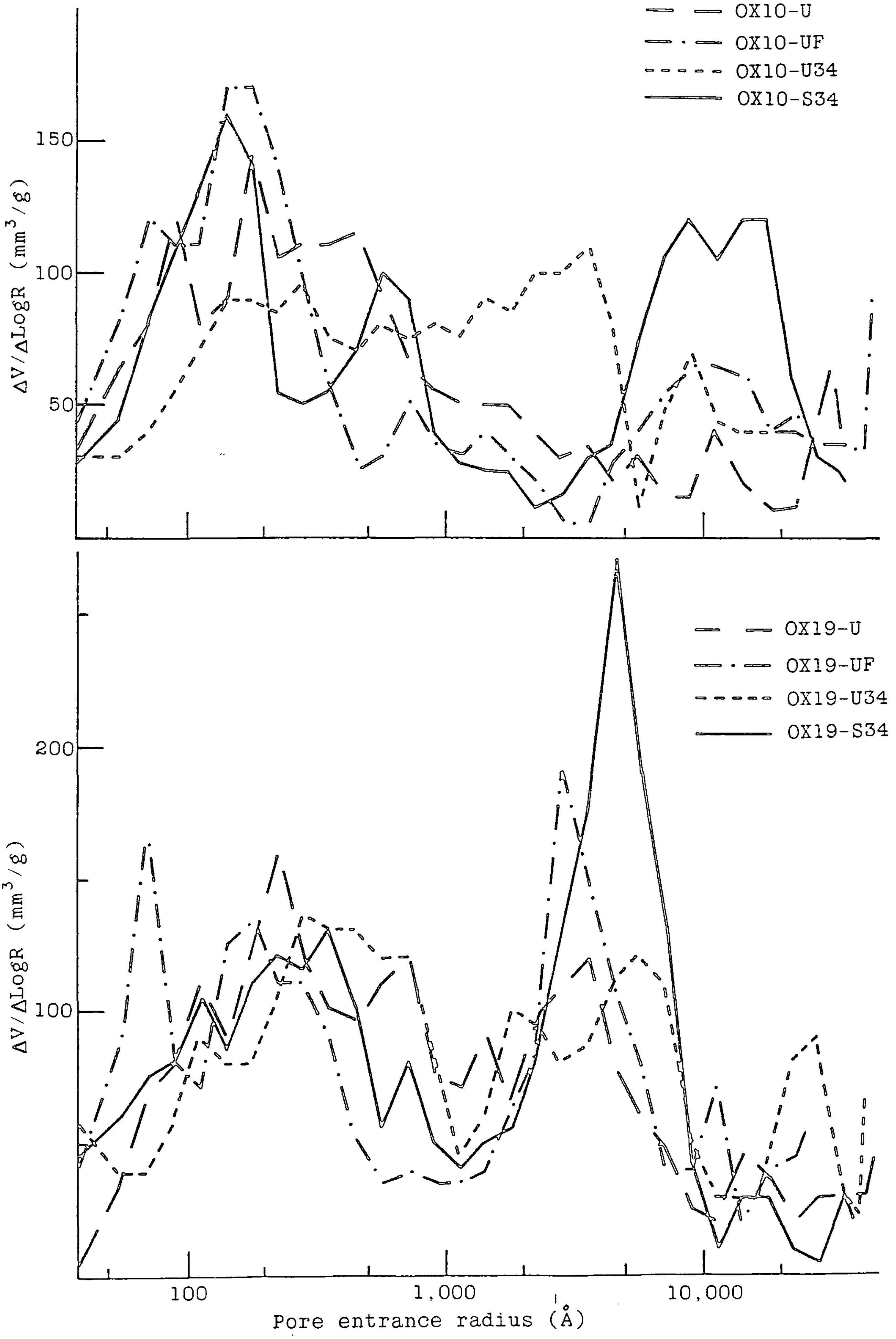


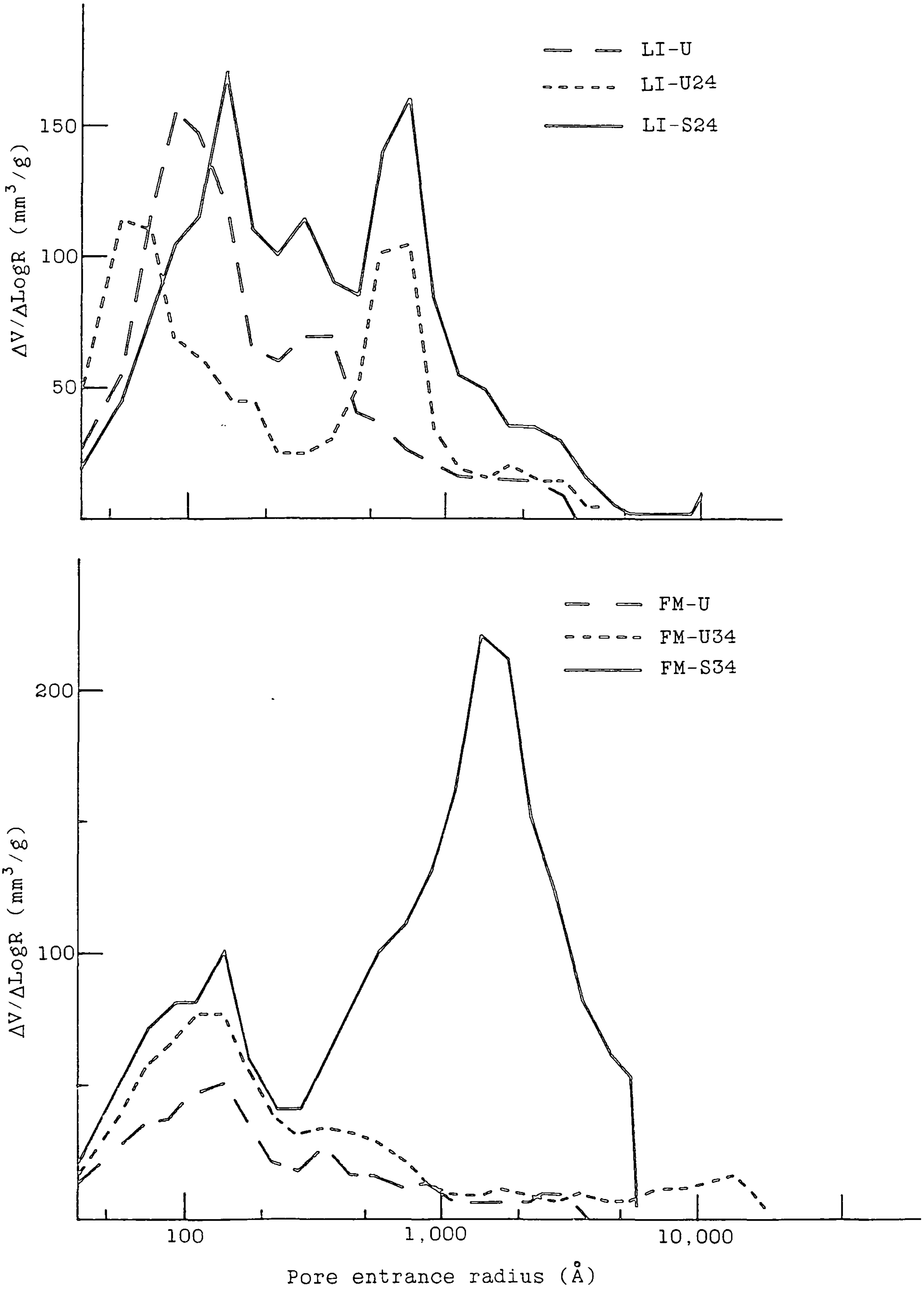
Fig. 3-3-3 Differentiated pore size distributions of the Fuller's Earth (Sample designation same as in Table 3-1)



Figs. 3-3-4(Top) and 3-3-5(Bottom) Differentiated pore size distributions of the Oxford Clay (Sample designation same as in Table 3-1)



Figs. 3-3-6(Top) and 3-3-7(Bottom) Differentiated pore size distributions of the Lias Clay and Flockton mudstone (Sample designation same as in Table 3-1)



same (FE-U & -U34 in Fig. 3-3-3). This conforms with the postulation in the fourth chapter that the compression beyond the pre-consolidation pressure of Fuller's Earth broke down the open fabric in the consolidation-swelling test.

3-4 Orientation of Clay Minerals

3-4-1 Experimental Method

Various methods have been used to investigate the preferred orientation of clay minerals. Morgenstern and Tschalenko (1967) used the optical microscope to measure the ratio of birefriengence in two inter-perpendicular directions. More favourable is X-ray diffraction (XRD), which relies on a comparison of basal and/or prism reflections of clay minerals in two directions (for example, Meade, 1961a; Diamond, 1971). Special X-ray goniometers are also available for this type of work (Attewell & Taylor, 1969; Attewell & Sandford; 1974), but their use and sample preparation are exceedingly time consuming.

In this study, a simple XRD technique was adopted to explore the preferred orientation of the undisturbed and remoulded samples. The procedure is explained in Appendix B-4. Freeze-drying was not used in the preparation of the specimens here, because it is effective only for thin and small specimens, which are difficult to handle in grinding (see Appendix B-4). Instead, air-drying was used to prepare the specimens. The orientations measured on the air-dried samples might have been influenced by the drying process. However, Diamond (1971) and Smith (1978) have shown that the effect of air-drying on the orientation ratio is insignificant for this type of study. The effect may be greater for the Fuller's Earth, which cracked during air-drying due to its high adsorbed moisture content.

For comparison, fully-oriented and random slides were produced by sedimentation and cavity-mounting, respectively; these were also X-rayed to provide a yard-stick for comparison with the unknowns. The techniques are described in Appendix B-4. Sedimentation first excludes large particles, especially quartz, and induces the alignment of platy clay particles. The orientation of clay minerals after sedimentation might not be perfect, but it is generally regarded as being not far from the ideal orientation.

3-4-2 Orientation Parameters

Various parameters have been used to evaluate the preferred orientation of clay minerals using simple X-ray diffraction methods. Among them Odom (1967) defined a 'fabric index' as follows:

$$\text{Fabric index} = \frac{(001)V}{(001)V + (001)H} \qquad \text{------------------------} \quad 3\text{-}5$$

where (001) is the intensity of a basal reflection, V the vertical section or the section parallel to the axis of compression, and H the horizontal section or the section normal to the axis of compression. The fabric index may range numerically from zero to unity. A fabric index of 0.50 would signify a random clay mineral arrangement; whereas a fabric index of zero (or unity) would indicate perfect parallelism on the horizontal (or vertical) section, or, on the section normal (or parallel) to the axis of compression. O'Brien (1964) used an orientation value which was defined and modified by Smith (1978) as:

$$\text{Orientation value} = \frac{\left(\dfrac{(001)K + (001)I + (001)S}{(020)K + (110)I + (020)S}\right)_H}{\left(\dfrac{(001)K + (001)I + (001)S}{(020)K + (110)I + (020)S}\right)_V} \qquad \text{---------} \quad 3\text{-}6$$

in which (001), (020) and (110) are the intensities of basal and prism reflections, and K = kaolinite, I = illite, S = smectite. The orientation values are relative; an orientation value of unity means a random arrangement of clay minerals; whereas greater values than unity indicates greater degrees of preferred orientation on the horizontal section.

In addition to Odom's and O'Brien's parameters of orientation, Diamond (1971) compared the measured ratio of intensity between basal and prism reflections with those ratios under the two extreme conditions, fully-oriented and random. He defined the degree of orientation as:

$$\text{Degree of orientation} = \frac{(\text{O.I. of sample}) - (\text{random O.I.})}{(\text{fully-oriented O.I.}) - (\text{O.I. of sample})} \qquad \text{-- } 3\text{-}7$$

where O.I. is the 'orientation index' which is the peak height ratio of basal to prism reflections of clay minerals.

Odom's fabric index can be applied to each clay mineral in the sample; whereas O'Brien's orientation value and Diamond's degree of orientation would only show the general orientation of clay minerals, because the prism reflections of kaolinite 020, illite 110 and smectite 020 overlap. Chlorite is not used as a criterion because it exists in a significant amount only in two samples (Table 2-4). Random mixed-layer clay minerals do not give distinct basal reflections or rational prism reflections, so no account can be taken of their orientation. Either peak height or area could be measured to represent the intensity of X-ray reflection; however, as shown by Smith (1978), both indicate similar orientation. Only peak height was used in this study. In addition to the orientation of clay minerals, other factors which affect the intensities of X-ray reflections - particle size, chemical composition, degree of crystallinity, and so on - are cancelled out in the orientation parameters discussed, except in Diamond's orientation index.

3-4-3 Experimental Result and Discussion

The experimental results are first presented in Table 3-4 in terms of Odom's (1967) fabric index and O'Brien's (1964) orientation value. They were also analysed with the aid of Diamond's (1971) orientation index and degree of orientation. Those numerical values are presented in Table 3-5.

All the fabric indices of the three reference minerals, kaolinite, illite and smectite, in the undisturbed and remoulded samples fall below 0.5 (Table 3-4), indicating a preferred orientation on the horizontal section or in the direction normal to the axis of loading. The same trend is also shown by the orientation values, greater than unity (Table 3-4). This phenomenon has been found frequently (for example, Olson, 1962). In comparison with the undisturbed samples. either before or after consolidation-swelling tests, the remoulded samples after consolidation and swelling invariably have smaller fabric indices and greater orientation values, showing that preferred orientation is enhanced in the remoulded samples. This could be explained as a result of a greater applied pressure increment during the consolidation process of the remoulded samples which causes the rigid bonds between clay particles to break and the particles to be separated from each other by liquid films of absorbed water (Terzaghi, 1941; Leonards & Ramiah, 1960). This kind of enhanced preferred orientation is most pronounced in the Fuller's earth, shown both by the much smaller fabric index and by the much greater orientation value of the remoulded sample (Table 3-4).

After the consolidation-swelling tests the undisturbed samples appear to have a preferred orientation almost the same as before the tests. This is probably because of the low moisture content in most samples (Table 2-2) and possibly that the diagenetic bonding does not

Table 3-4 Fabric indices and orientation values of the samples

Sample		Fabric index K	Fabric index I	Fabric index S	Orientation value
London Clay (LC)	U	0.37	0.38	0.48	8
	U24	0.31	0.35	0.42	7
	S24	0.22	0.20	0.37	15
London Clay (LCW)	U	0.42	0.41	0.42	6
	U24	0.38	0.38	0.41	9
	S24	0.24	0.29	0.42	13
Fuller's Earth (FE)	U	--	--	0.45	3
	U34	--	--	0.41	5
	S24	--	--	0.29	12
Oxford Clay (OX10)	U	0.13	0.18	--	21
	U34	0.14	0.13	--	19
	S34	0.10	0.11	--	28
Oxford Clay (OX19)	U	0.12	0.22	--	20
	U34	0.14	0.21	--	23
	S34	0.11	0.15	--	27
Lias Clay (LI)	U	--	0.11	--	20
	U24	--	0.13	--	18
	S24	--	0.092	--	30
Flockton mudstone (FM)	U	0.10	0.19	--	21
	U34	0.10	0.19	--	22
	S34	0.076	0.083	--	35

* Sample designation same as in Table 3-1.

** K=kaolinite, I=illite, S=smectite.

Table 3-5 Orientation indices and degrees of orientation of the samples

Sample		Orientation index Horizontal Section	Orientation index Vertical Section	Degree of orientation(%)
London Clay (LC)	U	2.55	0.32	2.0
	U24	3.36	0.48	3.0
	S24	4.12	0.27	4.0
	FO	78.6		
	R	1.04		
London clay (LCW)	U	2.56	0.43	1.1
	U24	4.32	0.48	3.5
	S24	5.07	0.39	4.5
	FO	76.0		
	R	1.71		
Fuller's Earth (FE)	U	2.12	0.64	0.1
	U34	2.50	0.52	0.4
	S24	4.01	0.33	1.8
	FO	112		
	R	2.05		
Oxford Clay (OX10)	U	5.25	0.24	5.6
	U34	6.16	0.32	6.7
	S34	8.13	0.29	9.3
	FO	77.5		
	R	1.00		
Oxford Clay (OX19)	U	8.05	0.40	9.7
	U34	7.81	0.34	9.4
	S34	8.52	0.32	10.4
	FO	72.5		
	R	1.00		
Lias Clay (LI)	U	6.80	0.35	6.8
	U24	6.30	0.36	6.1
	S24	8.71	0.29	9.2
	FO	80.5		
	R	1.44		
Flockton mudstone (FM)	U	8.09	0.39	9.9
	U34	8.30	0.38	10.2
	S34	12.6	0.36	17.0
	FO	65.0		
	R	1.85		

* Sample designation same as in Table 3-1, except FO (Fully-oriented) and R (Random).

permit particles to slide past each other freely (Lambe, 1958).

Mineralogy seems to play an important role in the development of the orientation with application of consolidation pressure. This is illustrated in Table 3-4 by the fabric indices of London Clay and Fuller's Earth, which approach a random condition with a fabric index of 0.5. These overconsolidated clays contain a substantial amount of smectite or have smectite as the major component mineral. Smectite has been found (for example, Meade, 1961b) to have poor orientation, compared with kaolinite and illite. It was pointed out in Section 1-4-4 that larger particles of kaolinite and illite develop a preferred orientation much more easily than fine particles of smectite. Although the Oxford Clay samples contain a lot of mixed-layer clay, their orientation parameters appear to show only slightly better preferred orientation than the Lias Clay and Flockton mudstone.

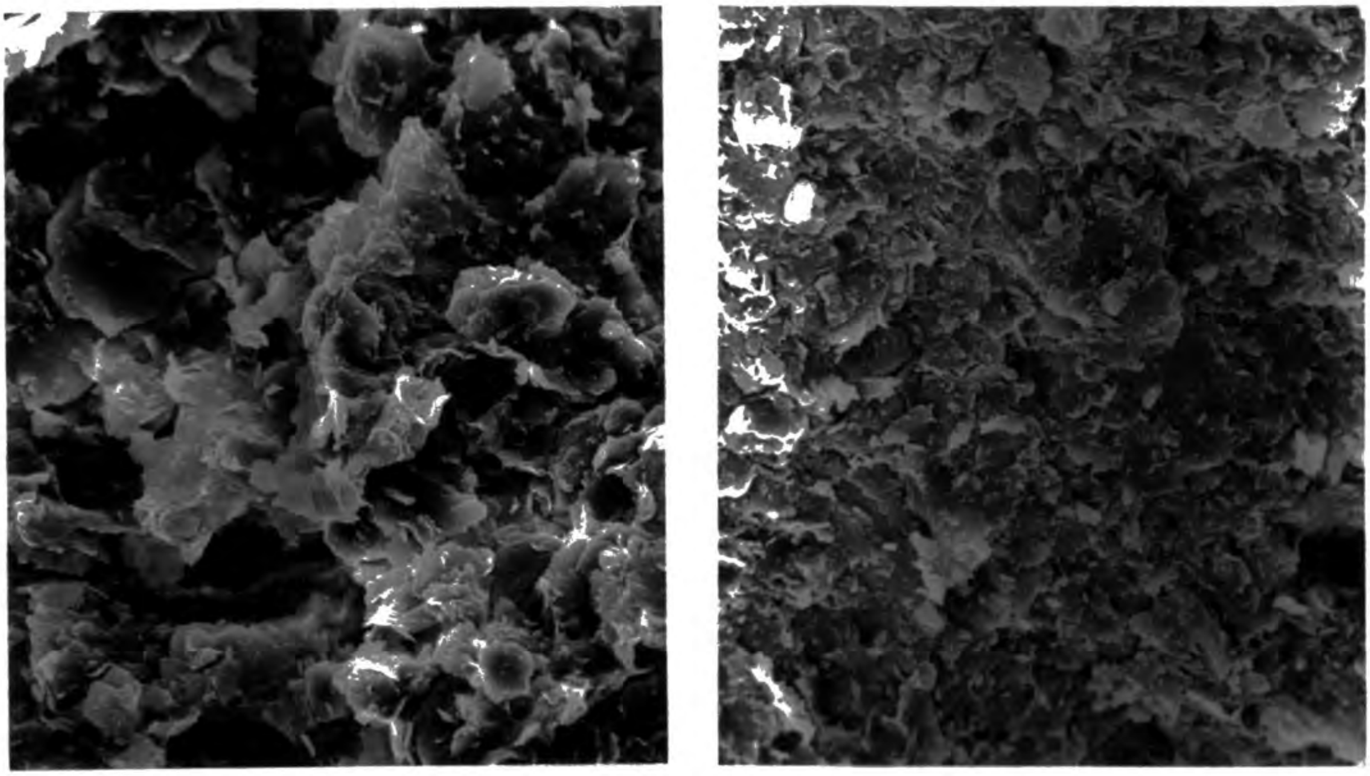
All the horizontal orientation indices of the samples fall between those of the fully-oriented and random conditions, as shown in Table 3-5. This indicates a preferred orientation on the horizontal section, in accord with what has been elucidated according to the data of Table 3-4. In each case, however, the orientation indices of the samples are very much lower than the fully-oriented ones. It is to be expected, therefore, that the degree of orientation of the samples is low. Indeed, no degree of orientation attains 20 per cent (*e.g.* Flockton mudstone 9.9-17 in Table 3-5). The Fuller's Earth, undisturbed and remoulded, has the smallest degree of orientation, 0.1 to 1.8 per cent, so approaching a random condition. The order of the samples in terms of degree of orientation is conformable to that in terms of fabric index and orientation value. The small degree of orientation can be ascribed partly to the inclusion of larger, equidimensional non-clay particles which disrupt the parallel orientation of platy clay minerals (see Section 1-4-4). However, the influence of specific clay mineral type is important, particularly in the Fuller's Earth where smectite makes up a relatively high percentage of the rock.

3-5 Scanning Electron Microscopy (SEM)

The freeze-dried samples (Section 3-1) were examined, using a scanning electron microscope (JSM-T20, JEOL Co.) at Newcastle University. The method of sample preparation is given in Appendix B-5. Photographs at magnifications of 500 to 10,000 were taken, and some of them, the majority at a magnification of 1,000, are shown in Fig. 3-4.

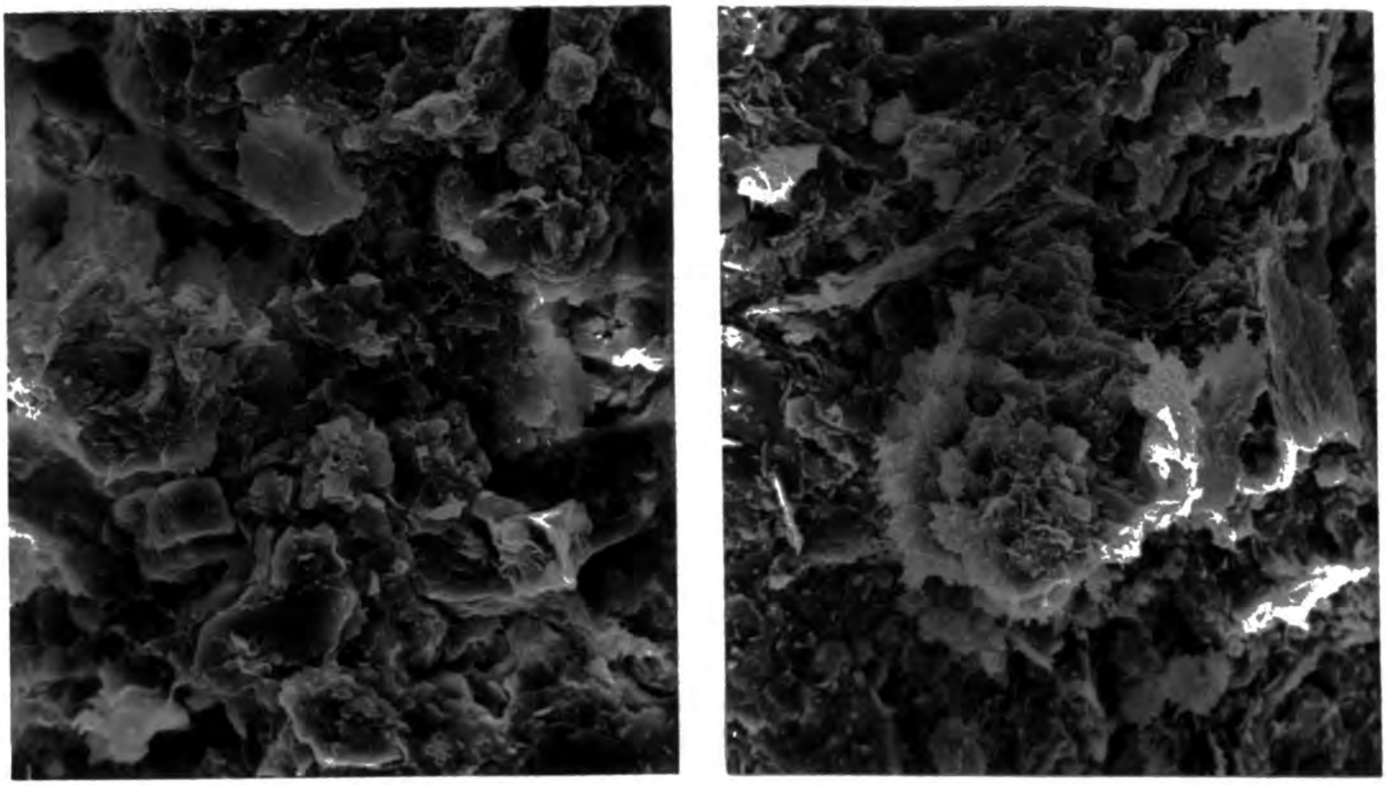
A strong preferred orientation is indicated for the undisturbed Lias Clay and Flockton mudstone specimens in Fig. 3-4(m,o). However, as found in Section 3-4, their orientations by X-ray diffractometry (XRD) are only 6.8 and 9.9 per cent (Table 3-4), *i.e.* apparently too low. It implies, therefore, that this parameter of orientation can only be considered as a relative value using simple X-ray technique. Their remoulded counterparts do not show any preferred orientation in the SEM photographs (Fig. 3-4(n,p)), although orientation parameters given by XRD show an opposite result (Section 3-4-3). In other samples no obvious preferred orientation can be found at any scale, even in the remoulded Oxford Clays (Fig. 3-4(j,l)), which have orientation values by XRD similar to the Lias Clay (Tables 3-4 & 3-5). Figure 3-4(c,d) shows that both of the two sections, parallel and perpendicular to the loading axis, have no preferred orientation. It is pertinent that the range of preferred orientation determined by Smith (1978) was quite wide for a number of mudrocks. This again could suggest that simple X-ray methods on their own merits may be inadequate for preferred orientation studies.

Fig. 3-4 Scanning electron microscopic photographs of the samples (The surface of each photograph is parallel to the loading axis, unless designated. The length of each photograph is 100 μm, unless designated.)



(a) Undisturbed London Clay LC-U

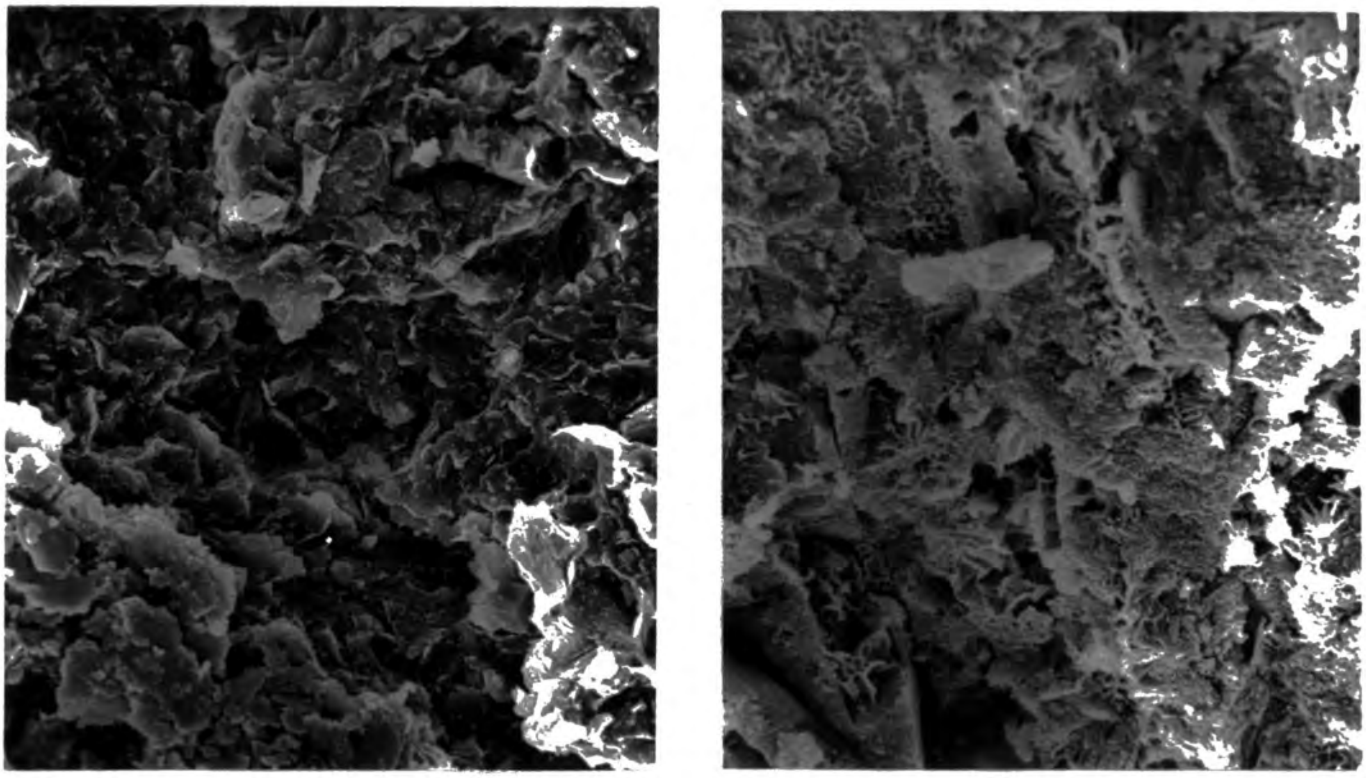
(b) Remoulded London Clay LC-S



(c) Undisturbed London Clay LCW-U

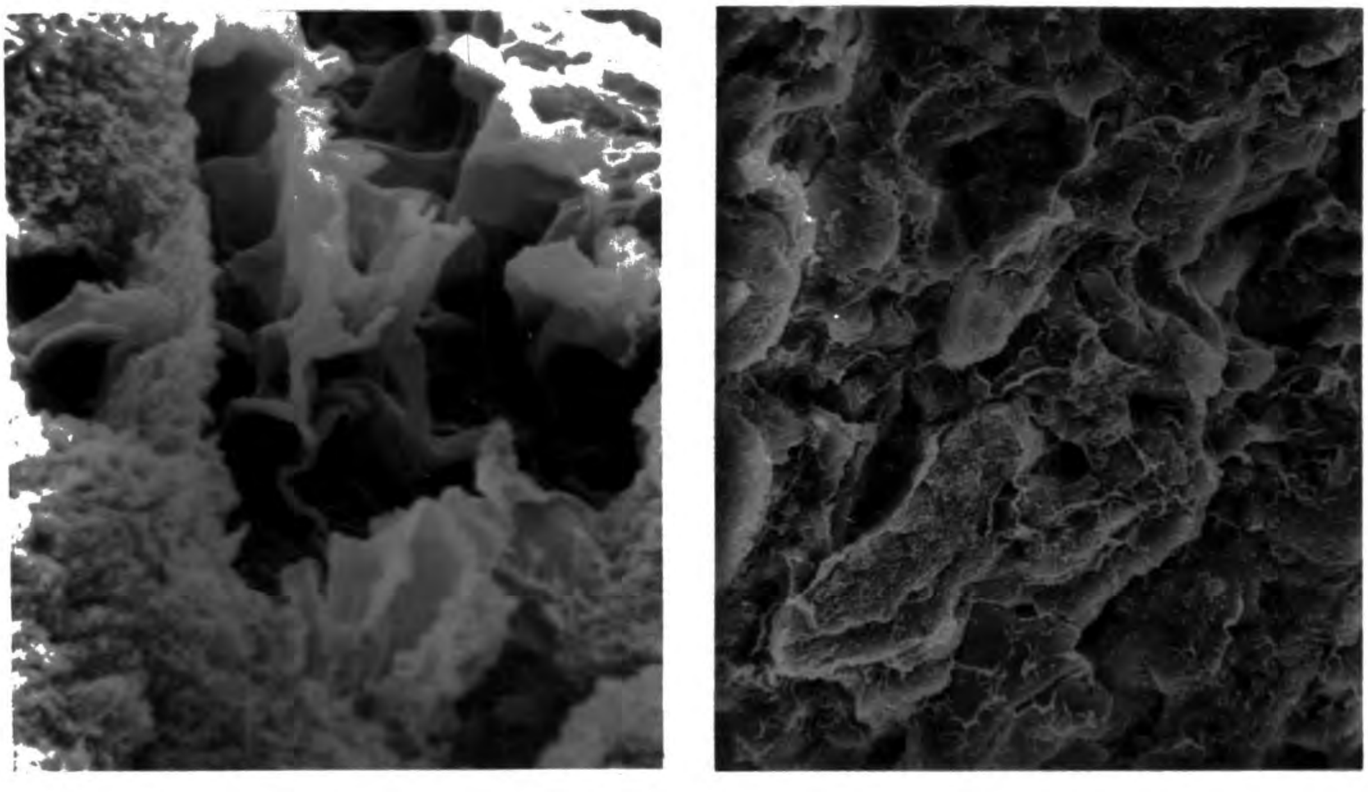
(d) Remoulded London Clay LCW-S (The surface is perpendicular to the loading axis)

Fig. 3.4 (continued)



(e) Remoulded London Clay LCW-S

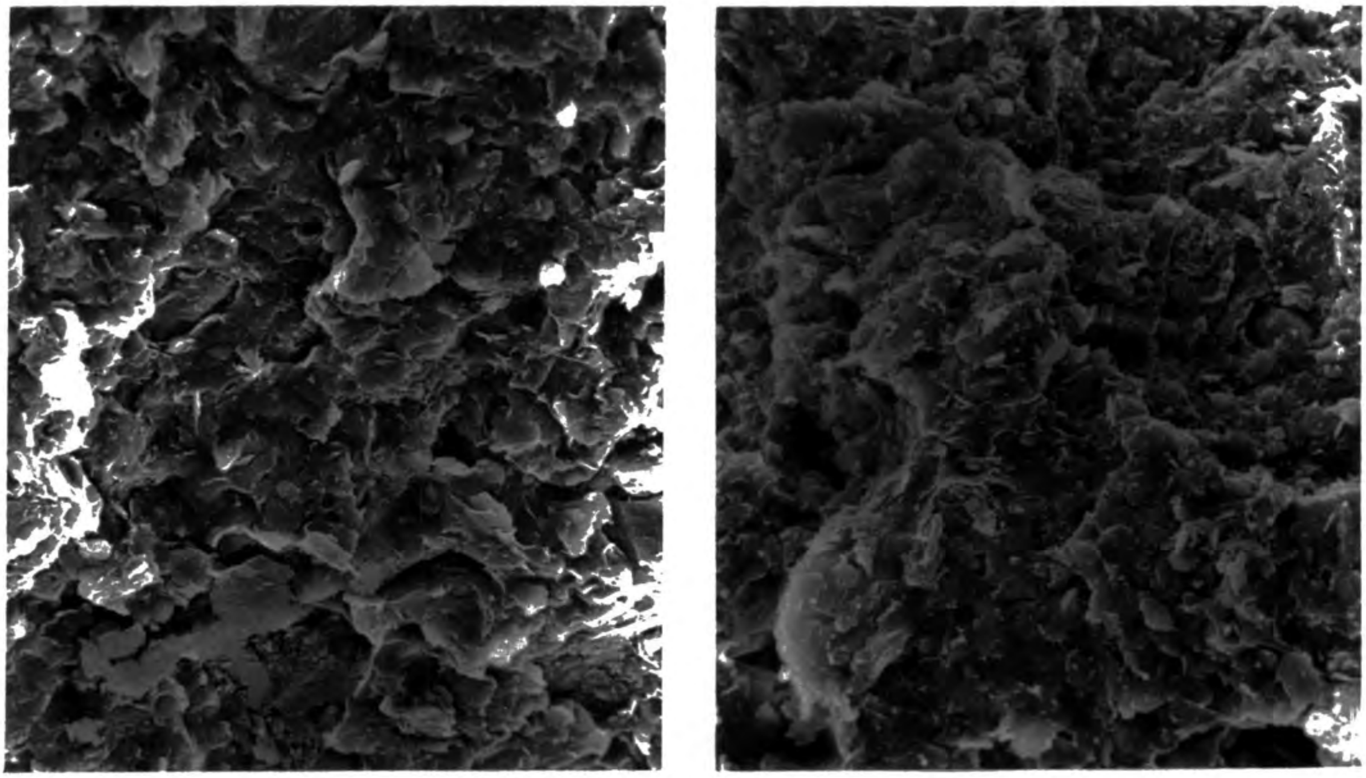
(f) Undisturbed Fuller's Earth



(g) Undisturbed Fuller's Earth
(The length is 20 μm)

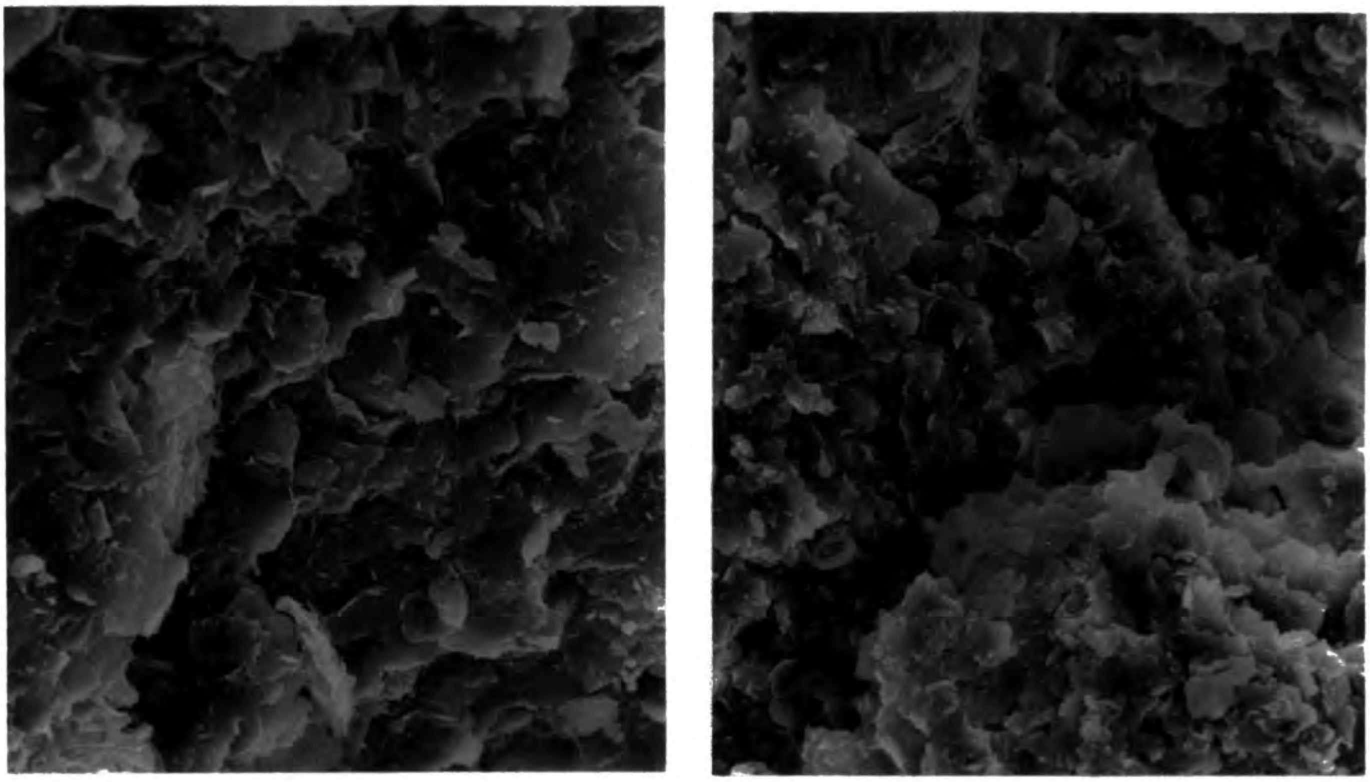
(h) Remoulded Fuller's Earth

Fig. 3-4 (continued)



(i) Undisturbed Oxford Clay OX10-U

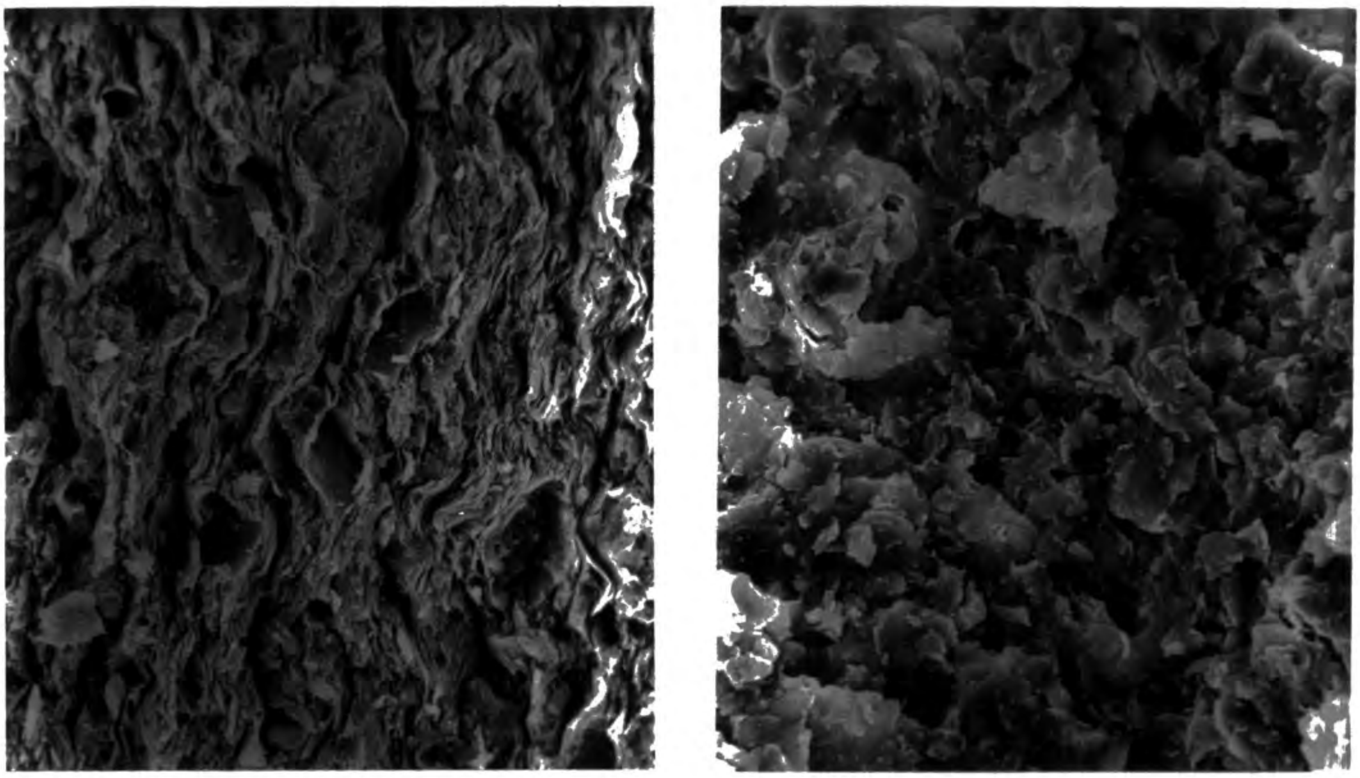
(j) Remoulded Oxford Clay OX10-S



(k) Undisturbed Oxford Clay OX19-U

(l) Remoulded Oxford Clay OX19-S

Fig. 3-4 (continued)



(m) Undisturbed Lias Clay
Preferred orientation
in N-S direction

(n) Remoulded Lias Clay

(o) Undisturbed Flockton mudstone
(The length is 50 μm)
Preferred orientation
in NE-SW direction

(p) Remoulded Flockton mudstone

The SEM examination reveals that pores in the samples vary in shape and are usually irregular. Some cylindrical pores can occasionally be seen, for example, in Fig. 3-4(h). The undisturbed Flockton mudstone shows a very compact, undulating fabric (Fig. 3-4(o)). This probably demonstrates the existence of less macro-pores in this sample (Section 3-3). Other samples show a much looser arrangement of particles and varied pore sizes. The highest SEM magnification used in the present research test is 10,000 times; hence, only macro-pores (>0.1 μm or 1,000 Å, Table 3-3) can be seen. From the photographs in Fig. 3-4, it can be observed that macro-pores exist in all the undisturbed and remoulded samples.

The Fuller's Earth, either undisturbed or remoulded, is clearly shown to have a 'cabbage-leaf' fabric in Fig. 3-4(f,h), which is typical of smectite minerals. This kind of fabric could be inferred in the London Clay (LCW, Fig. 3-4(c)), which also has a substantial amount of smectite (Table 2-4), but it is not as clear as in the Fuller's Earth. In other samples, usually larger and platy particles are found (for example, Fig. 3-4(a)). Figure 3-4(g) shows that the very fine smectite flakes are curved and platy.

3-6 X-ray Radiography

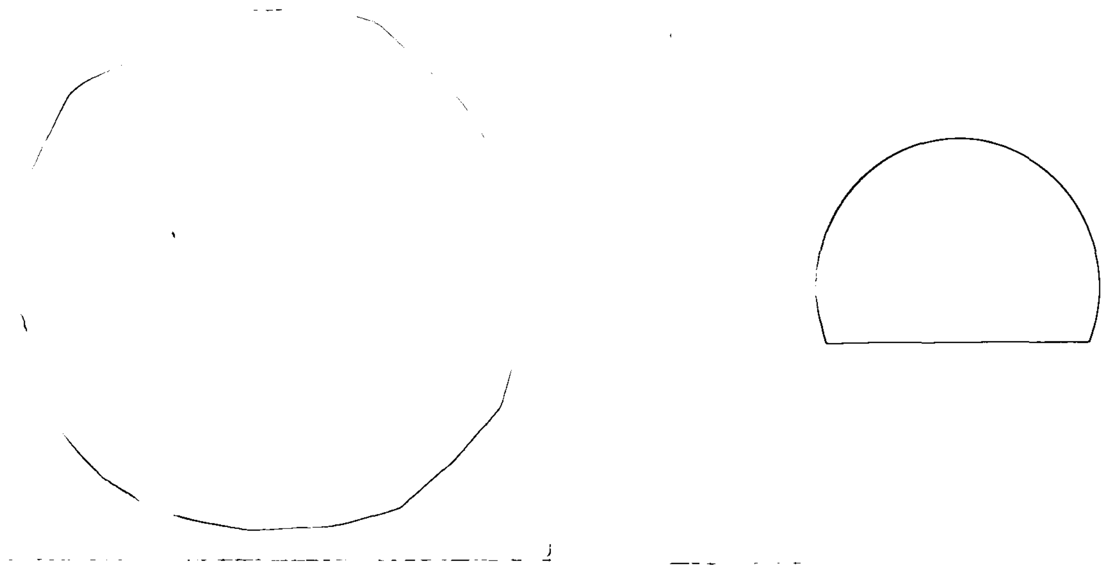
X-ray radiography, which is based on the difference in composition (or density) throughout a material (Bouma, 1969), was applied to the undisturbed samples and also to some remoulded samples immediately after the consolidation-swelling tests. The resultant pictures are shown in Fig. 3-5.

It is clearly shown in Fig. 3-5(a,c,d,e,g) that all the undisturbed samples have irregular fissures, except the Fuller's Earth (Fig. 3-5(c)), which is macroscopically homogeneous. The undisturbed Flockton mudstone has a cloud-like appearance (Fig. 3-5(g

Fig. 3-5 X-ray radiographs of the samples (Scale 1:1)

(a) Undisturbed London Clay
LCW-U

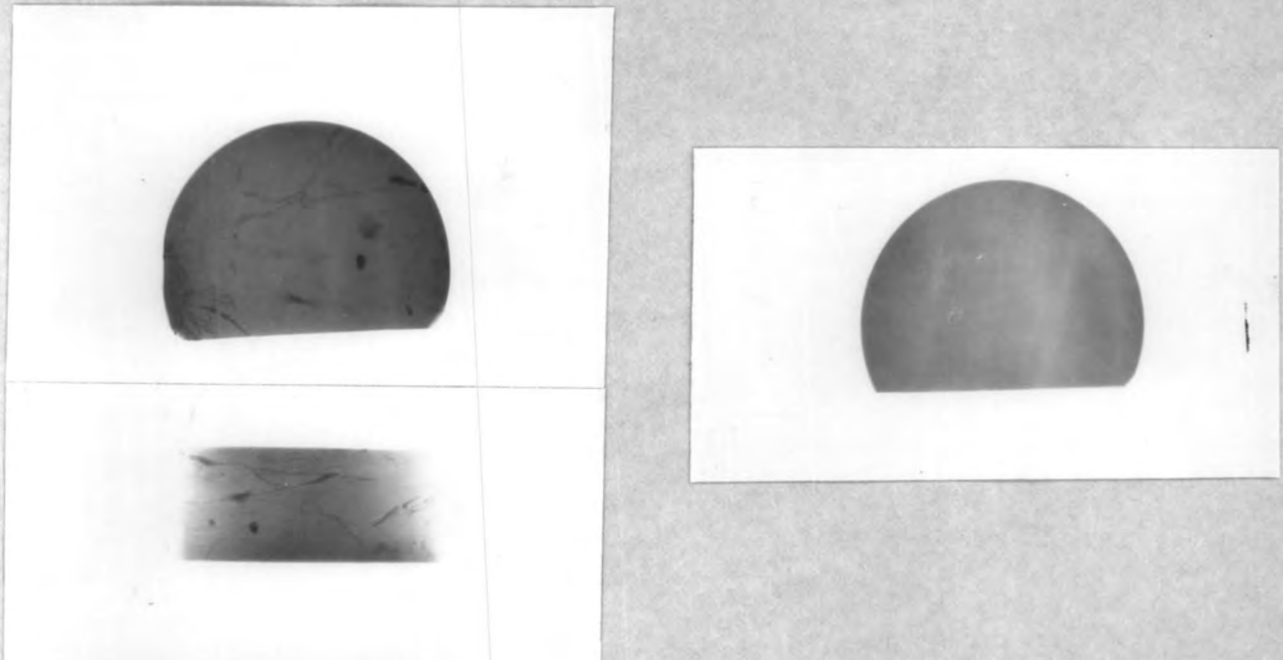
(b) Remoulded London Clay
LCW-S



(c) Undisturbed Fuller's Earth

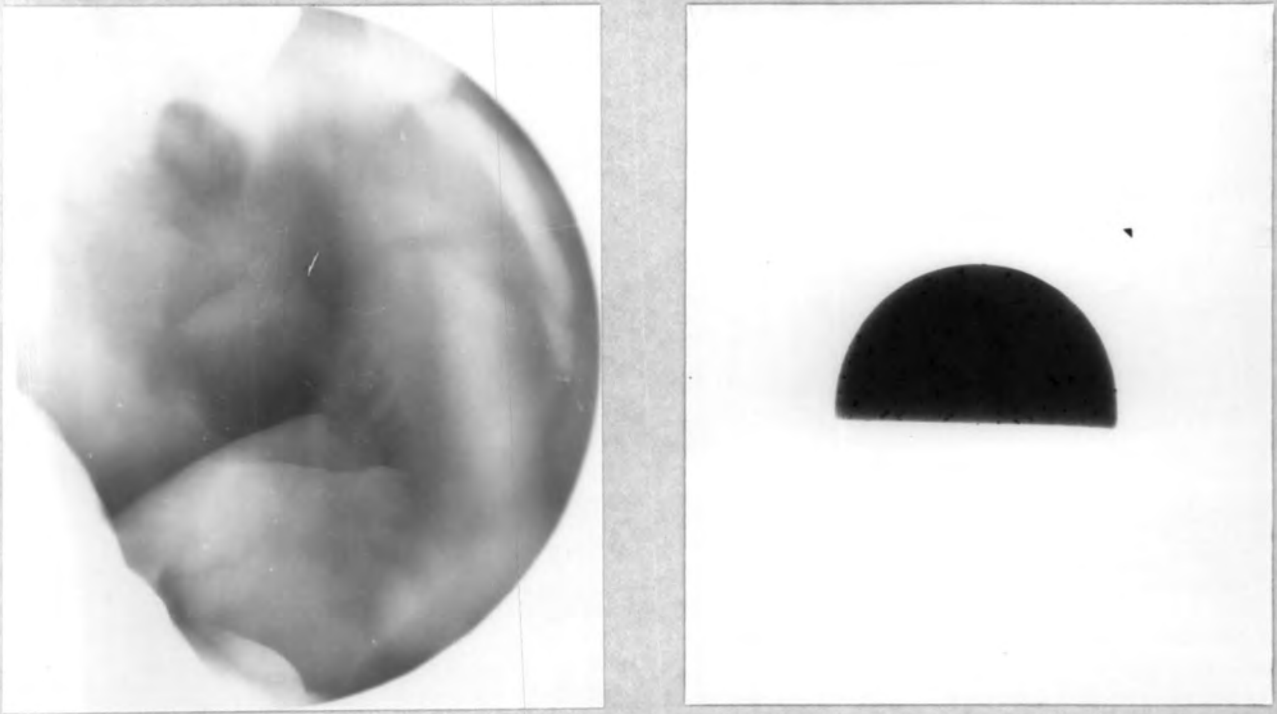
(d) Undisturbed Oxford Clay
OX10-U

Fig. 3-5 (continued)



(e) Undisturbed Lias Clay

(f) Remoulded Lias Clay



(g) Undisturbed Flockton mudstone

(h) Remoulded Flockton mudstone

)). This is probably a reflection of the hackly-type fracturing of the rock.

Figure 3-5(b,f,h) reveals that the remoulded samples have a macroscopically homogeneous texture. One of the purposes in this radiographic examination is check whether there is any shear failure feature after the consolidation-swelling tests (*i.e.* following the hypothesis of Singh *et al.*, 1973). As shown by their homogeneity, however, no macroscopic sign of shear failure can be found in these samples. Quite differently, radiographs reveal that the remoulded Flockton mudstone contains many large particles (Fig. 3-5(h)), which the slaking process (Appendix C-1-2(b)) failed to disintegrate, because of its high degree of induration.

3-7 Summary

1. The samples, undisturbed and remoulded, before and after the consolidation-swelling and free swelling tests, were freeze-dried and used in the analyses of surface area, pore size distribution and scanning electron microscopy.
2. The external surface areas, determined by nitrogen adsorption, of the samples range from 10 to 107 m^2/g and are in an order of:

   Fuller's Earth > London Clays & Oxford Clays > Lias Clay & Flockton mudstone
3. The remoulded London and Oxford Clays and Fuller's Earth have external surface areas similar to their undisturbed counterparts. However, the remoulded Flockton mudstone has an external surface area twice that of the undisturbed, illustrating the effect of slaking on this highly-indurated material.
4. Mercury porosimetry was used to investigate the pore size distribution greater than 37.5 Å in radius. The coefficient of sorting shows a high correlation with liquid limit in the

remoulded samples, indicating a wider pore size distribution in a more plastic clay. Principally the samples have a polymodal pore size distribution, whereas the remoulded samples more commonly have a bimodal pattern.

5. It was found that the undisturbed Flockton mudstone and Lias Clay distinctively have few macro-pores (>1,000 Å), most probably due to diagenetic (induration) effects. The undisturbed samples after free swelling show a greater increase in the macro-pore region and less in the micro-pore (<200 Å) region. The undisturbed Fuller's Earth exhibits a great reduction in macro-pore volume after the consolidation-swelling test.
6. The analysis of clay mineral orientation by X-ray diffractometry revealed that a preferred orientation existed in the samples. The remoulded samples have a higher preferred orientation than the undisturbed counterparts. And the London Clays and Fuller's earth approach a random orientation, probably due to the presence of fine-grained smectite.
7. The scanning electron microscopic photographs show no preferred orientation in most samples, except in undisturbed Lias Clay and Flockton mudstone. Pores in the samples vary in shape and are usually irregular.
8. The smectite flakes are fine and curved in the Fuller's Earth, giving the fabric a 'cabbage-leaf' effect. In other samples particles are larger and platy.
9. The X-ray radiographic pictures show that the undisturbed samples, except Fuller's Earth, contain irregular fissures, whereas the remoulded samples are macroscopically homogeneous.
10. Large particles existed in the remoulded Flockton mudstone, indicating the failure of slaking to completely disintegrate this highly-indurated material.

CHAPTER 4 MECHANICAL SWELLING

Having discussed the composition and basic properties of the samples, the results of the swelling behaviour of samples (undisturbed and remoulded) will be considered in this chapter, based on the mechanical model which has been mentioned in Section 1-6.

The one-dimensional consolidation-swelling tests were conducted in the modified oedometers. The consolidation data obtained have been analysed first, including pre-consolidation pressure, relative positions of the compression curves of the undisturbed and remoulded samples, coefficient of consolidation and compression index. A systematic trend of the coefficient of swelling with overconsolidation ratio has been found. Swelling rate curves have been compared with Terzaghi's theoretical curve. Also identified is a good correlation between coefficient of swelling and mudrock plasticity. Secondary swelling has also been studied in detail in one remoulded sample and found to play an important role in the whole swelling process at high overconsolidation ratios. The swelling indices of the undisturbed and remoulded samples and also the differences between them have been examined in terms of diagenetic bonding, coefficient of earth pressure at rest and fabric. The ratio of swelling to compression index has been used as a parameter of recovered strain ratio, in order to deduce the strength and nature of diagenetic bonds in the samples investigated and their influence on swelling. The significance of the prolonged primary swelling and prominent secondary swelling have been discussed with reference to the well-known progressive softening characteristics of mudrocks during unloading. Also included in the discussions are the role and nature of diagenetic bonds in swelling.

4-1 Theory of Consolidation or Swelling

The process of one-dimensional consolidation (or swelling) is governed by the equation, derived by K. Terzaghi in 1923 (Terzaghi & Peck, 1948):

$$c_v \, (d^2u/dz^2) = du/dt \qquad \text{------------------------------------} \qquad 4\text{-}1$$

where u = excess hydrostatic pressure,

z = coordinate distance parallel to the loading direction,

t = time,

c_v = coefficient of consolidation.

The coefficient of consolidation, c_v, can be expressed as (Terzaghi & Peck, 1948):

$$c_v = k\,(1+e)\,/\,(a_v\,\gamma_w) \quad \text{or} = k\,/\,(m_v\,\gamma_w) \qquad \text{---------------} \qquad 4\text{-}2$$

in which k = coefficient of permeability,

e = void ratio,

$a_v = de/dP$ = coefficient of compressibility,

γ_w = unit weight of water,

$m_v = a_v/(1+e)$ = coefficient of volume compressibility.

In formulating these equations, Terzaghi adopted the following assumptions (Taylor, 1948):

(a) homogeneous soil,

(b) complete saturation,

(c) negligible compressibility of soil grains and water,

(d) action of infinitesimal masses no different from that of larger, representative masses,

(e) one-dimensional flow,

(f) one-dimensional compression,

(g) the validity of Darcy's Law,

(h) constant values for certain soil properties which actually vary somewhat with pressure,

(i) the greatly idealized linear relationship between the void ratio and the logarithm to base ten of pressure during a pressure increment.

Except for (d), (h) and (i), these assumptions are usually considered not far different from actual conditions. Refined approaches have been made to accommodate the large strain during consolidation (for instance, Koppula & Morgenstern, 1982). In swelling, smaller strains are involved than in consolidation. Assumption (h) introduces some errors, but is considered to be of minor importance in most conditions (Taylor, 1948). Assumption (i) would lead to the limited validity of the theory, but a more correct relationship would make the analysis unduly complex, according to Taylor (1948).

4-2 Experimental Methods

The one-dimensional consolidation-swelling tests were conducted using the modified oedometers. The modified oedometers (Appendix C-1-1) were designed to accommodate a high pressure of 24,280 or 34,340 kN/m^2. All the parts in contact with water of the oedometers were made up of stainless steel, so contamination was kept to a minimum. The compression of the oedometer cells and filters became significant when the pressure was greater than 10,000 kN/m^2 and a correction had to be made for the amount of compression or rebound. The details of the experimental procedures are shown in Appendix C-1-2. The samples used include undisturbed and those remoulded by slaking.

In most oedometer tests, a pressure increment or decrement ratio of unity was used. For some undisturbed samples, including the Flockton mudstone and Lias Clay, a pressure decrement or increment ratio of 2 or more was frequently used, because the measurement was not sensitive enough to determine the end of primary consolidation or swelling when the consolidation or swelling amount was small. Each pressure increment or decrement was applied for 24 hours or until the end of primary swelling or consolidation, the determination of which is described later in this chapter. In the test on the remoulded Oxford Clay (OX10-S) each pressure increment or decrement was allowed to proceed for at least a logarithmic cycle of time after the end of primary consolidation or swelling, in order to investigate the development of secondary consolidation and swelling.

4-3 Consolidation Test Results

4-3-1 Void Ratio - Pressure Relationship

In all the consolidation-swelling tests the void ratios were calculated in accordance with the standard methods applied in soil mechanics, and based on the final thickness and moisture content and the measured specific gravity (Table 2-2). All the results are given in Table C-1, based on a condition of primary consolidation, and also presented graphically on the plots of void ratio versus logarithm of effective pressure in Figs. 4-1-1 to -7.

Casagrande's construction method has been used to estimate the pre-consolidation pressures, P_c, of the undisturbed samples. This is the previous overburden pressure to which a sample has been subjected during geological time. In addition Schmertmann (1953) suggested another method, which uses the swelling curve to trace back to its virgin compression state. As found by Khera and Schulz (1984) and Bjerrum (1967), the estimation of P_c by laboratory testing is very unreliable because of the effect of diagenetic bonds and varied geological history. As a guide, however, both methods were applied in this study. Since the maximum pressure applied in this project does not compress the Flockton mudstone back to the virgin compression line, neither method can be used with this particular rock. For the Lias Clay and one of the Oxford Clay specimens, the

Fig. 4-1-1 Compression and swelling curves of the London Clay (LC)

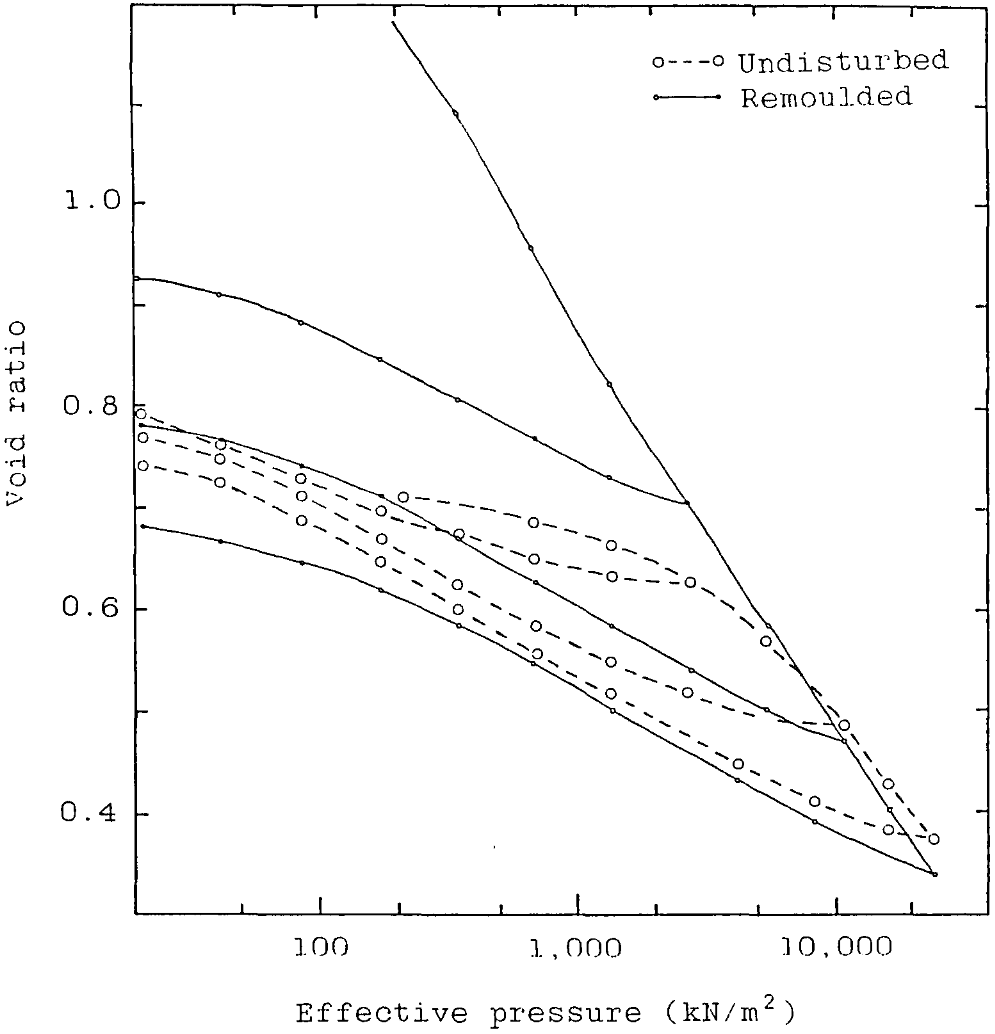


Fig. 4-1-2 Compression and swelling curves of the London Clay (LCW)

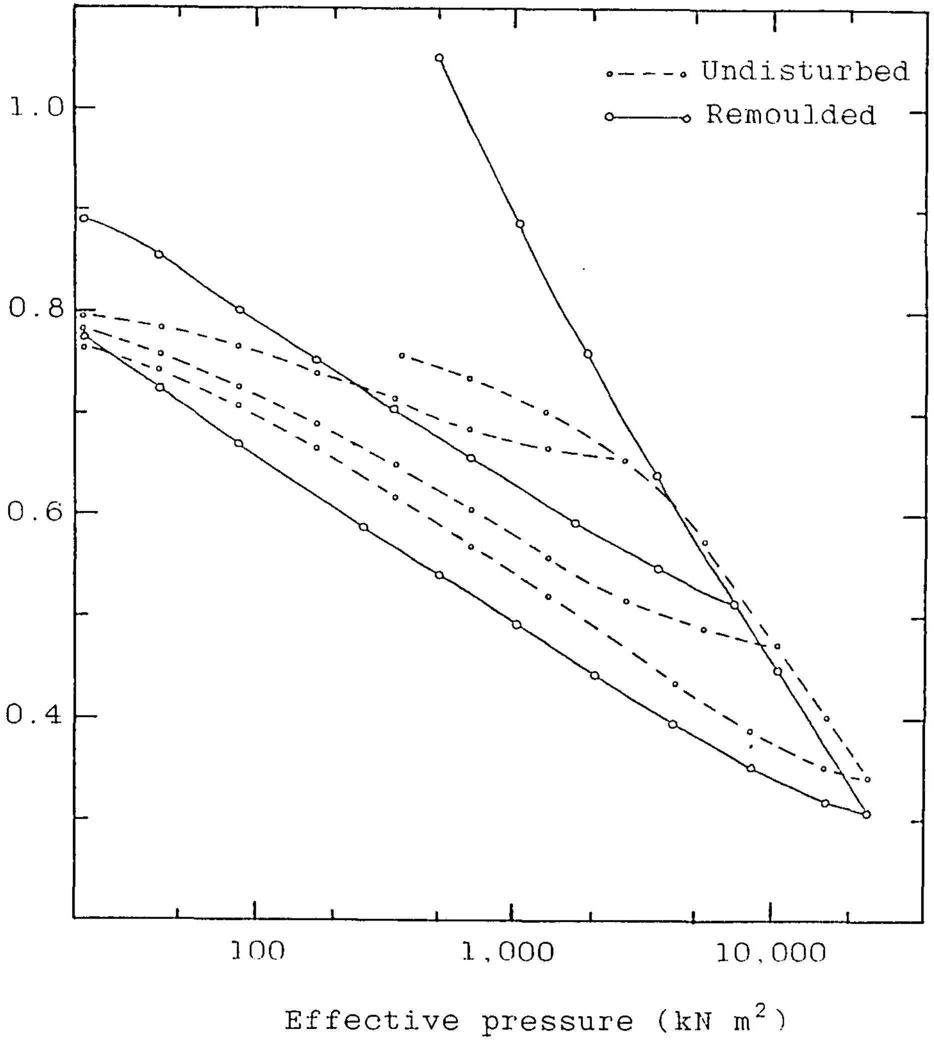


Fig. 4-1-3 Compression and swelling curves of the Fuller's Earth

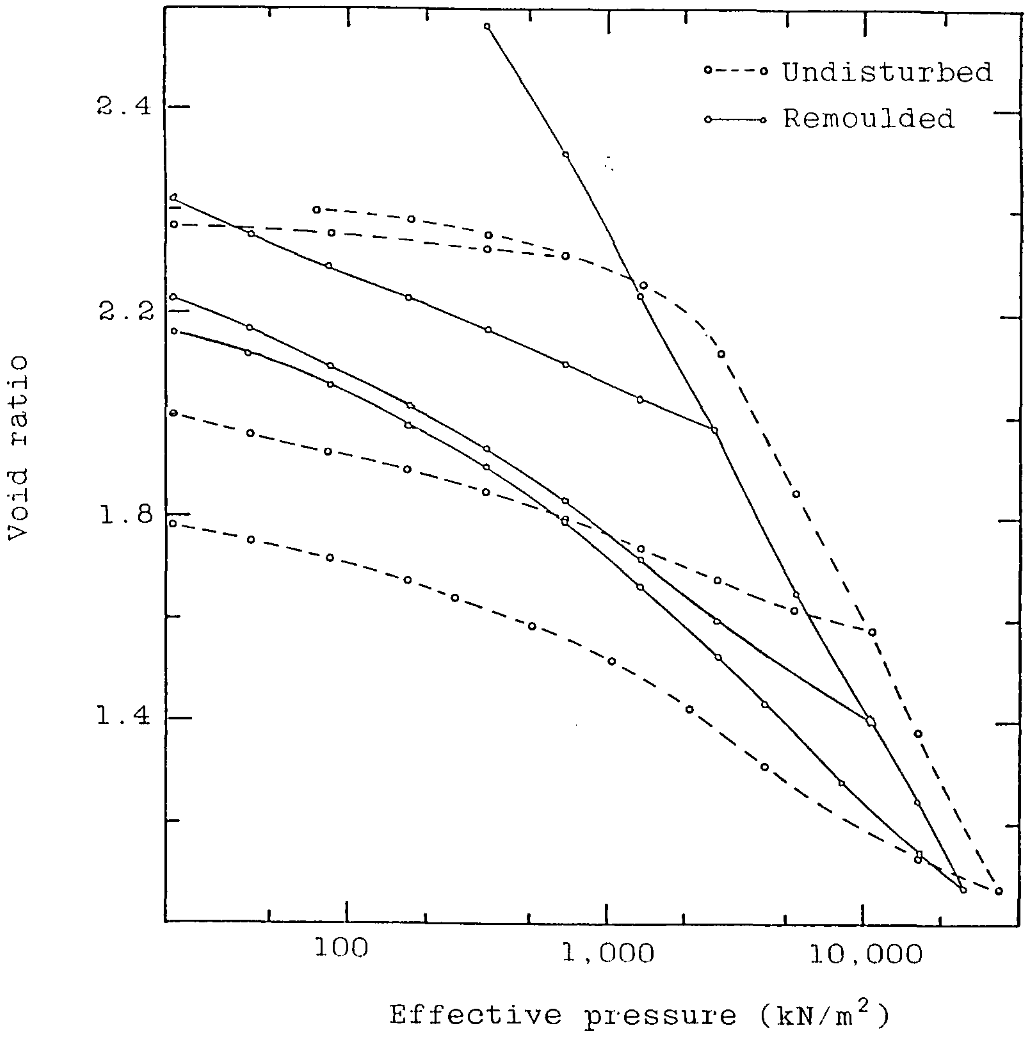


Fig. 4-1-4 Compression and swelling curves of the Oxford Clay (OX10)

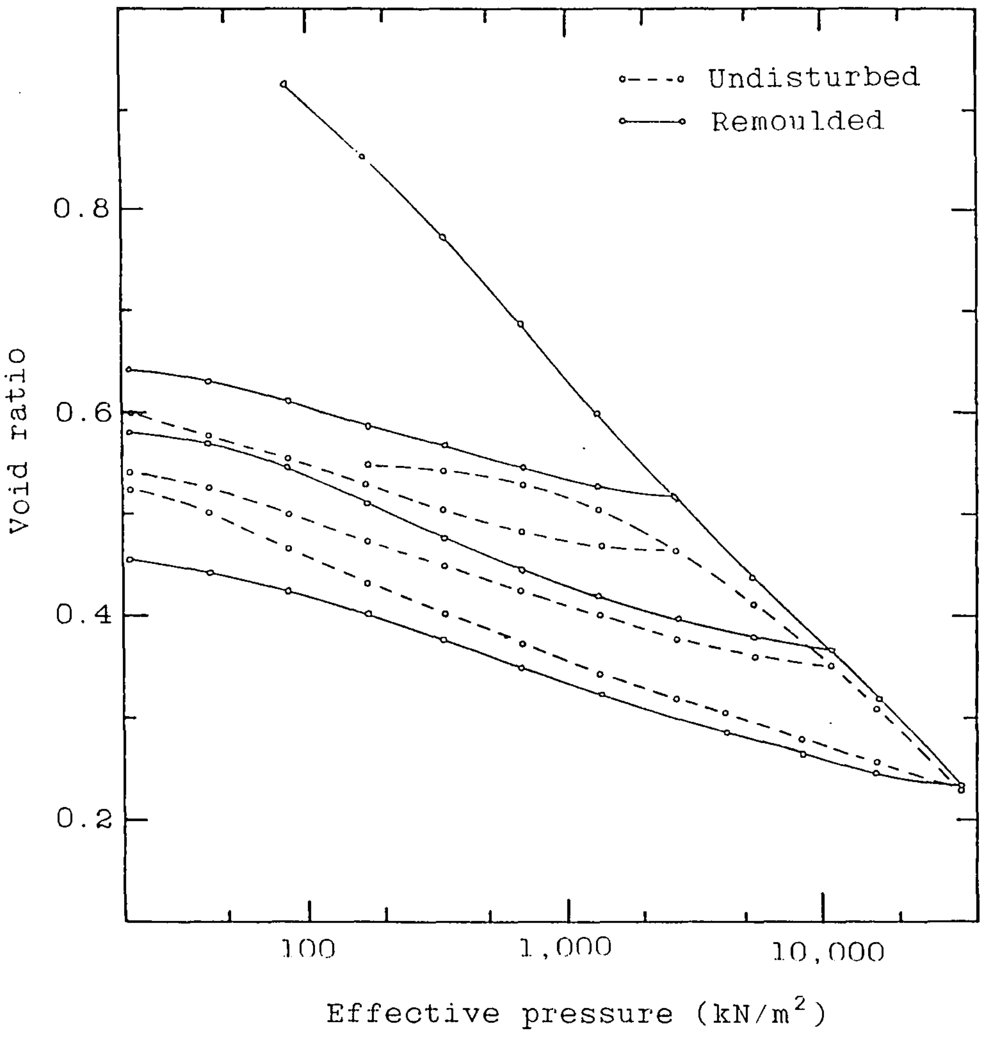


Fig. 4-1-5 Compression and swelling curves of the Oxford Clay (OX19)

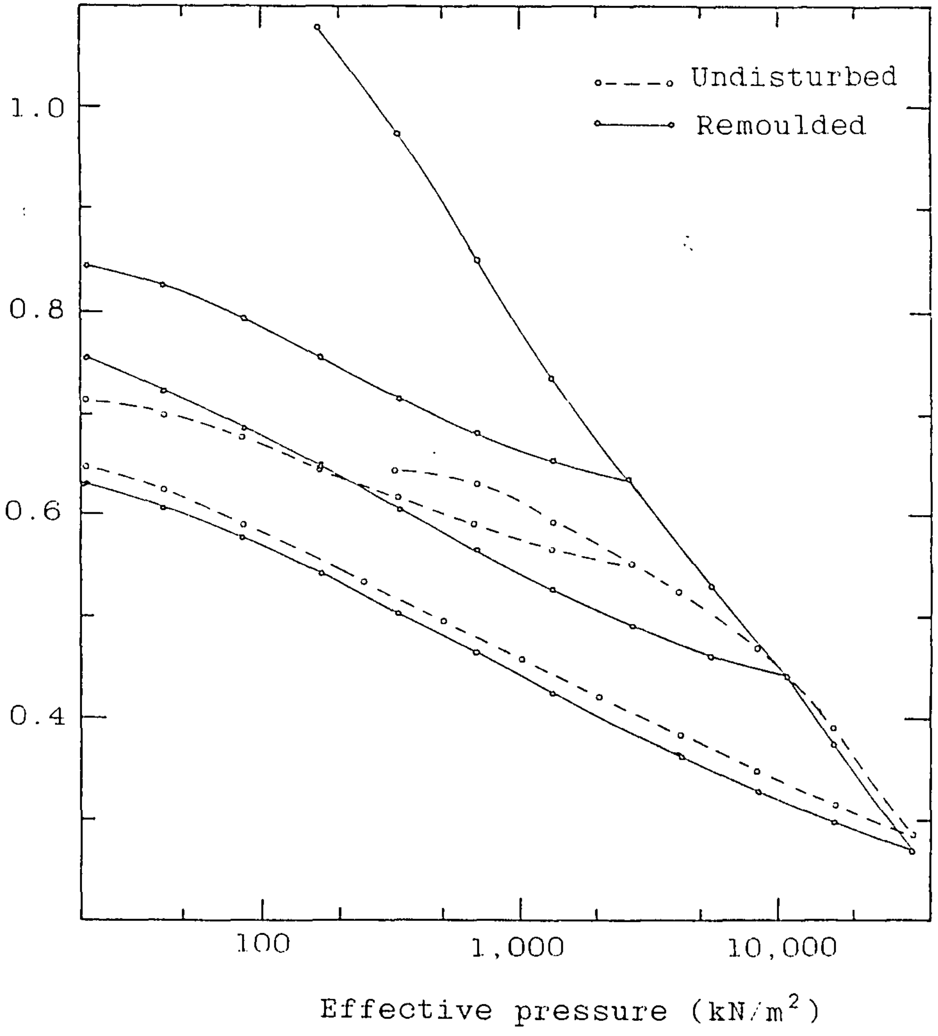


Fig. 4-1-6 Compression and swelling curves of the Lias Clay

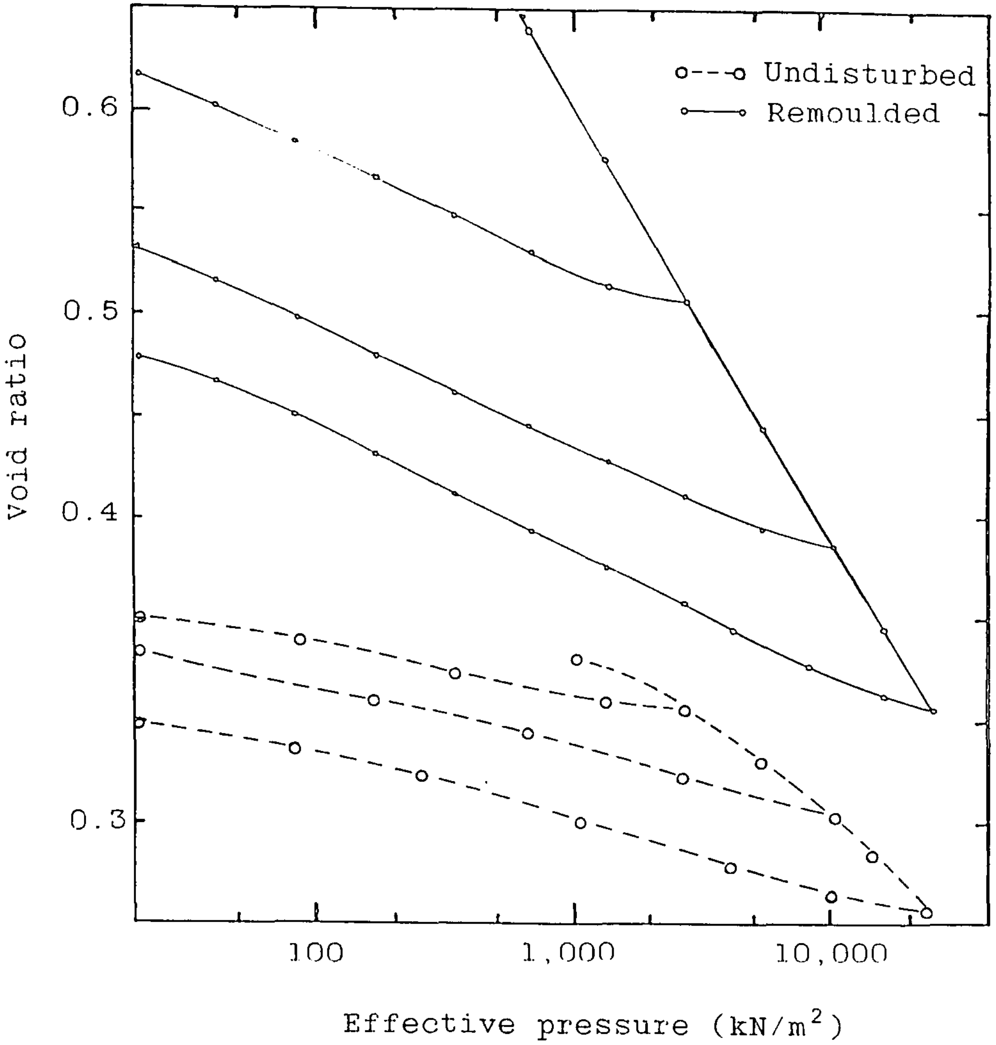
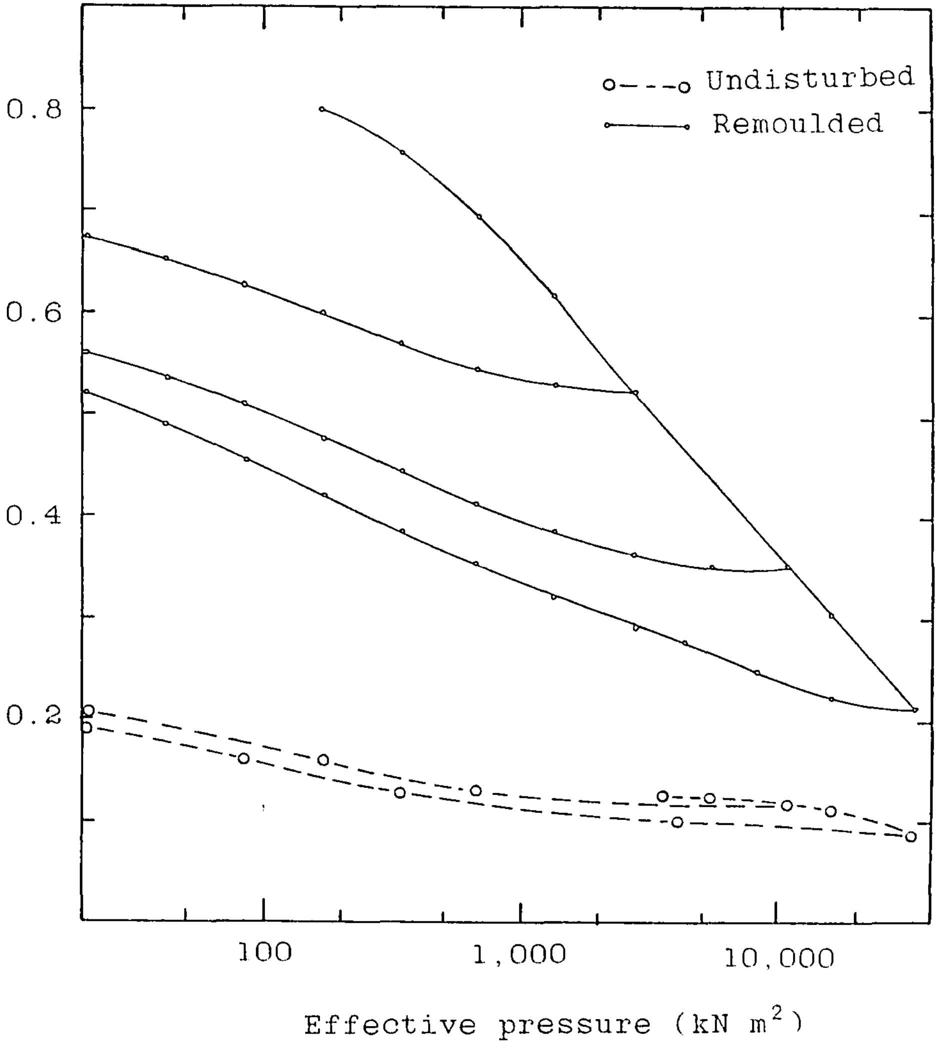


Fig. 4-1-7 Compression and swelling curves of the Flockton mudstone



points of greatest curvature, which are needed in Casagrande's construction procedure, are poorly defined, and so this method fails to determine their P_c values with any degree of accuracy.

The estimated pre-consolidation pressures are given in Table 4-1, together with those published in the literature. All these *in situ* P_c values fall within a wide range, 1,800 to about 50,000 kN/m^2. Schmertmann's method underestimates P_c when the uppermost swelling curves in Figs. 4-1-1 to -6 are used. If the second swelling curves are applied, it gives the P_c values of London Clay (LC), Fuller's Earth and Oxford Clay (OX19), comparable to those by Casagrande's method, but lower values of the London Clay (LCW) and Oxford Clay (OX10). For analysis of the latter samples the values found by Casagrande's method are used. The obtained P_c values for the two London Clay samples are near, or slightly greater than, the highest value in the literature. On the contrary, the value obtained for the Fuller's Earth is much less than those given in the literature. For the Oxford Clay the value obtained is not far from the smallest value quoted in the literature. Past overburden pressures do vary from location to location since individual basins of deposition can be involved (Coulthard (1972) for Lower Lias Clay), or, there may be sufficient variation across an individual basin for depth contours to be drawn (*e.g.* Burnett *&* Fookes (1974) for London Clay). Also included in Table 4-1 are the calculated overconsolidation ratios (OCR). The P_c value of OX19 was used to derive the OCR values of OX10, since both of them were from the same borehole. The *in situ* OCR values of the samples fall within a wide range. The highest value is for the Fuller's Earth, if based on the P_c values in the literature. The smallest is for the Flockton mudstone, recovered from the greatest depth (Section 2-1), although it has the highest P_c value.

Table 4-1 Estimated pre-consolidation pressures (kN/m^2) and overconsolidation ratios (OCR) of the samples

Deposit	Stratigraphic evidence* (Cripps & Taylor, 1981)	Smith's(1978) tests
London Clay	1,490-5,070	1,440-6,780
LC	OCR =6-35**	
LCW	OCR =2-12	
Fuller's Earth (Cretaceous)	5,980-9,730 OCR=92-200	7,100
Oxford Clay	8,340-12,100	9,540-14,500
OX10	OCR=62-148	
OX19	OCR=33-78	
Lias Clay	8,380-12,480 OCR=10-24	14,800
Flockton mudstone	29,900-48,800 OCR=5-10	--

Sample		Values obtained in this project		For latter analysis in text
		Casagrande method	Schmertmann method	
London Clay	LC	6,570 OCR=26-34**	3,600-6,200***	6,570
	LCW	7,140 OCR=9-12	2,300-4,200	7,140
Fuller's Earth	FE	2,400 OCR=37-49	1,800-3,000	2,400
Oxford Clay	OX10	-- OCR=58-80	3,000-4,200	7,800
	OX19	7,800 OCR=31-42	5,000-8,000	7,800
Lias Clay Clay	LI	--	--	10,500
Flockton mudstone	FM	--		40,000

* Based on a submerged unit weight, 9.81-12.8 kN/m^2/m.

** Based on the effective overburden pressures in Table 5-1.

*** Based on the uppermost(L) and second (R) swelling curves in Figs. 4-1-1 to -7.

In an examination of the relative positions of the compression curves in Figs. 4-1-1 to -7, the seven undisturbed samples can be separated into four groups. Both of the London Clay samples have higher void ratios than the remoulded ones beyond their P_c's, and the Fuller's Earth has a much higher void ratio. The two undisturbed Oxford Clay samples can be considered to have similar void ratios to the remoulded material beyond their P_c's. The (more indurated) undisturbed Lias Clay and Flockton mudstone have much smaller void ratios than their remoulded counterparts, even though the maximum compression is less than the P_c of the Flockton mudstone. A pressure increment of unity or more was used in the consolidation tests, which is much greater than in the field compression process (Section 1-4-3). According to Skempton (1944 & 1953) and Bjerrum (1967), the remoulded samples would have smaller void ratios than the undisturbed, if little diagenetic effect exists, as in the cases of the London Clay samples. In terms of the strength of Bjerrum's diagenetic bonds (Section 1-5-1), the London Clay samples are weakly-bonded. The Fuller's Earth would also be classed as weakly-bonded, if the strong carbonate-cementing agent, as found in Section 2-3-4 and later in Sections 4-6-3 and -4, did not exist. The Oxford Clay samples appear to be moderately-bonded, whilst the Lias Clay and Flockton mudstone are very-strongly-bonded (that is, highly-indurated).

4-3-2 Coefficient of Consolidation

The coefficient of consolidation, c_v, is dependent upon the permeability and compressibility of a material, as shown in Equation 4-2. It is commonly used in the prediction of the time for excess positive pore pressure dissipation in the consolidation process and of the rate of settlement of a foundation. In this study it has been

Table 4-2 Average coefficients of consolidation (m^2/yr.) of the samples

Sample	Coefficient of consolidation *	
	Undisturbed	remoulded
London Clay (LC)	0.320	0.236
London Clay (LCW)	0.155	0.132
Fuller's Earth (FE)	0.0736	0.0472
Oxford Clay (OX10)	0.482	0.445
Oxford Clay (OX19)	0.318	0.290
Lias Clay (LI)	3.06 ?	1.83
Flockton mudstone (FM)	--	1.31

* Under normal consolidation conditions.

Table 4-3 Average compression indices of the samples

Sample	Compression index	
	Undisturbed	Remoulded*
London Clay (LC)	0.336	0.408
London Clay (LCW)	0.379	0.447
Fuller's Earth (FE)	0.979	0.924
Oxford Clay (OX10)	0.243	0.265
Oxford Clay (OX19)	0.321	0.353
Lias Clay (LI)	0.128 ?	0.211
Flockton mudstone(FM)	-----	0.273

* Between 170 and 34,340 or 24,280 kN/m^2.

calculated by reference to the t_{90} value obtained by the square root of time fitting method (see Section 4-4-1).

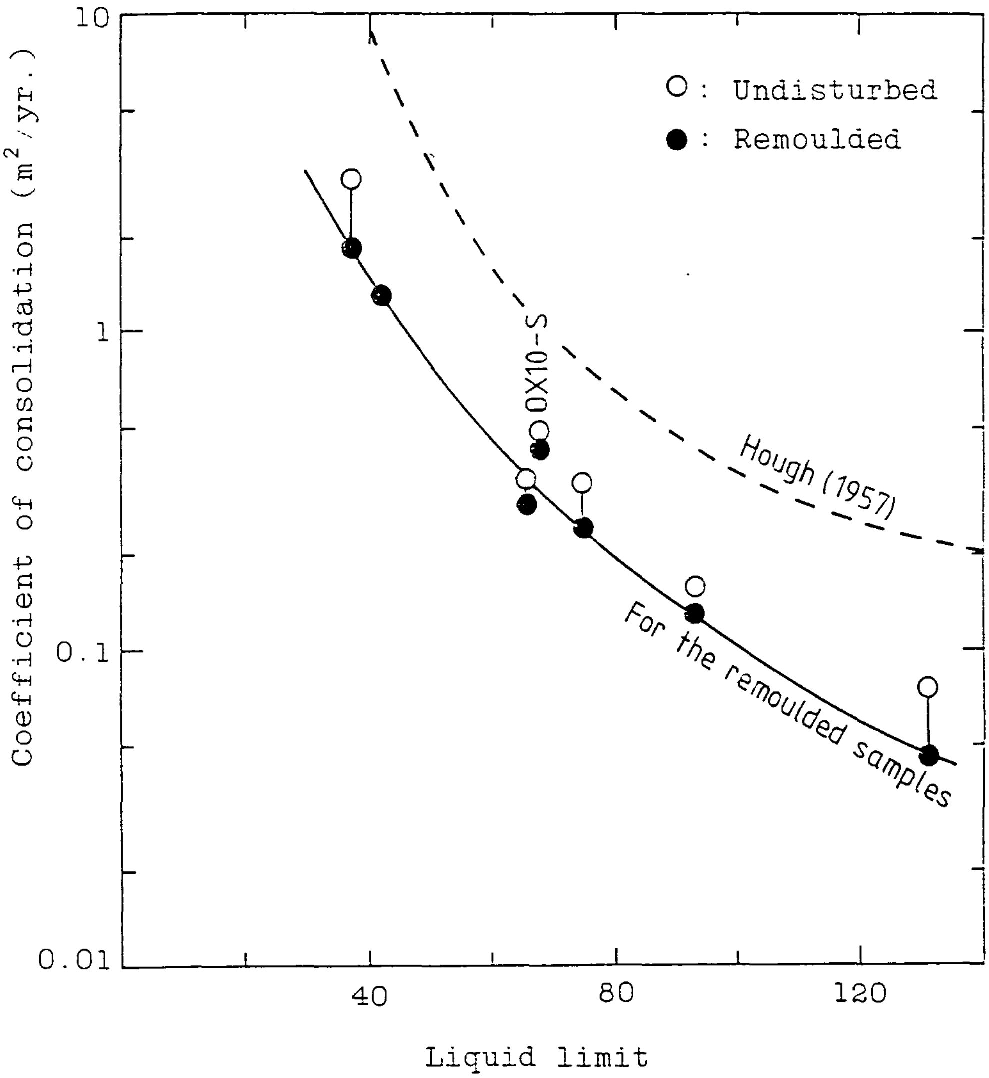
All the c_v values of undisturbed and remoulded samples during normal consolidation are given in Table C-1, and average values are presented in Table 4-2. No c_v value was obtained for the undisturbed Flockton mudstone sample, since the compression pressure did not exceed its pre-consolidation pressure. It should be noted that the c_v values for each sample, either undisturbed or remoulded, lie within a small range during normal consolidation (Table C-1). With decreasing void ratio, both k (coefficient of permeability) and m_v decrease rapidly, but the ratio k/m_v in Equation 4-2 is fairly constant over a considerable range of pressure (Terzaghi & Peck, 1948). As a result, c_v does not change much in different pressure ranges.

The average c_v values of the remoulded samples are plotted against liquid limit (L.L.) in Fig. 4-2. It clearly shows that c_v decreases with increasing L.L. in the remoulded samples investigated, although Terzaghi and Peck (1948) demonstrated that c_v varied within a wide range at a given L.L. Hough (1957) gives a relationship between c_v and L.L., as plotted in Fig. 4-2. It appears that the c_v values obtained in this project are smaller than his. Also shown in Fig. 4-2 are the c_v values of the undisturbed samples. The undisturbed samples invariably have greater c_v values than their remoulded counterparts, probably because the undisturbed samples have smaller compressibility at the same void ratio (that is, the same permeability), according to Equation 4-2.

4-3-3 Compression Index

The compressibility of a material is expressed as compression index, C_c, and defined by the equation as follows:

Fig. 4-2 Relationship between coefficient of consolidation and liquid limit in the samples
(Hough's line is for undisturbed samples)



$$C_c = -(e_o - e_p) / \log(P_o/P) \quad \text{------------------------------} \quad 4\text{-}3$$

where e_o and P_o are the void ratio and the effective pressure at the beginning of a pressure increment and e_p and P the corresponding values at the end of primary consolidation during the same pressure increment. In other words, C_c represents the gradient of the virgin compression curve on the e-logP plot in Figs. 4-1-1 to -7.

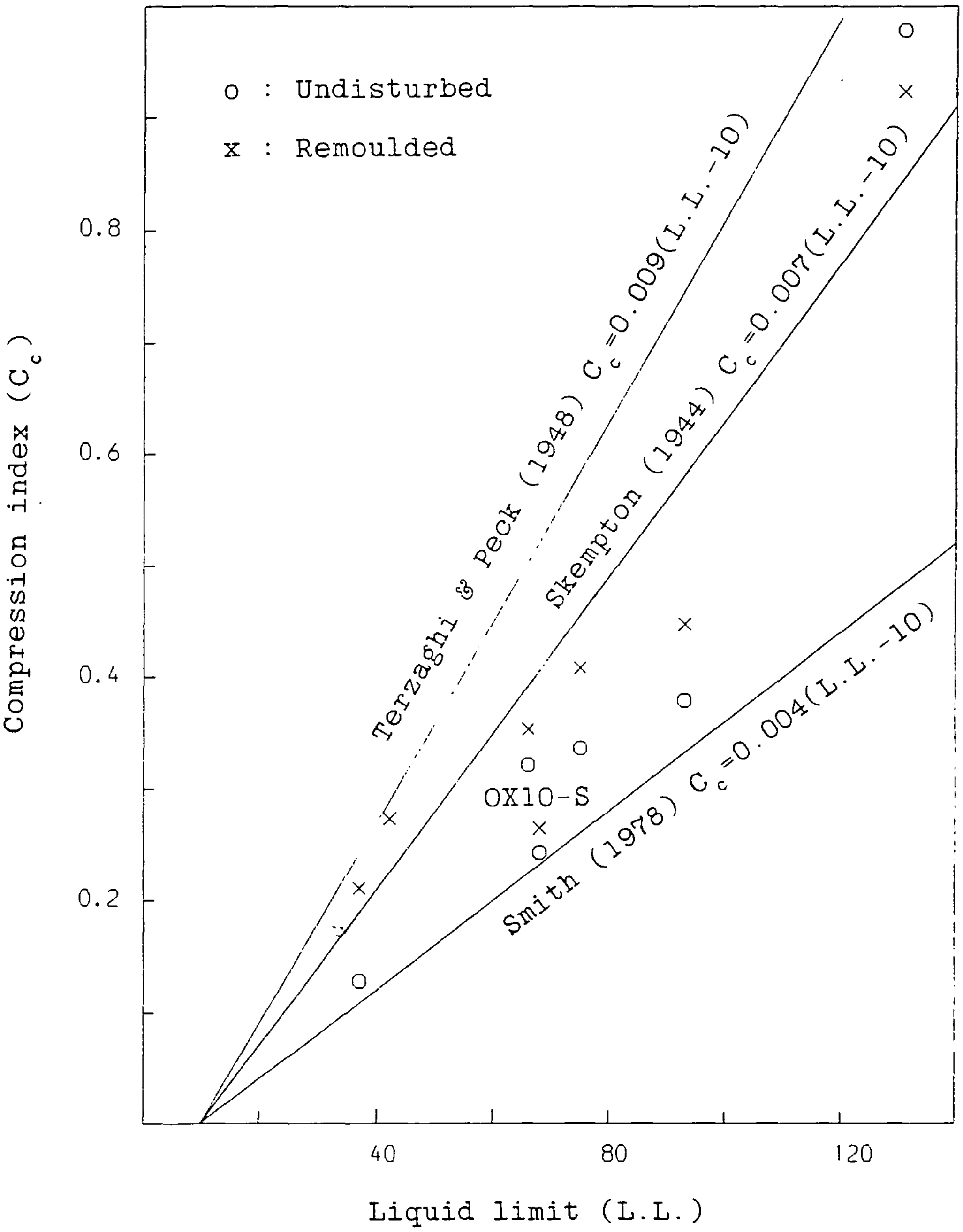
The average C_c values under normal consolidation conditions for both the undisturbed and remoulded samples are given in Table 4-3. Because the applied pressure is smaller than the pre-consolidation pressure (P_c) of Flockton mudstone, no C_c value is shown for this rock in the table. The C_c value given for the undisturbed Lias Clay is questionable, since the compressive pressure was only about twice its P_c and only one C_c value in a normal consolidation state was obtained in the test.

The average C_c values of the undisturbed and remoulded samples are plotted against liquid limit (L.L.) in Fig. 4-3. It shows that C_c increases with L.L. in the remoulded state. This has long been observed and expressed as a linear relationship, as shown by the straight lines in Fig. 4-3. It appears that Skempton's (1944) equation better correlates the data here. The average C_c values of undisturbed samples are smaller than those of remoulded ones, except that obtained for Fuller's Earth. The greater C_c of the undisturbed Fuller's Earth beyond its P_c is probably an indication of its highly open structure with easily-destroyed cementing material under compression (Sections 4-6-3 & -4), compared with the remoulded (Section 3-3-2). This is an unusual effect which to the writer's knowledge has not been recorded previously.

4-4 Rate of Swelling

4-4-1 Determination of the Coefficient of Swelling

Fig. 4-3 Relationship between compression index and liquid limit in the samples



There are two methods of determining the coefficient of consolidation from laboratory volume change data, the square root and the logarithm of time fitting (Taylor, 1948). The theoretical curve on the square root plot, devised by Taylor (1948), is a straight line up to about 60 per cent consolidation. To establish the time (t_{90}) at 90 per cent consolidation, a line is drawn with the abscissa 1.15 times that of an extension of the straight line and it cuts the curve at the 90 per cent point. The theoretical curve of degree of consolidation versus logarithm of time has an inflexion point, and the intersection of the tangent and the asymptote to the final part of the curve is at the ordinate of 100 per cent consolidation (d_{100}) (see Fig. 4-4). The departure of laboratory curves from the theoretical curve has usually been ascribed to secondary consolidation in clays. Having established the 100 per cent consolidation amount, the time (t_{50}) at 50 per cent of consolidation can be obtained. Taylor (1948) stated that the two fitting methods in general showed fairly good agreement. Swelling data are customarily analysed in a similar manner.

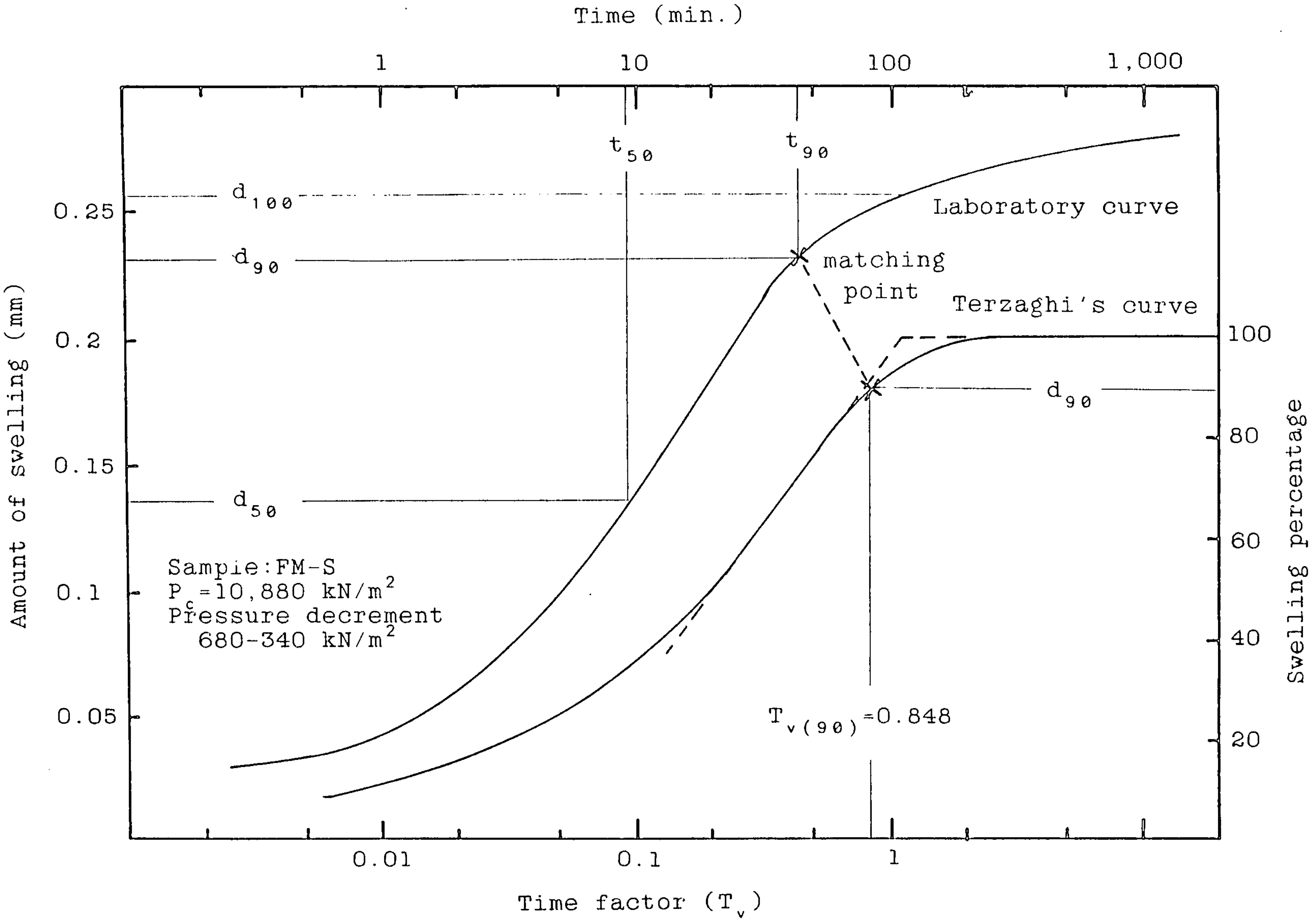
In this study. all the consolidation and swelling data were processed by means of the square root of time fitting method. As will be shown later in this chapter, prolonged primary swelling and prominent secondary swelling usually exclude the use of the logarithm of time fitting method. For swelling, after t_{90} and d_{90} are established, d_{50} is determined as follows:

$$d_{100} = (d_{90}-d_s) \Big/ 0.9 + d_s \quad \text{------------------------------} \quad 4\text{-}4$$

$$d_{50} = (d_{100}+d_s) \Big/ 2 \quad \text{-------------------------------------} \quad 4\text{-}5$$

in which d_s is the corrected initial swelling amount, as suggested by Taylor (1948). The coefficient of consolidation (c_v) corresponding to t_{90} and the coefficients of swelling ($c_{vs(t50)}$ & $c_{vs(t90)}$) corresponding to t_{50} and t_{90} are computed from the following

Fig. 4-4 An example of measured swelling rate curves and the Terzaghi theoretical curve



equation:

$$c_v \text{ (or } c_{vs}) = T_v H^2 / t \qquad \text{4-6}$$

where T_v : time factor (0.197 for 50 per cent consolidation and 0.848 for 90 per cent),

H : the shortest drainage path, equivalent to half the sample thickness for the double drainage conditions used,

t : time.

The reason for the derivation of two coefficients of swelling is that their difference will be used as a criterion in the evaluation of Terzaghi's theory of swelling. All the coefficients of consolidation and swelling determined are given in Table C-1.

The end of primary (100 per cent) swelling is defined as the 100 per cent dissipation of excess negative pore pressure after unloading, as for primary consolidation. In this project, however, no pore pressure measurement was made, and the 100 per cent swelling was estimated by the square root of time fitting method, as already mentioned above. This kind of estimation is supported by the work of Sherif *et al.* (1982), which has been mentioned in the first chapter. In contradiction to this, Mesri *et al.* (1978) reported that observed excess negative pore pressures dissipated faster than was predicted by Terzaghi's theory and the rate of swelling data on a semi-log plot. Nevertheless, the main function of the coefficient of swelling in this study is to compare overconsolidated clays and mudrocks of different geological age, and also to investigate the influence of stress level and overconsolidation ratio on swelling. As a result of this, the suitability of the square root of time fitting method does not affect the subsequent discussions.

4-4-2 **Swelling Rate Curves**

All the measured swelling rate curves have been compared with

Terzaghi's curve by fitting them at 90 per cent of primary swelling to Terzaghi's (Fig. 4-4), according to the following equations:

Swelling percentage (%) $= (d-d_s)/(d_{100}-d_s) \times 100\%$ --------- 4-7

Time factor, $T_v = (t/t_{90}) \times 0.848$ ----------------------- 4-8

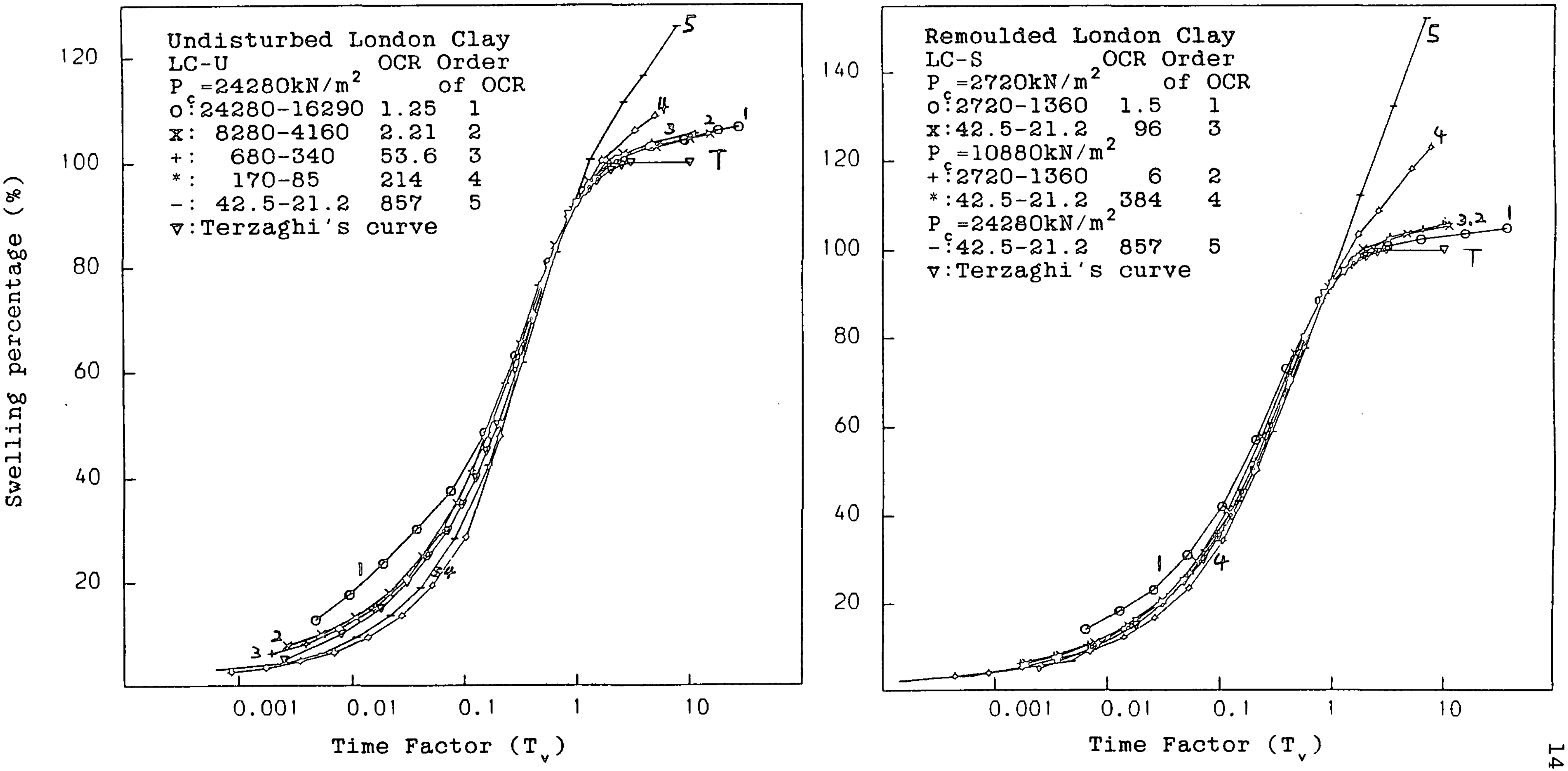
in which d is the measured swelling amount at time t, the time factor for 90 per cent swelling is 0.848, and the other symbols are those defined earlier in the text. Both swelling percentage and time factor are dimensionless parameters. Five example curves are presented for each sample and 15 for the remoulded Oxford Clay (OX10-S) in Figs. 4-5-1 to -16. These are taken from over 250 swelling rate curves of the undisturbed and remoulded samples. Other swelling rate curves, not given in those figures, show the same phenomena considered in the following discussion.

Figures 4-5-3 and -6 show that the swelling rate curves of undisturbed London Clay (LCW-U) and remoulded Fuller's Earth fit well to Terzaghi's curve. In other samples the measured curves always lie above Terzaghi's at OCR=*c*. 1.5 (for instance, no. 1 curves in Figs. 4-5-1 & -4), indicating a faster swelling rate than is predicted by Terzaghi's theory. As OCR increases, they gradually merge with Terzaghi's. At high OCR, they tend to lie below Terzaghi's in most cases (for example, nos. 4 & 5 in Fig. 4-5-1 and nos. 3 & 5 in Fig. 4-5-4). This means that swelling proceeds more slowly at high OCR than is predicted by the theory. There are two exceptions, the undisturbed Lias Clay and Flockton mudstone, for which no curve lies below Terzaghi's (Figs. 4-5-13 & -15). Beyond 100 per cent primary swelling, all the curves lie above Terzaghi's curve. This will be discussed in the section on secondary swelling (Section 4-5).

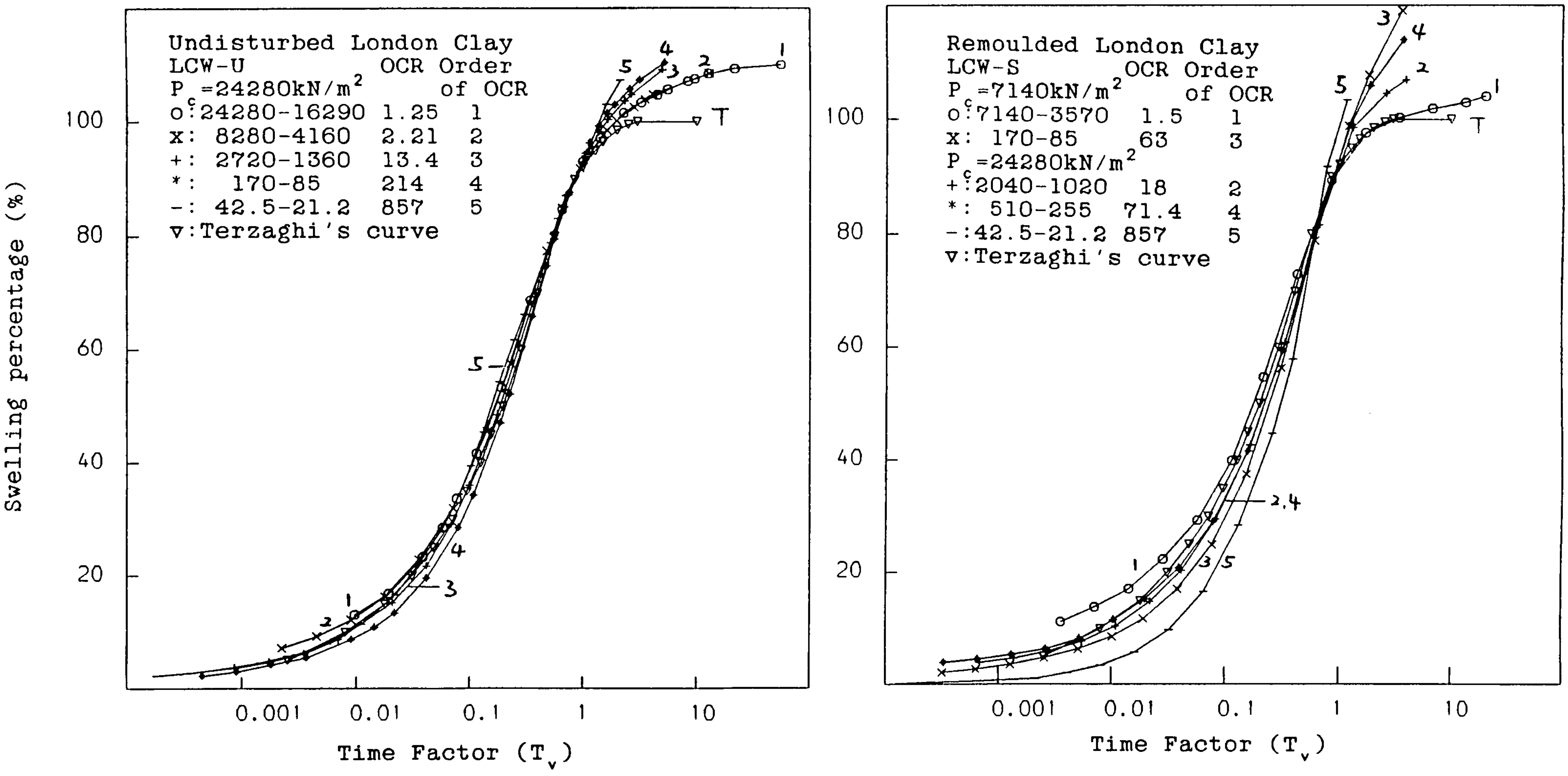
In general, Figures 4-5-1 to -16 show that Terzaghi's theory of swelling approximately predicts the shape of the swelling rate curves in spite of the radical simplifications involved (Section 4-1). The departure of the measured swelling rate curves from Terzaghi's theory can be investigated in a clearer way in the following manner:

The two coefficients of swelling, $c_{vs(t50)}$ and $c_{vs(t90)}$, computed from t_{50} and t_{90}, respectively, should have the same value, according to Terzaghi's theory. However, as shown in Figs. 4-6-1 to -14, the difference between $c_{vs(t50)}$ and $c_{vs(t90)}$ values can be considerable. This is exemplified by those points at low OCR in Figs. 4-6-7 (Oxford Clay OX10-U) and -14 (Flockton mudstone FM-S). When $c_{vs(t50)}$ is greater than $c_{vs(t90)}$, the earlier part of a swelling rate curve lies above Terzaghi's curve, and vice versa. The value of $c_{vs(t50)}$ is always greater than $c_{vs(t90)}$ at low OCR. The two c_{vs} values gradually become the same, as OCR increases. At high OCR, $c_{vs(t90)}$ can be even greater than $c_{vs(t50)}$, which is probably affected by prominent secondary swelling (Section 4-5). The rate of this decreasing difference varies among the samples as shown in Figs. 4-6-1 to -14. For the remoulded London Clay (LCW-S) and undisturbed and remoulded Fuller's Earth samples, $c_{vs(t90)}$ becomes the same as, or greater than, $c_{vs(t50)}$ at OCR = *c*. 6 to 10. Whereas, the remoulded Lias Clay and Flockton mudstone reach the same state only when the OCR is greater than 100. The undisturbed Lias Clay and Flockton mudstone are the only samples which do not have any $c_{vs(t90)}$ greater than $c_{vs(t50)}$. This has also been shown by their swelling rate curves lying above Terzaghi's curve in Figs. 4-5-13 and -15. The other samples lie between those two extremes, reaching the state at OCR =*c*. 20 to 100. Since the Fuller's earth and London Clay (LCW) specimens have a substantial amount of smectite and are the most plastic (Sections 2-2 & 2-3), it seems that the swelling of more plastic samples conforms more with Terzaghi's theory than the less plastic Lias Clay and Flockton mudstone.

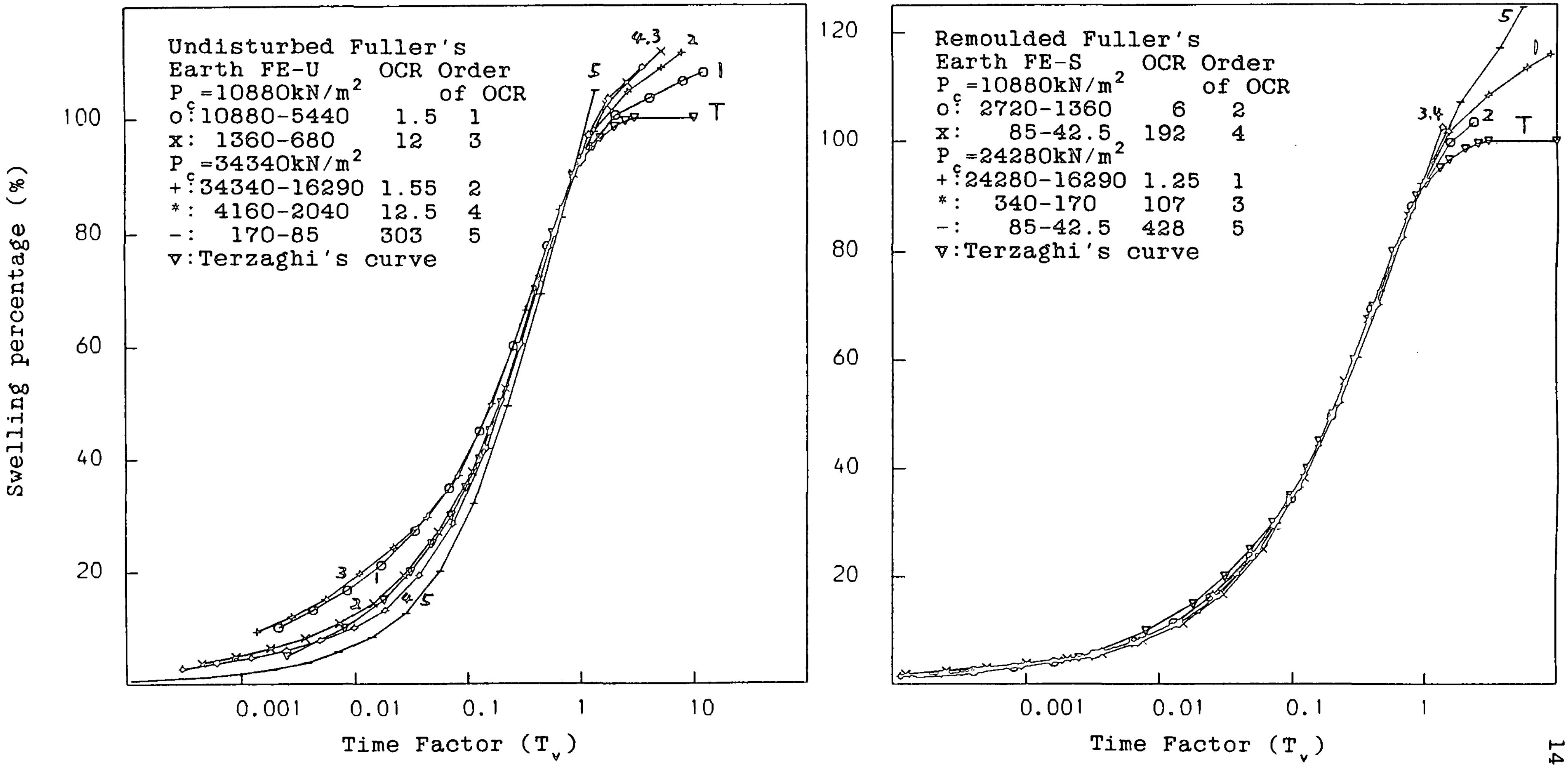
Figs. 4-5-1 (left) and 4-5-2 (right) Swelling rate curves



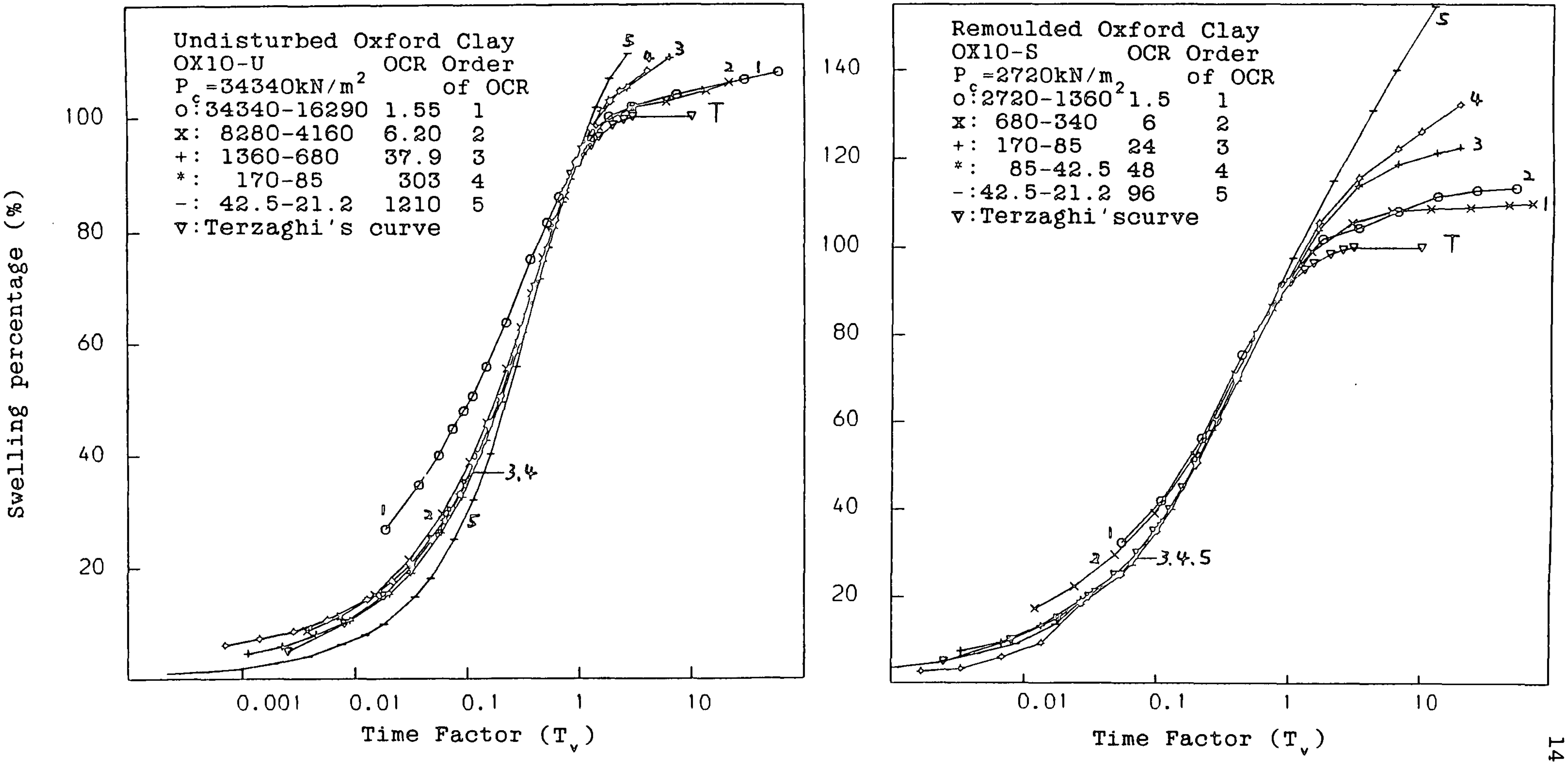
Figs. 4-5-3 (left) and 4-5-4 (right) Swelling rate curves



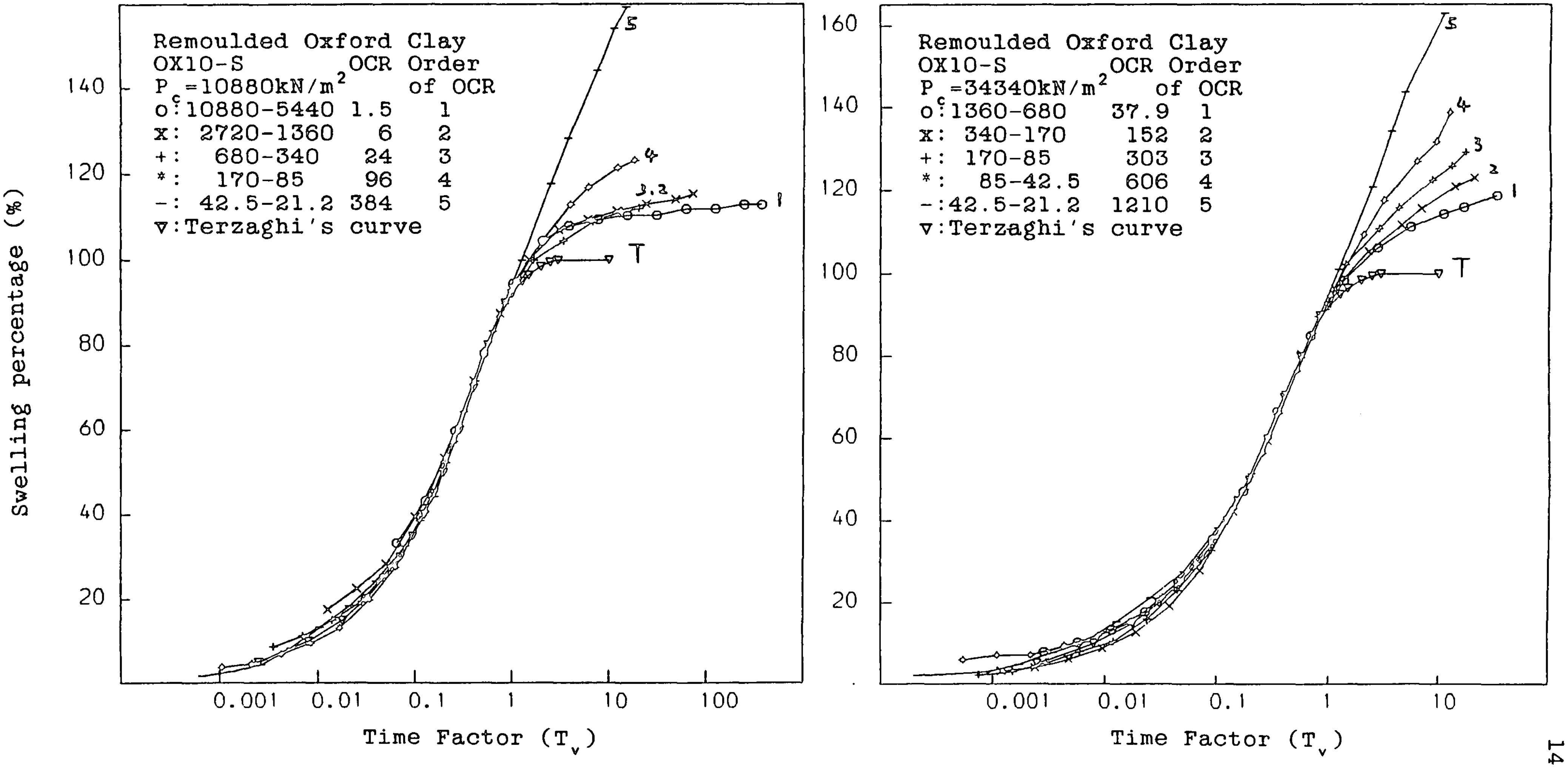
Figs. 4-5-5 (left) and 4-5-6 (right) Swelling rate curves



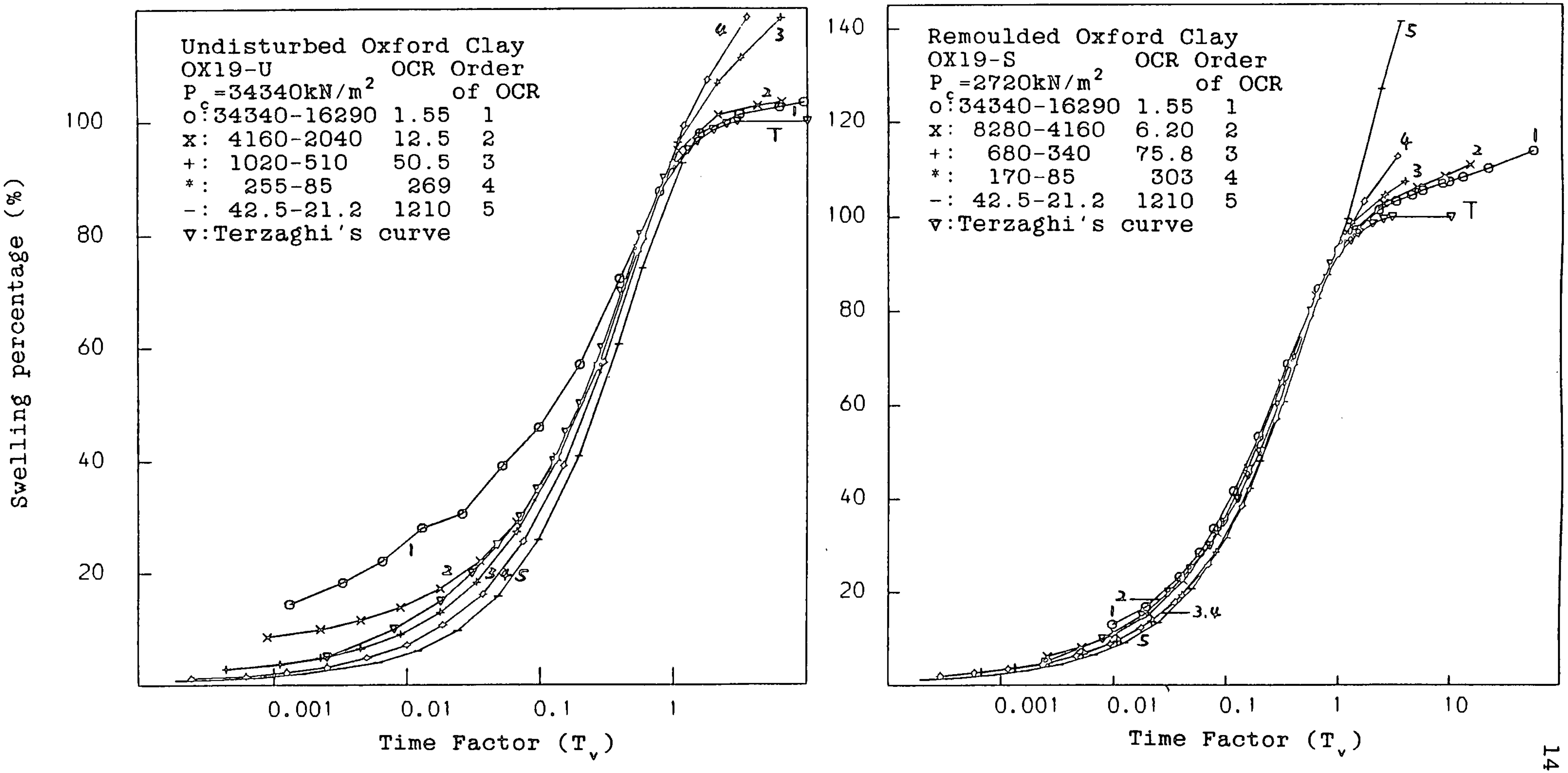
Figs. 4-5-7 (left) and 4-5-8 (right) Swelling rate curves



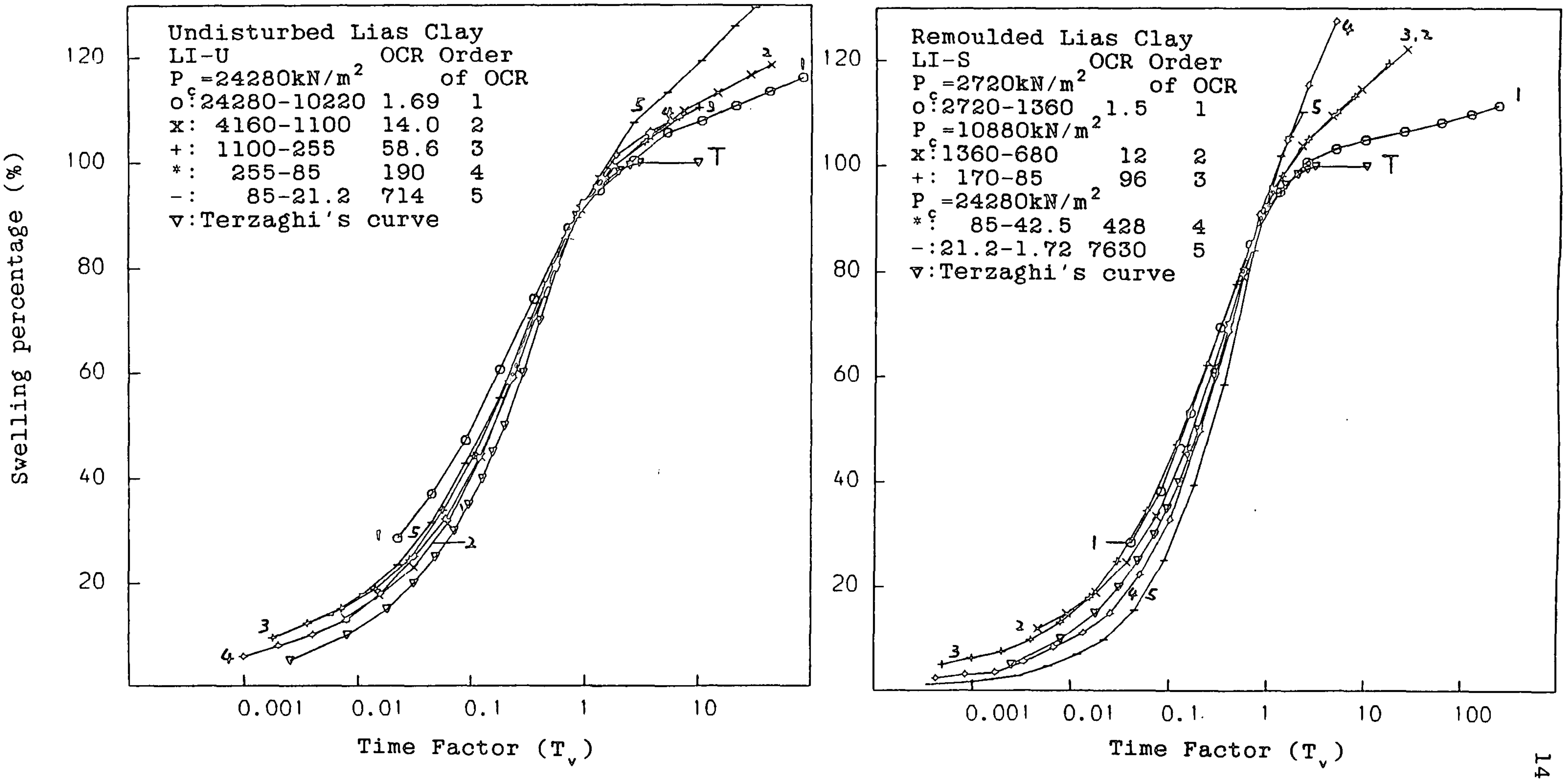
Figs. 4-5-9 (left) and 4-5-10 (right) Swelling rate curves



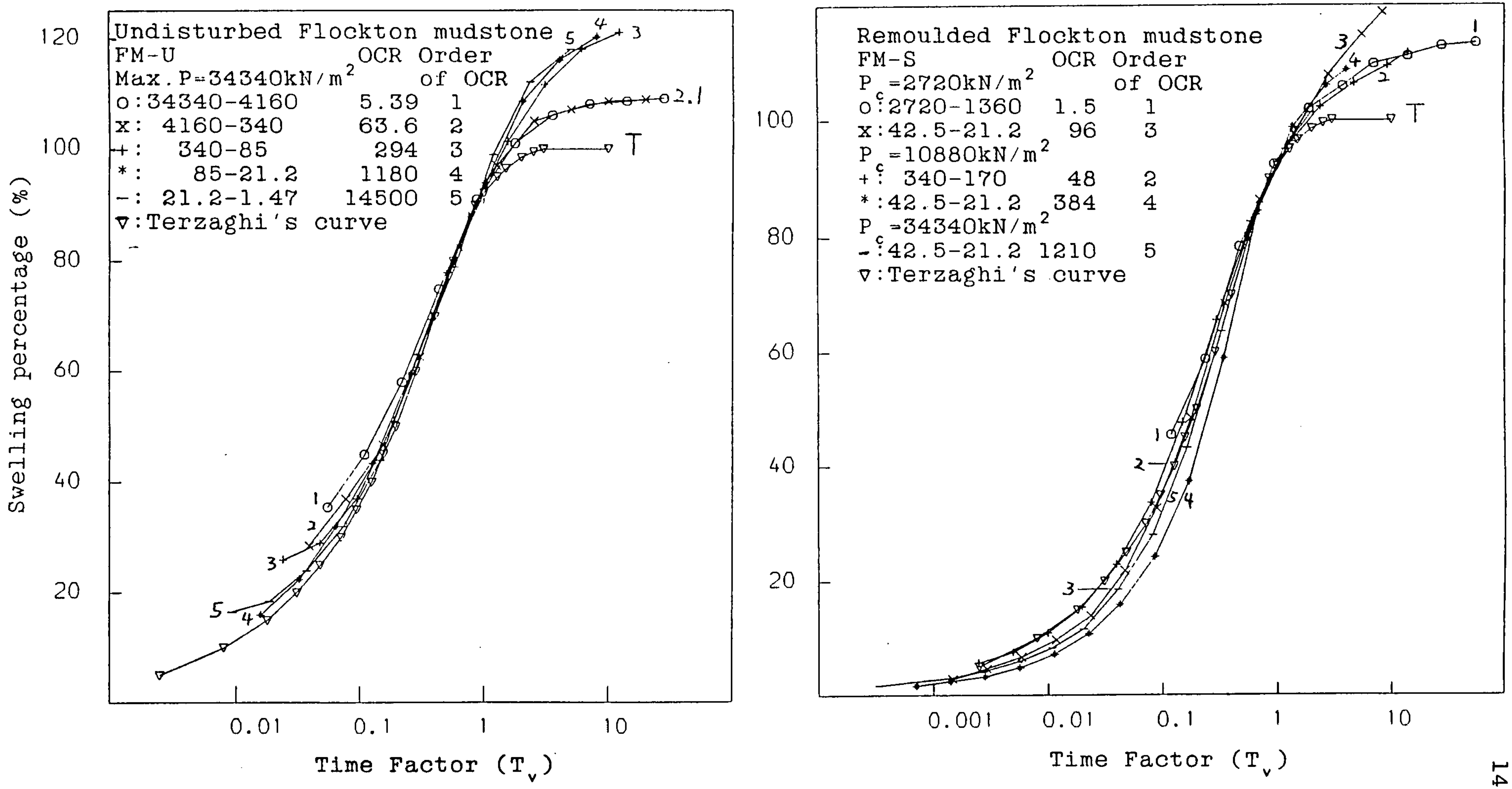
Figs. 4-5-11 (left) and 4-5-12 (right) Swelling rate curves



Figs. 4-5-13 (left) and 4-5-14 (right) Swelling rate curves



Figs. 4-5-15 (left) and 4-5-16 (right) Swelling rate curves



4-4-3 Coefficient of Swelling and Overconsolidation Ratio

The two coefficients of swelling ($c_{vs(t50)}$ & $c_{vs(t90)}$) are plotted on a logarithmic scale against overconsolidation ratio (OCR) for each undisturbed and remoulded sample in Figs. 4-6-1 to -14. Each OCR represents an average value before and after a pressure decrement. The OCR values of those undisturbed samples, which are not compressed beyond their *in situ* pre-consolidation pressures (P_c), are based on P_c values given in Table 4-1. Also shown are the coefficients of consolidation (c_v) for a condition of normal consolidation. These are given as a range for reference.

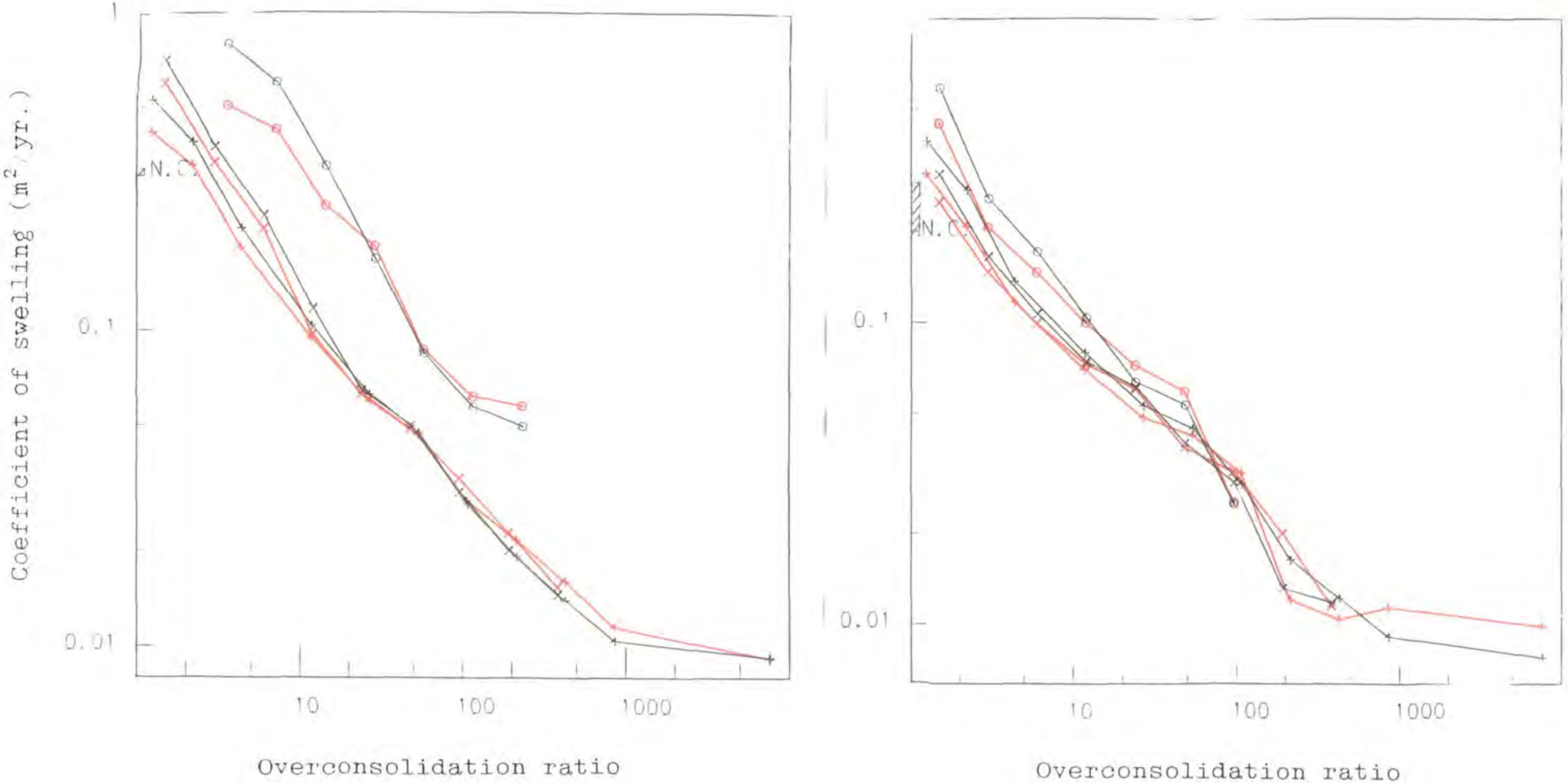
It is evident from Figs. 4-6-1 to -14 that c_{vs} consistently decreases with increasing OCR, starting above the c_v values for normal consolidation or at a similar level. The c_{vs} value decreases rapidly and drops by more than an order of magnitude below the corresponding c_v. Although c_{vs} exhibits a spread in values at a given OCR, it almost invariably follows the same trend, based on either t_{50} or t_{90}. The few exceptions (for example, an unusually high c_{vs} value at OCR= *c*. 200 in Fig. 4-6-14) may be due to some malfunction of the recording system or a small disturbance during the long experimental period. c_{vs} seems not to be affected much by P_c in the remoulded samples, but is a function of OCR. At lower OCR values or in the undisturbed samples, however, c_{vs} shows a greater range of values, decreasing with increasing P_c. It is quite difficult to determine precisely c_v or c_{vs} values, according to Lambe and Whitman (1969), because the fitting method contains arbitrary steps, and there are some limitations in the Terzaghi theory of consolidation. Even so, the close association between c_{vs} and OCR is quite consistent.

It has been shown (for instance, Lambe & Whitman, 1969) that c_v increases with increasing OCR, the opposite trend to swelling. It is

Figs. 4-6-1(L) and 4-6-2(R) Relationship between coefficient of swelling and overconsolidation ratio in the undisturbed(L) and remoulded(R) London Clay (LC)

o : P_c = *in situ*(L), 2,720(R) kN/m^2
x : 10,880 kN/m^2
+ : 24,280 kN/m^2

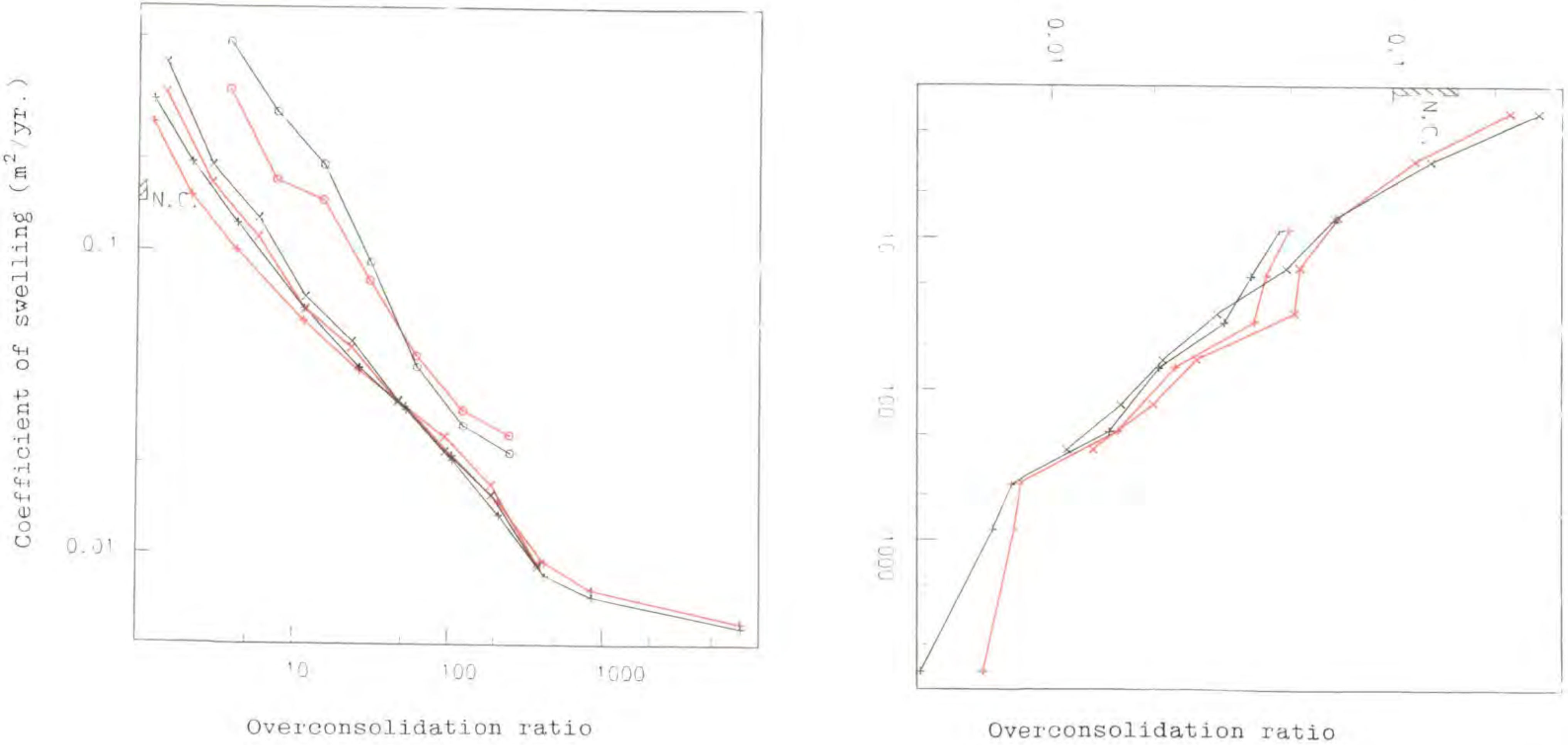
Black : $c_{vs(t50)}$
Red : $c_{vs(t90)}$
N.C. : c_v range



Figs. 4-6-3(L) and 4-6-4(R) Relationship between coefficient of swelling and overconsolidation ratio in the undisturbed(L) and remoulded(R) London Clay (LCW)

o : P_c = *in situ*(L)
x : 10,880(L), 7,140(R) kN/m^2
+ : 24,280 kN/m^2

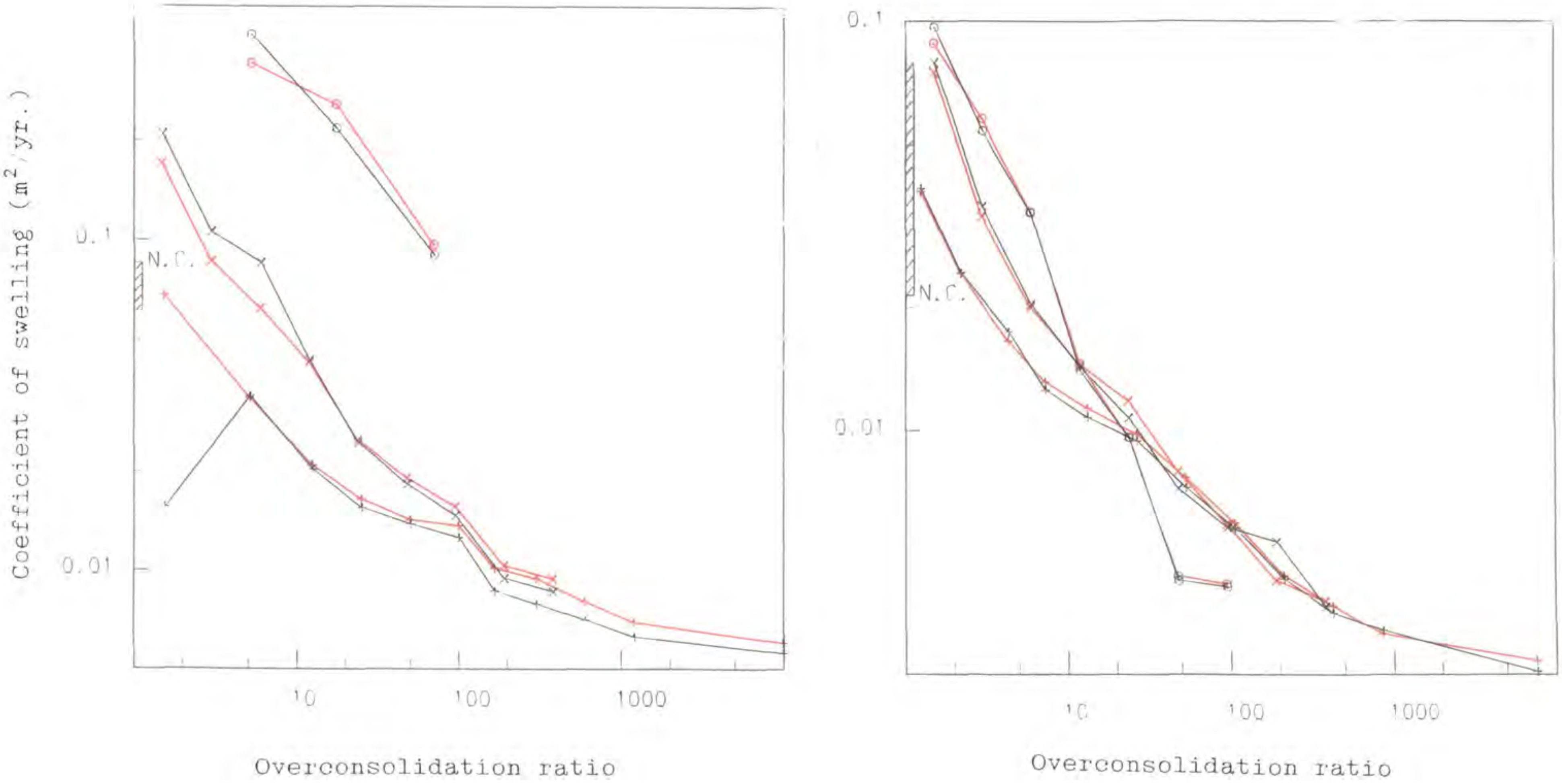
Black : $c_{vs(t50)}$
Red : $c_{vs(t90)}$
N.C. : c_v range



Figs. 4-6-5(L) and 4-6-6(R) Relationship between coefficient of swelling and overconsolidation ratio in the undisturbed(L) and remoulded(R) Fuller's Earth

o : P_c = *in situ*(L), 2,720(R) kN/m^2
x : 10,880 kN/m^2
+ : 34,340(L), 24,280(R) kN/m^2

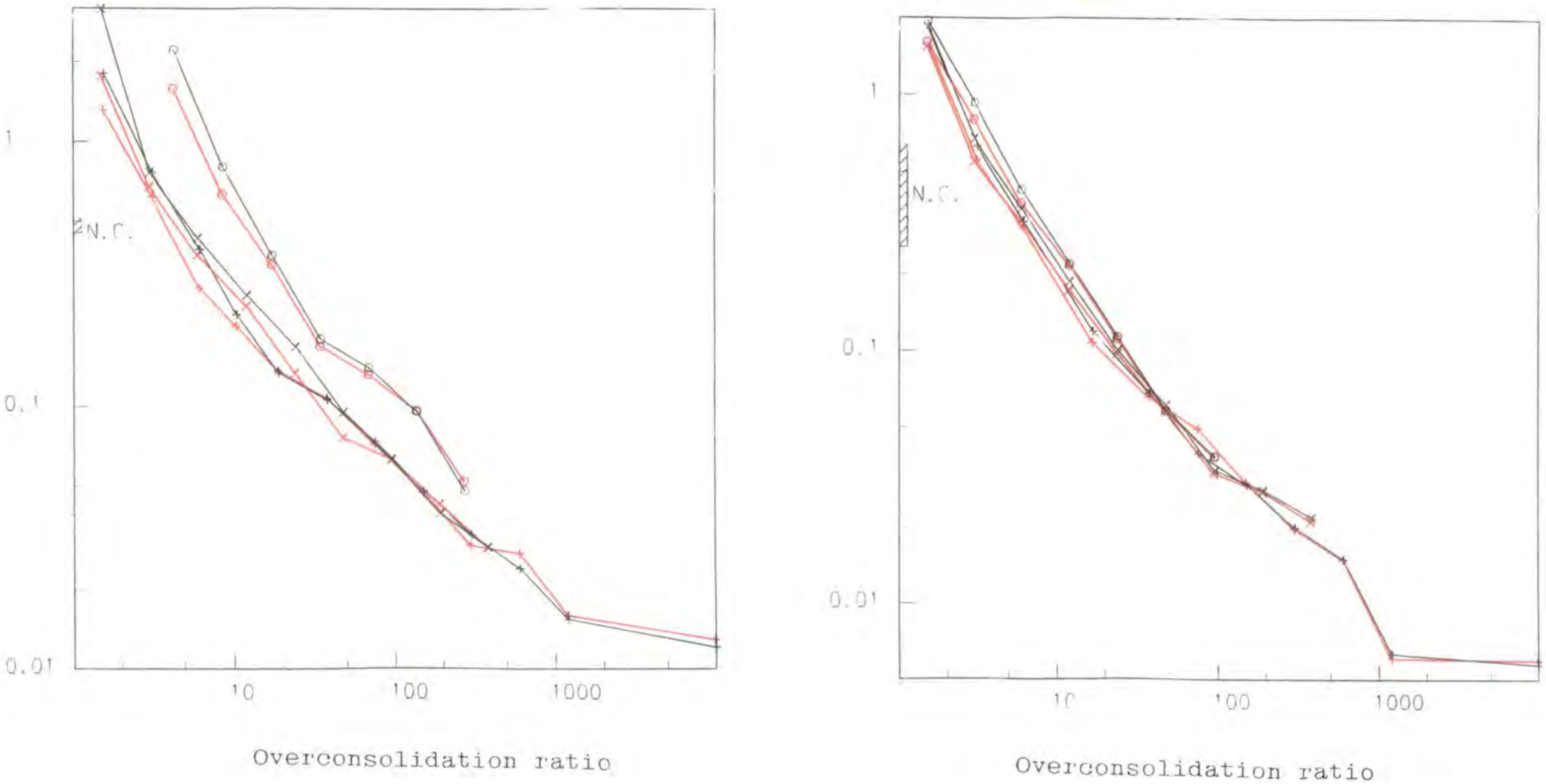
Black : $c_{vs(t50)}$
Red : $c_{vs(t90)}$
N.C. : c_v range



Figs. 4-6-7(L) and 4-6-8(R) Relationship between coefficient of swelling and overconsolidation ratio in the undisturbed(L) and remoulded(R) Oxford Clay (OX10)

o : P_c = *in situ*(L), 2.720(R) kN/m^2
x : 10.880 kN/m^2
+ : 34.340 kN/m^2

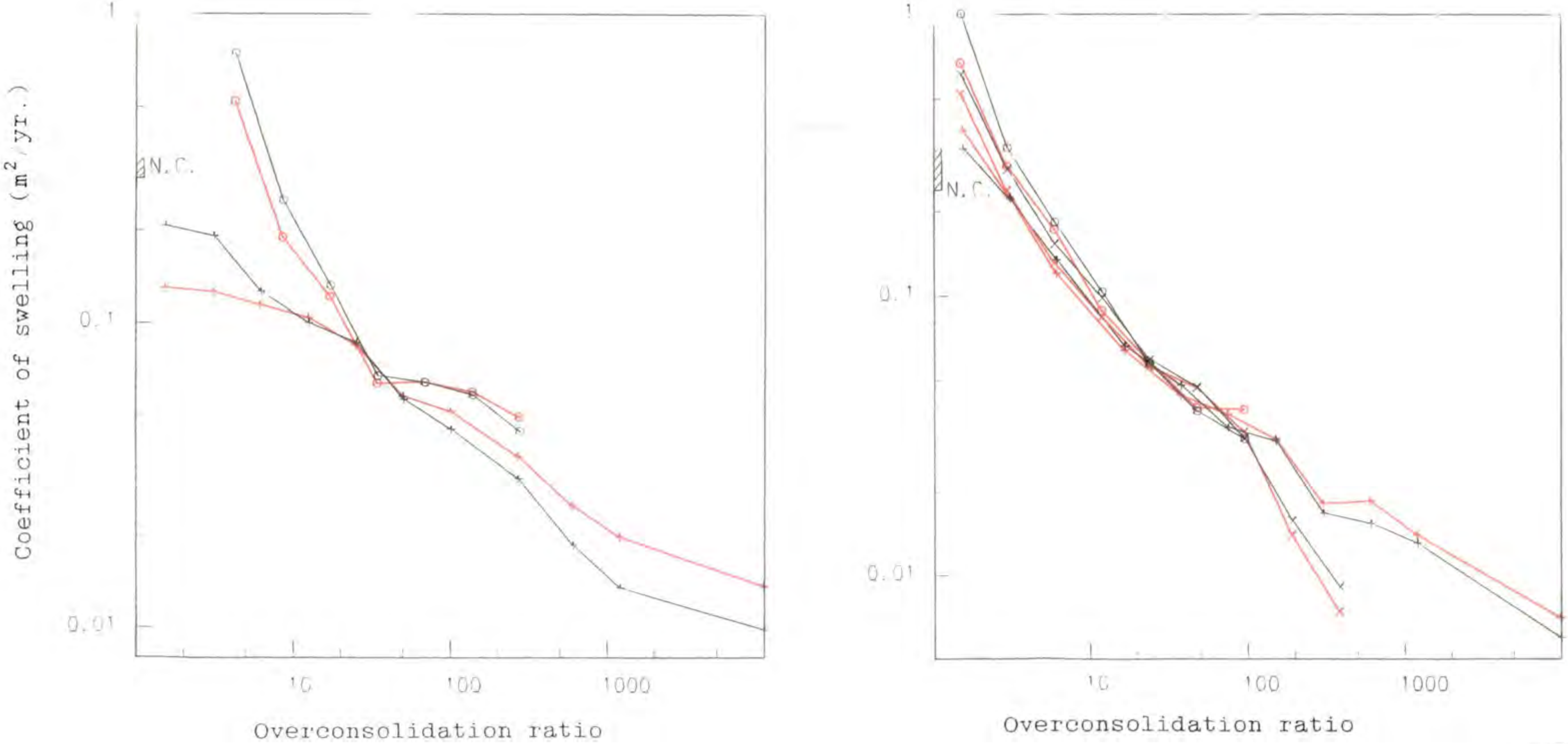
Black : $c_{vs(t50)}$
Red : $c_{vs(t90)}$
N.C. : c_v range



Figs. 4-6-9(L) and 4-6-10(R) Relationship between coefficient of swelling and overconsolidation ratio in the undisturbed(L) and remoulded(R) Oxford Clay (OX19)

o : P_c = *in situ*(L), 2,720(R) kN/m^2
x : 10,880 kN/m^2
+ : 34,340 kN/m^2

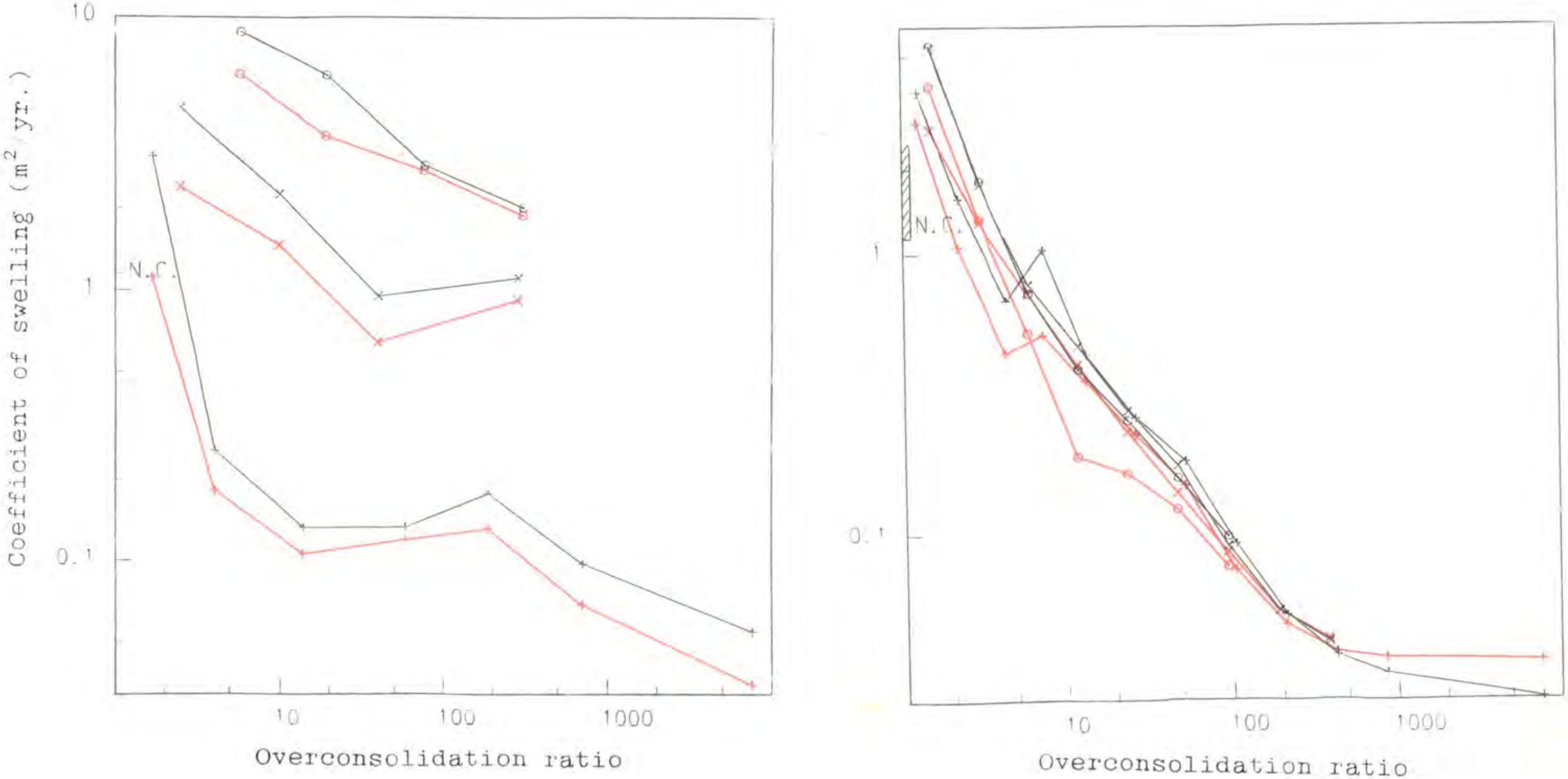
Black : $c_{vs(t50)}$
Red : $c_{vs(t90)}$
N.C. : c_v range



Figs. 4-6-11(L) and 4-6-12(R) Relationship between coefficient of swelling and overconsolidation ratio in the undisturbed(L) and remoulded(R) Lias Clay

o : P_c = *in situ*(L), 2,720(R) kN/m^2
x : 10,880 kN/m^2
+ : 24,280 kN/m^2

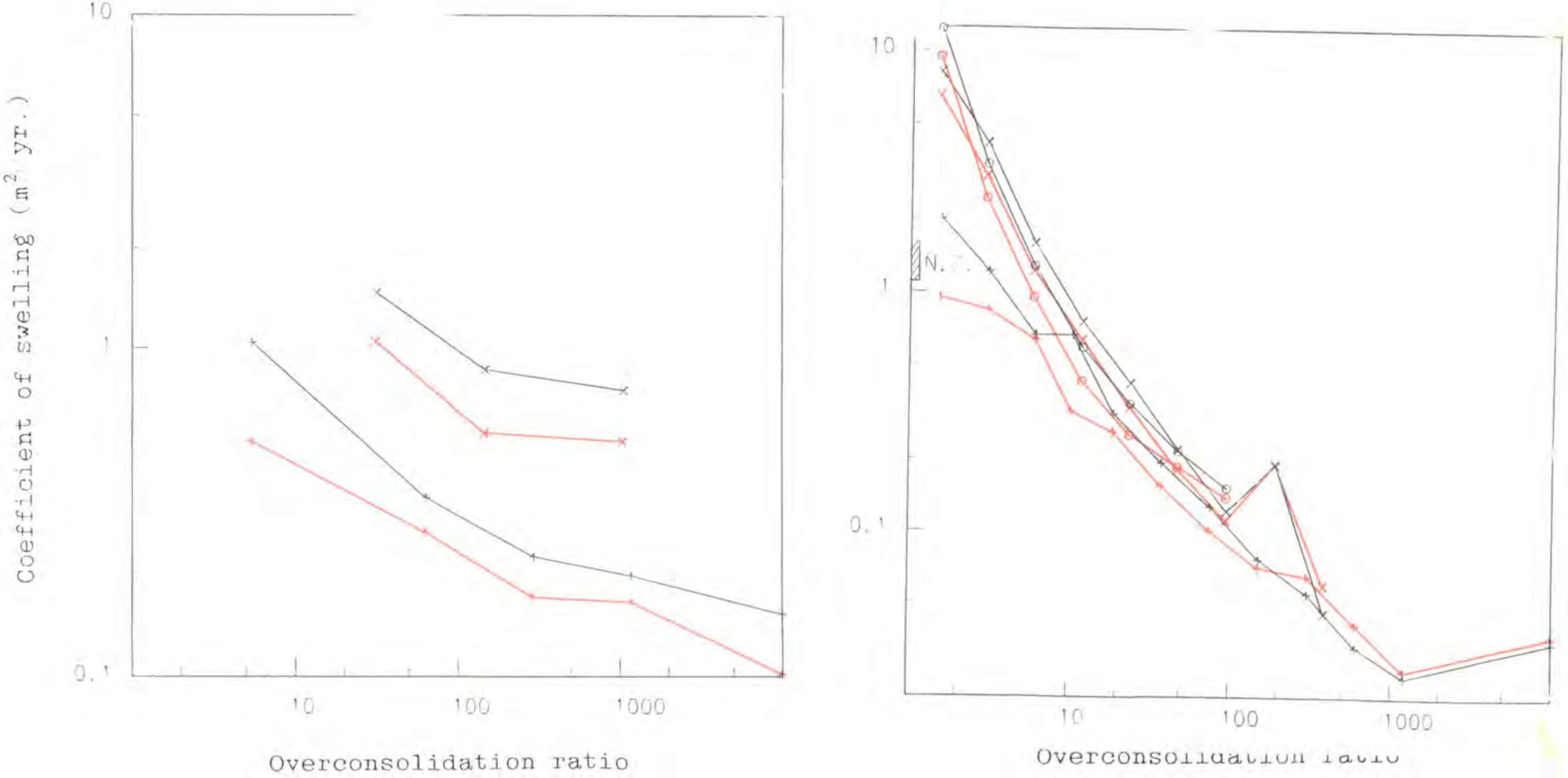
Black : $c_{vs(t50)}$
Red : $c_{vs(t90)}$
N.C. : c_v range



Figs. 4-6-13(L) and 4-6-14(R) Relationship between coefficient of swelling and overconsolidation ratio in the undisturbed(L) and remoulded(R) Flockton mudstone

o : P_c = 2,720 kN/m^2
x : *in situ*(L), 10,880 kN/m^2(R)
+ : *in situ*(L), 34,340 kN/m^2(R).

Black : $c_{vs(t50)}$
Red : $c_{vs(t90)}$
N.C. : c_v range



shown in Figs. 4-1-1 to -7 that the amount of swelling is always less than that of consolidation. This will be discussed more thoroughly in Section 4-6. According to Equation 4-2, therefore, c_{vs} should always be greater than c_v in normal consolidation within the same void ratio range (that is, given the same coefficient of permeability). Very truly, Lambe and Whitman (1969, Fig. 27.5) demonstrate that c_{vs} is greater than c_v in normal consolidation, although no scale is given. Since c_v lies within a relatively small range of values during normal consolidation and increases with increasing OCR, c_{vs} is usually less than c_v. This phenomenon has rarely been demonstrated in the literature; of course, no obvious reason has been assigned to it. Judging from the close relationship between K_o and OCR in clays and mudrocks in the field and in the one-dimensional swelling tests in the laboratory (as reviewed in Section 1-5-2), an increasing K_o, approaching a limit, K_p, would cause a large shear stress at the contact points between particles, and so the swelling process would be delayed. During the stage of low OCR values, however, K_o approaches unity (see Fig. 1-7) and the shear stress would be smaller; that is, the decreasing c_{vs} at low OCR cannot be ascribed to an increasing K_o. Instead, this can be due to the ever-increasing swelling amount at low OCR (Section 4-6-1), according to Equation 4-2. Relative to c_v, c_{vs} becomes much smaller at high OCR values. This means that a much longer period of time is necessary for mudrocks to reach equilibrium during swelling, or perhaps to complete primary swelling. Without the support of pore pressure dissipation evidence, it is difficult to justify the end of primary swelling, which is defined as the complete dissipation of excess pore water pressure.

4-4-4 Coefficient of Swelling and Mudrock Properties

As the coefficient of swelling (c_{vs}) tends to be a function of overconsolidation ratio (OCR), as pointed out in the previous section, average $c_{vs(t50)}$ and $c_{vs(t90)}$ values at four OCR values were calculated from Figs. 4-6-1 to -14. These are presented in Table 4-4. The values for the undisturbed samples, compressed beyond and behind their P_c's, are given separately. Once again, it is clearly shown that $c_{vs(t50)}$ is greater than $c_{vs(t90)}$ at low OCR and becomes equal or less at high OCR.

The relationship between the average c_{vs} values and the material properties of the remoulded mudrocks is best demonstrated by the c_{vs} - liquid limit (L.L.) - OCR plot in Fig. 4-7. Also plotted are the c_v values from Table 4-2, designated as OCR=1, for comparison. The average c_{vs} values at a given OCR of the remoulded samples generally decrease with increasing L.L. Figure 4-7 shows clearly once again the systematic trend between c_{vs} and OCR and the difference between c_{vs} and c_v. The c_{vs} values of the remoulded Oxford Clay (OX10-S, L.L.=68) at low OCR are greater than the trend given by the other data, as shown in Fig. 4-7. A possible reason for this departure is the sustained secondary swelling allowed in the OX10-S test, which according to Mesri *et al*. (1978), causes a faster swelling rate (that is, a greater coefficient of swelling). This remoulded Oxford Clay also has a greater c_v than the trend given by the other data, as shown in Fig. 4-2.

The $c_{vs(t50)}$ and $c_{vs(t90)}$ values, shown in Table 4-4 and plotted in Fig. 4-7, show that there is a greater difference between them at smaller L.L., particularly at low OCR. This means that the swelling process departs more from Terzaghi's theory in less plastic remoulded mudrocks. A similar postulation has been made in Section 4-4-2, based on Figs. 4-6-1 to -14.

As shown in Figs. 4-6-1 to -13 and Table 4-4, the undisturbed

Table 4-4 Average coefficients of swelling (c_{vs}, m^2/yr.) of the samples

Sample		$c_{vs(t50)}$*				$c_{vs(t90)}$*			
		Overconsolidation ratio							
		1.5	12	96	384	1.5	12	96	384
London Clay (LC)	U	--	0.40	0.062	--	--	0.31	0.068	--
	UC	0.62	0.11	0.031	0.014	0.51	0.097	0.034	0.015
	S	0.43	0.089	0.027	0.012	0.34	0.087	0.029	0.011
London Clay (LCW)	U	--	0.21	0.032	--	--	0.15	0.034	--
	UC	0.36	0.068	0.022	0.0092	0.29	0.062	0.025	0.0097
	S	0.27	0.055	0.019	0.0085	0.22	0.059	0.021	0.0090
Fuller's Earth (FE)	U	--	0.27	--	--	--	0.27	--	--
	UC	0.15	0.032	0.014	0.0084	0.12	0.032	0.014	0.0096
	S	0.072	0.013	0.0061	0.0037	0.067	0.012	0.0061	0.0038
Oxford Clay (OX10)	U	--	0.54	0.11	--	--	0.45	0.11	--
	UC	2.30	0.23	0.063	0.029	1.54	0.18	0.063	0.029
	S	1.86	0.19	0.036	0.021	1.57	0.18	0.037	0.021
Oxford Clay (OX19)	U	--	0.18	0.061	--	--	0.15	0.061	--
	UC	0.21	0.14	0.049	0.031	0.13	0.13	0.052	0.025
	S	0.65	0.095	0.031	0.013	0.53	0.088	0.036	0.013
Lias Clay Clay (LI)	U	--	7.0	2.8	--	--	4.5	2.6	--
	UC	3.09	0.15	0.15	0.10	1.12	0.10	0.10	0.069
	S	4.82	0.47	0.12	0.050	3.20	0.30	0.098	0.047
Flockton mudstone (FM)	U	--	--	0.66	0.51	--	--	0.45	0.36
	S	7.52	0.59	0.13	0.045	5.64	0.48	0.12	0.057

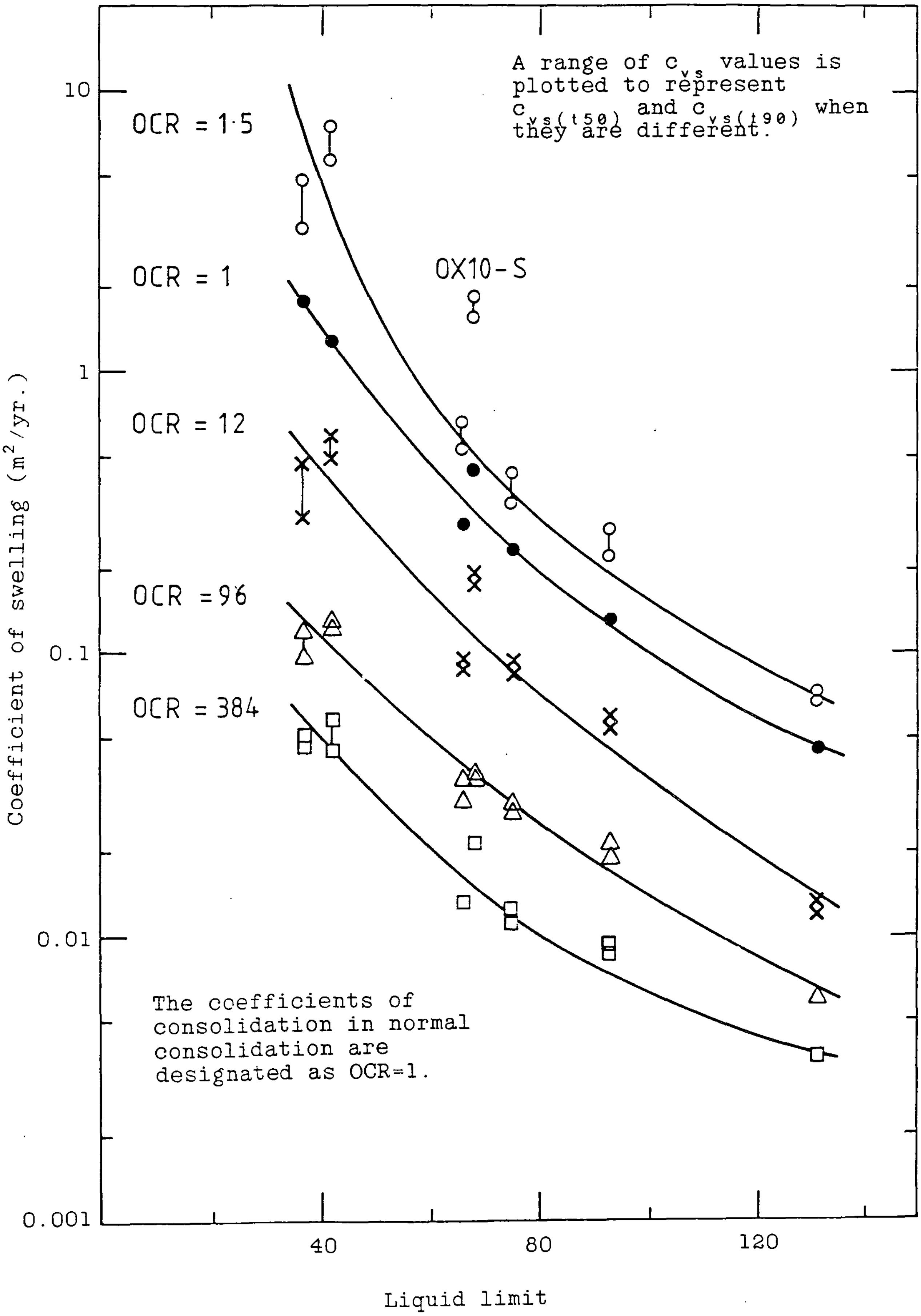
U : Undisturbed sample.

UC: Undisturbed sample compressed beyond *in situ* pre-consolidation pressure.

S : Remoulded sample.

* $c_{vs(t50)}$ and $c_{vs(t90)}$: coefficients of swelling computed from t_{50} and t_{90}, respectively.

Fig. 4-7 Relationship between coefficient of swelling, liquid limit and overconsolidation ratio in the remoulded samples



samples have greater c_{vs} values when compression is less than *in situ* P_c. The OCR values might be overestimated, but the difference is quite large, especially in the Lias Clay and Flockton mudstone (Figs. 4-6-5 and -11). This can be due to the breakdown of diagenetic bonds, since greater swelling is encountered when compression is greater than *in situ* P_c (Section 4-6-3). The undisturbed samples always have greater c_{vs} values at high OCR than the remoulded ones, as shown in Table 4-4. At low OCR, the c_{vs} values of the undisturbed Lias and Oxford Clays are less than those of the remoulded, whilst the reverse is true in the London Clay and Fuller's Earth. It must be pointed out that the determination of c_{vs} at OCR=1.5 was usually more difficult, especially in the undisturbed samples. There are some experimental reasons for this difficulty. The swelling amount was small at OCR=1.5 (the first pressure decrement), so the precision of the measurement might not be good enough. Meanwhile the period of primary swelling was short at OCR=1.5. Since thin specimens (*c.* 15 mm) were used in this project, the first recorded swelling amount would be a high percentage of primary swelling. In some extreme cases, only five readings were taken before 90 per cent primary swelling was reached.

4-5 Secondary Swelling

A swelling process may conveniently be divided into two phases, primary and secondary. The continued swelling after primary swelling is called secondary swelling, as in the consolidation process. However, secondary swelling is also occurring during primary swelling. In the consolidation process, the ratio of secondary to primary consolidation is largest when the ratio of stress increment to initial stress is small (Lambe & Whitman, 1969). When the stress increment ratio is small enough, the consolidation - logarithm of time curve does not have any inflection point. This applies to the swelling process as well, as demonstrated by the tests of Mesri *et al.* (1978). In this project the stress decrement and increment ratios were made to be not less than unity; thereby, an inflection point would be expected to occur in all the swelling and consolidation curves. Nevertheless exceptions have been found, as shown by those swelling rate curves at very high overconsolidation ratios (OCR), for instance, in Figs. 4-5-2 (LC-S, P_c=24,280 kN/m^2, from 42.5 to 21.2 kN/m^2), -8 (OX10-S, P_c=2,720 kN/m^2, from 42.5 to 21.2 kN/m^2) and -14 (LI-S, P_c=24,280 kN/m^2, from 85 to 42.5 kN/m^2). These examples actually cover samples of high to medium plasticity. Without a distinct inflection point, the logarithm of time fitting method becomes inapplicable.

Secondary swelling can be expressed as secondary swelling index, C_{as}, which is defined as follows (Mesri *et al.*, 1978):

$$C_{as} = (e-e_p) \,/\, \log(t/t_p) \qquad \text{------------------------------} \qquad 4\text{-}9$$

in which e and e_p are the void ratios at time t and at the end of primary swelling (time t_p), respectively. With the converse process of secondary consolidation, some investigators (Newland & Allely, 1960; Wahls, 1962; Leonards & Altschaeffle, 1964) consider that C_a is independent of pressure increment ratio; whilst Goldberg (1964) (quoted by Mesri, 1973) claims its dependence. No conclusion has been drawn on this matter by the present writer. Even less has been done on the effect of pressure decrement ratio on secondary swelling.

Secondary swelling can also be expressed in terms of strain as follows (Myslivec. 1969; Lo *et al.*, 1978):

$$\varepsilon_{as} = ((e-e_p)/(1+e_o)) \,/\, \log(t/t_p) \qquad \text{--------------------} \qquad 4\text{-}10$$

$$= C_{as} \,/\, (1+e_o)$$

in which e_o is the void ratio at the beginning of a pressure decrement. The ratio of secondary to primary swelling can be expressed as $C_{\alpha s}/(e_p-e_o)$, which represents the gradient of a swelling rate curve after the completion of primary swelling. Instead, Mesri *et al.* (1978) used $C_{\alpha s}/C_s$, which implies an influence of pressure decrement ratio on the ratio of secondary to primary swelling. Both expressions have been adopted here. There is a relationship between these two parameters as follows:

$$C_{\alpha s}/C_s = (C_{\alpha s}/(e_p-e_o)) \cdot \log(P/P_o) \qquad \text{---------------------} \qquad 4\text{-}11$$

in which P_o and P are the effective pressure at the beginning of a pressure decrement and at the end of primary swelling, respectively. As already demonstrated, a long period of time is usually needed to reach the end of primary swelling. In order to complete this project within a 3-year time limit, most tests proceeded only a little way beyond primary swelling. Secondary swelling requires not less than six weeks per specimen.

$C_{\alpha s}$ is not a constant with time, as shown by the changing gradient of swelling rate curves in the secondary swelling region (after 100 per cent primary swelling) in Figs. 4-5-1 to -16 (see for example, nos. 1 to 4 curves above 100 per cent primary swelling in Fig. 4-5-8). In most cases $C_{\alpha s}$ decreases with the logarithm of time immediately after the end of primary swelling. At very high OCR, it can increase continuously with time, without giving any sign of approaching a constant rate in the testing period, or it decreases only slightly within a logarithmic cycle of time (for instance, LC-S, OX10-S and OX19-S in Figs. 4-5-2, -8 to -10 & -12). Among others, Myslivec (1969) and Lo *et al.* (1978) have observed a continuous increase in $C_{\alpha s}$ with logarithm of time.

The average C_α and $C_{\alpha s}$ values of the remoulded Oxford Clay (OX10-S) within a logarithmic cycle of time immediately after the end of primary consolidation and swelling are presented in Table 4-5. Average C_α values range from 0.0087 to 0.0128. In contrast, the range of average $C_{\alpha s}$ values is much greater, from 0.0008 to 0.0075; they are always less than the average C_α values. The average $C_{\alpha s}$ value seems to increase invariably with overconsolidation ratio from low OCR values and to reach a constant or to decrease slightly at high OCR, as shown in Fig. 4-8(a).

Also presented in Table 4-5 are some other secondary consolidation and swelling parameters of the remoulded Oxford Clay (OX10), including ε_α, $\varepsilon_{\alpha s}$, $C_\alpha/(e_p-e_o)$, $C_{\alpha s}/(e_p-e_o)$, C_α/C_c and $C_{\alpha s}/C_s$ within a logarithmic cycle of time after 100 per cent primary swelling. Values of ε_α lies within a relatively small range of 4.67 to 6.90 $\times 10^{-3}$, whilst in a greater range of 0.58 to 4.76 $\times 10^{-3}$, $\varepsilon_{\alpha s}$ generally shows a similar trend to $C_{\alpha s}$. Relative to $C_{\alpha s}$ and $\varepsilon_{\alpha s}$, $C_{\alpha s}/(e_p-e_o)$ and $C_{\alpha s}/C_s$ have greater ranges, *i.e.* 5.24 to 57.8% and 1.54 to 17.4%, respectively. The other parameters ($C_\alpha/(e_p-e_o)$ and C_α/C_c) are fairly constant, varying from 10.6 to 19.6% and 3.44 to 5.90%, respectively, in the pressure range of 170 to 34,340 kN/m^2. Mesri *et al.* (1978) and Mesri and Rokhsar (1974) found that $C_{\alpha s}/C_s$ could be as high as 40%, but C_α/C_c had a smaller range of values, 1 to 5%. The parameters $C_{\alpha s}/(e_p-e_o)$ or $C_{\alpha s}/C_s$ show consistent trends which exemplify the increasing importance of secondary swelling in the whole swelling process. In Fig. 4-8(b) $C_{\alpha s}/(e_p-e_o)$ is plotted against OCR, which is based on the pressure at the end of each pressure decrement. It appears that $C_{\alpha s}/(e_p-e_o)$ remains relatively unchanged at OCR values of less than 30, but increases markedly at higher values. It also appears to be dependent upon pre-consolidation pressure (P_c). A greater P_c tends to decrease $C_{\alpha s}/(e_p-e_o)$. Mesri *et al.* (1978) also found that $C_{\alpha s}/C_s$ increased with OCR in four remoulded mudrocks of varied plasiticity.

Inasmuch as $C_{\alpha s}/(e_p-e_o)$ represents the gradient of a swelling

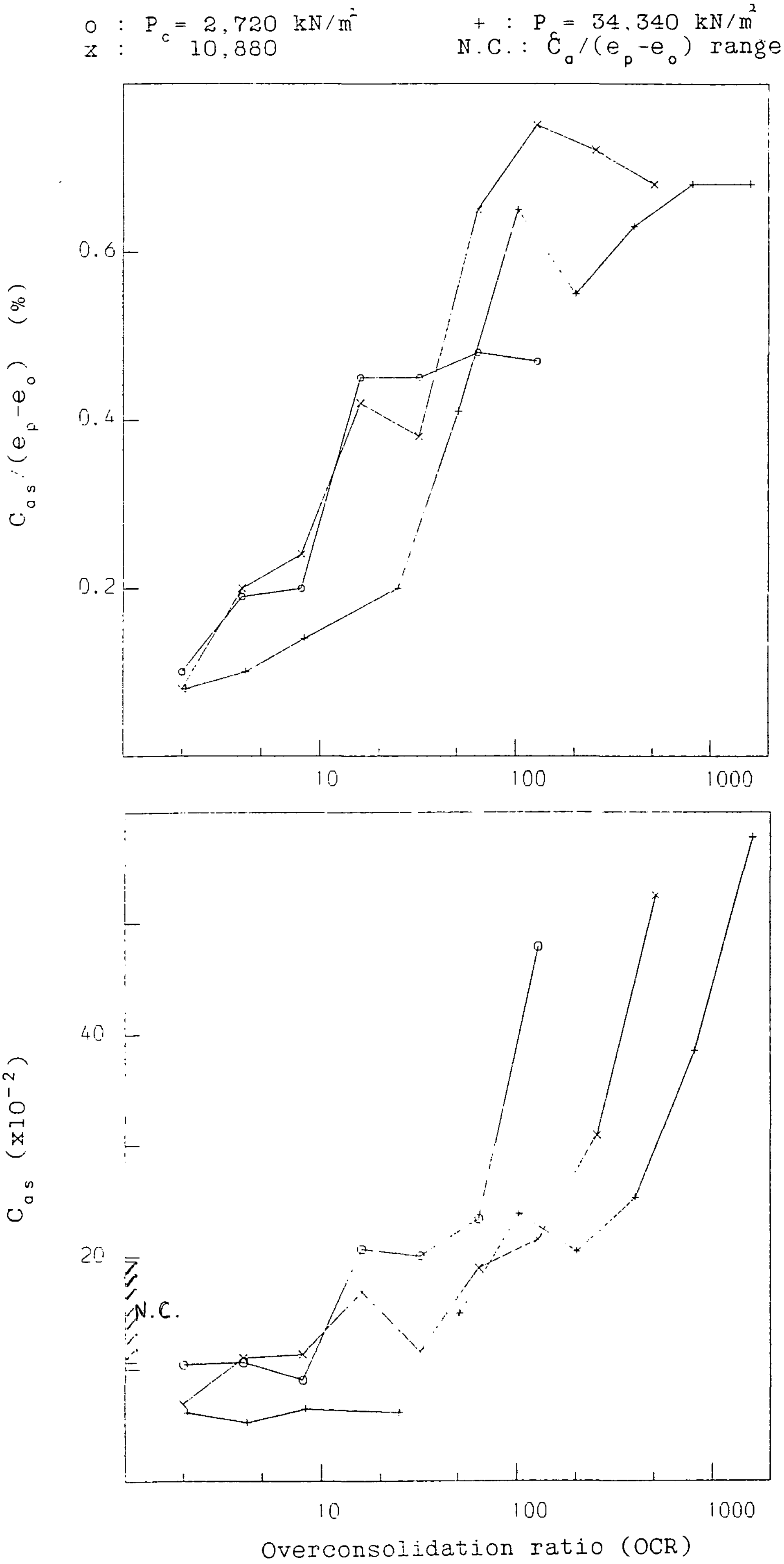
Table 4-5 Secondary swelling and consolidation parameters of the remoulded Oxford Clay OX10-S (average values within a logarithmic cycle of time after primary swelling)

	$C_{\alpha s}$	$\varepsilon_{\alpha s}$	$C_{\alpha s}/(e_p-e_o)$	$C_{\alpha s}/C_s$
P_c=2720 kN/m^2				
OCR = 2	0.10×10^{-2}	0.66×10^{-3}	10.4 %	3.13%
4	0.19	1.24	10.6	3.19
8	0.20	1.29	9.01	2.71
16	0.45	2.87	20.6	6.20
32	0.45	2.83	20.0	6.02
64	0.48	2.97	23.3	7.01
128	0.47	2.88	47.9	14.4
P_c=10880 kN/m^2				
OCR = 2	0.08	0.58	6.93	2.09
4	0.20	1.45	11.0	3.31
8	0.24	1.71	11.3	3.40
16	0.42	2.95	16.8	5.06
32	0.38	2.63	11.5	3.46
64	0.65	4.39	18.9	5.69
128	0.75	4.95	21.5	6.47
256	0.72	4.65	30.9	9.30
512	0.68	4.32	52.5	15.8
P_c=34,340 kN/m^2				
OCR = 2.1	0.08	0.65	6.15	1.99
4.2	0.10	0.80	5.24	1.54
8.3	0.14	1.10	6.45	1.93
25	0.20	1.55	6.08	2.95
51	0.41	3.10	14.9	4.49
102	0.65	4.82	23.8	7.16
202	0.55	3.99	20.4	6.14
404	0.63	4.49	25.2	7.59
808	0.68	4.76	38.5	11.6
1616	0.68	4.70	57.8	17.4

Consolidation pressure (kN/m^2)	C_α*	ε_α*	$C_\alpha/(e_p-e_o)$*	C_α/C_c*
170	0.90×10^{-2}	4.67×10^{-3}	15.0%	4.52%
340	1.28	6.90	19.6	5.90
680	1.15	6.48	13.6	4.09
1360	1.09	6.45	12.4	3.73
2720	1.06	6.62	15.7	4.73
5440	0.87	5.79	17.2	5.18
10880	0.98	6.79	16.9	5.09
34340	0.91	6.89	10.6	3.44

* in a normal consolidation condition.

Fig. 4-8 Relationship between secondary swelling and overconsolidation ratio in the remoulded Oxford Clay (OX10-S)
(a) C_{as} -- OCR (top)
(b) $C_{as}/(e_p-e_o)$ -- OCR (bottom)



rate curve in the post-100 per cent region, it can be evaluated from Figs. 4-5-8 to -10. A greater $C_{\alpha s}/(e_p-e_o)$ means a steeper slope and also a higher position in the plot of swelling percentage against logarithm of time factor. Although enough time was not allowed in most tests, the swelling rate curves in Figs. 4-5-1 to -7 and -11 to -16 seem to support the trend of increasing $C_{\alpha s}/(e_p-e_o)$ with OCR and its dependence on P_c. They appear to be positioned according to their OCR and P_c values, although in some cases they coalesce at low OCR. For example, nos. 1, 2 and 3 curves at low OCR in Fig. 4-5-1 are almost superimposed on one another after 100 per cent primary swelling; whilst no. 3 curve with a lower P_c value lies above no. 4 curve in Fig. 4-5-4, although no. 4 curve has a slightly higher OCR value. Secondary swelling index, $C_{\alpha s}$, increases with increasing liquid limit, as shown in Table 4-6 (after Mesri *et al.*, 1978). However, as indicated by the relative positions of swelling rate curves in the post-100 per cent region in Figs. 4-5-1 to -16, all the undisturbed and remoulded samples have a similar trend of increasing $C_{\alpha s}/(e_p-e_o)$ with OCR. Nevertheless, as the undisturbed samples have smaller primary swelling, (e_p-e_o), than the remoulded ones (see Section 4-6-3), their $C_{\alpha s}$ values would be smaller, especially in the Lias Clay and Flockton mudstone.

The decrease in $C_{\alpha s}/(e_p-e_o)$ with increasing P_c is probably due to the greater strength of a sample at higher pressure, which reduces the ratio of secondary to primary swelling. The cause for the increasing $C_{\alpha s}/(e_p-e_o)$ with OCR might be the effect of K_o. Although shear failure surface, as claimed by the analysis of Singh *et al.* (1973) and indirectly suggested by Mesri *et al.* (1978), was not found by X-ray radiography (Section 3-5), it is not unreasonable to exclude the possibility of failure occurring. High secondary swelling indices have also been found in isotropic swelling tests (Table 4-6),

Table 4-6 Secondary swelling indices of some remoulded mudrocks (after Mesri *et al.*, 1978)

Sample	$C_{\alpha s}$ * one-dimensional test	$C_{\alpha s}$ * isotropic test	L.L.
Duck Creek	0.15×10^{-2}	0.42×10^{-2}	30
Crab Orchard	0.25	0.96	37
Cucaracha	0.75	1.89	55
Bearpaw	2.03	3.57	110

* At OCR=16 (P_c=500 psi).

where K_o is unity. Therefore, the K_o effect can not be the principal factor.

The effect of prominent secondary swelling on the determination of the coefficient of swelling (c_{vs}) would be significant at high OCR, because secondary swelling tends to delay the process of primary swelling and to shift t_{90} and d_{90} (also d_{100}) to higher values. However, secondary swelling does not proceed at a constant rate so that the extent of its influence on c_{vs} can not be estimated accurately. The large ratio of secondary to primary swelling would also distort swelling rate curves at high OCR values, since the method of fitting measured swelling rate curves to that of Terzaghi employs $c_{vs(t90)}$ and d_{100} (Equations 4-7 & -8). As a result of this, secondary swelling would tend to depress swelling rate curves so that they lie below their theoretical position. That is to say, secondary swelling slows down the development of swelling in terms of volume change at high OCR values. In addition, the values of those secondary swelling parameters in Table 4-5 would be underestimated, especially at high OCR. Since $C_{\alpha s}$ and $\varepsilon_{\alpha s}$ decrease with increasing time, they would be greater if the end of primary swelling is set at an earlier time. $C_{\alpha s}/(e_p-e_o)$ and $C_{\alpha s}/C_s$ would also be greater because of the overestimation of d_{100} (also e_p-e_o).

4-6 Swelling Index

The ability of a mudrock to swell is usually expressed as the swelling index, C_s, which is defined by the equation as follows:

$$C_s = -(e_p-e_o) / \log(P/P_o) \qquad \text{------------------------------} \qquad 4\text{-}12$$

where e_o and P_o are the void ratio and the effective pressure at the beginning of a pressure decrement and e_p and P the corresponding values at the end of primary swelling during the same pressure decrement. That is to say, swelling index is the gradient of the swelling or rebound curves in Figs. 4-1-1 to -7. The end of primary swelling would be delayed at high overconsolidation ratios by prominent secondary swelling, as found in Section 4-5, so the swelling index obtained is probably overestimated.

The pressure used in Equation 4-12 is the effective vertical stress, σ_v. As pointed out by Yudhbir (1969) and Ullrich (1975), the average effective stress, $P=\sigma_v(1+2K)/3$ (K = coefficient of earth pressure) (see Section 5-3), can be used instead. Since K increases as σ_v decreases during one-dimensional unloading (Section 1-5-2), P decreases at a lower rate than σ_v. Therefore, the C_s value calculated from P would be greater. Since no horizontal stress measurement was made in this project, only the C_s values, based on σ_v stress, are presented. The void ratios, tabulated in Table C-1 and plotted in Figs. 4-1-1 to -7, represent a condition of primary swelling.

4-6-1 Swelling Indices of Remoulded Samples

The average swelling indices (C_s) between pre-consolidation pressures (P_c) and 21.2 kN/m^2 of the undisturbed and remoulded samples are given in Table 4-7. Also shown in this table are the C_s values for the linear parts of swelling curves in Figs. 4-1-1 to -7. The value of C_s varies during unloading from P_c to the minimum pressure. As shown by the change in gradient of swelling curves in Figs. 4-1-1 to -7, C_s generally increases with decreasing pressure immediately after consolidation and remains fairly constant within a pressure range. And then, in most cases, C_s decreases with decreasing pressure at a slower rate, as shown by the S shape of those swelling curves in Figs. 4-1-1 to -7. A typical example is given in Fig. 4-9 on the C_s-OCR plot. In a few cases the C_s values of remoulded samples remain almost constant up to 21.2 kN/m^2, as

Table 4-7 Swelling indices of the samples

Sample		Swelling index		
		2,720-21.2 kN/m^2	10,880-21.2 kN/m^2	24,280 or 34,340 -21.2 kN/m^2
London Clay(LC)	U	0.080*(0.110)**	0.095 (0.144)	0.120 (0.145)
	S	0.106 (0.132)	0.114 (0.139)	0.111 (0.137)
London Clay(LCW)	U	0.065 (0.071)	0.113 (0.146)	0.137 (0.177)
	S	----	0.146 (0.159)	0.153 (0.165)
Fuller's Earth(FE)	U	0.037 (0.039)	0.147 (0.194)	0.222 (0.351)
	S	0.210 (0.210)	0.303 (0.364)	0.353 (0.473)
Oxford Clay(OX10)	U	0.065 (0.075)	0.070 (0.082)	0.093 (0.110)
	S	0.059 (0.074)	0.080 (0.116)	0.070 (0.091)
Oxford Clay(OX19)	U	0.077 (0.090)	----	0.112 (0.117)
	S	0.099 (0.128)	0.114 (0.135)	0.110 (0.148)
Lias Clay(LI)	U	0.021 (0.025)	0.030 (0.037)	0.030 (0.040)
	S	0.052 (0.061)	0.054 (0.058)	0.056 (0.066)
Flockton mudstone (FM)	U	----	0.033 (0.053)	0.033 (0.052)
	S	0.070 (0.084)	0.079 (0.097)	0.097 (0.108)

U : Undisturbed sample.

S : Remoulded sample.

* Average swelling index in the pressure range.

** Swelling index from the linear part of the swelling curve in Figs. 4-1-1 to -7.

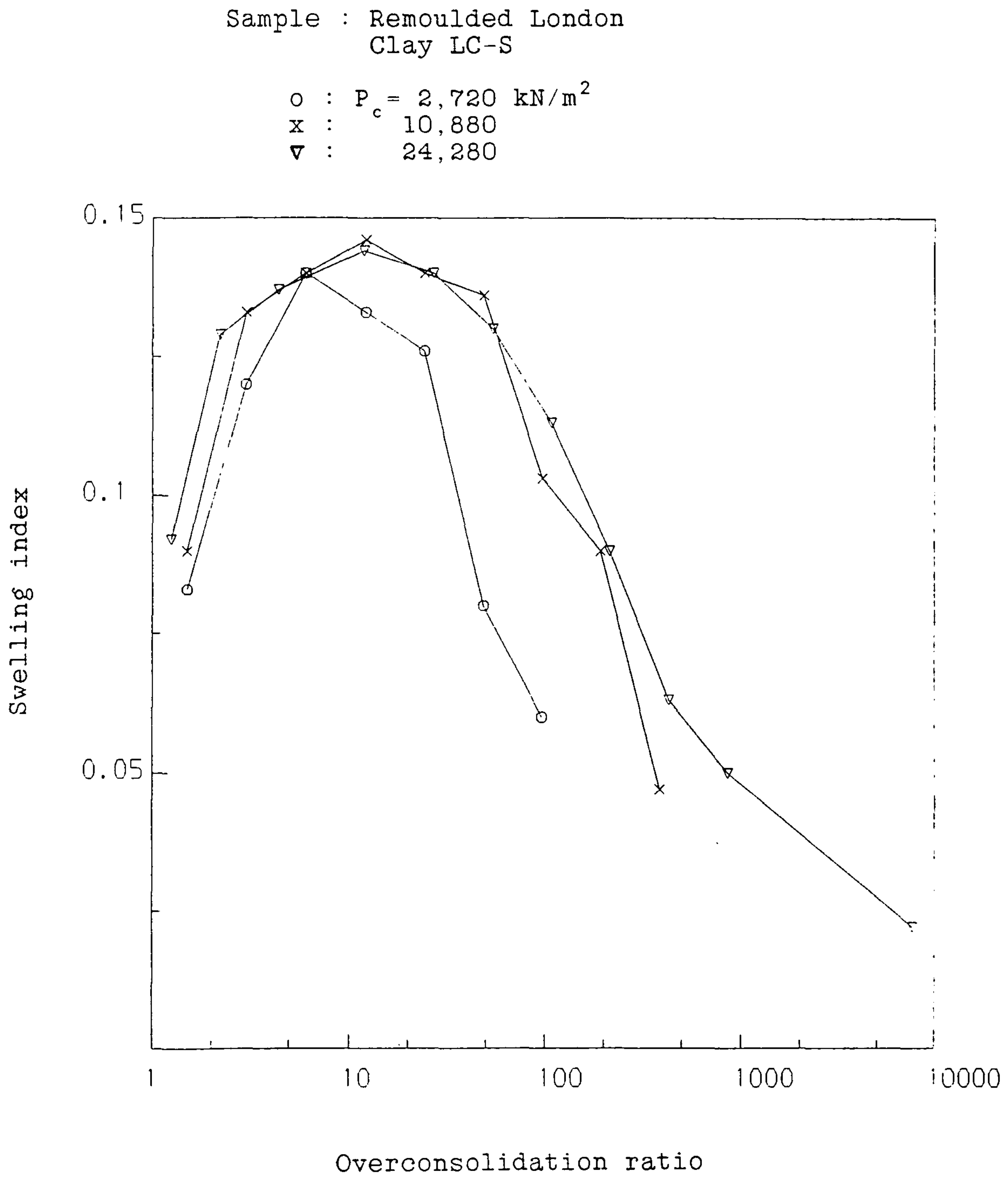
shown in Figs. 4-1-2 (LCW-S, P_c= 24,280 kN/m^2), -3 (FE-S, P_c=2720 kN/m^2) and -7 (FM-S, P_c=34,340 kN/m^2). This does not occur in the undisturbed samples. After 21.2 kN/m^2, however, C_s invariably decreases, as shown by the linear section beyond an OCR value of 1,000 in Fig. 4-9.

Figure 4-9 also demonstrates the influence of the P_c magnitude on the C_s values of remoulded samples. As listed in Table 4-7, the average C_s value invariably increases with increasing P_c from 2,720 to 10,880 kN/m^2. When P_c increases from 10,880 to 24,280 or 34,340 kN/m^2, the average C_s value either increases or slightly decreases. This increase in C_s is very prominent in the remoulded Fuller's Earth. The phenomenon has been observed by others (for instance, Crisp, 1955; Smith, 1978). The C_s values for the linear parts of swelling curves in Figs. 4-1-1 to -7 also show the same increase or decrease as the average C_s values do in Table 4-7.

Several possible factors can cause an increase in C_s with increasing P_c. First, the fabric of the sample changes with P_c. Most notable are the decrease in macro-pores (Sridharan *et al.*, 1971; Delage & Lefebvre, 1984) and the increase in preferred orientation (Section 3-4). Macro-pores would decrease swelling, since more space is available for particles to expand into without changing conditions. A high degree of preferred orientation with increase in pressure (and decrease in pore space) would increase swelling if the physico-chemical force between clay platelets dominates the swelling phenomenon. This will be discussed in more detail in the fifth chapter.

Another factor is the influence of the coefficient of earth pressure at rest (K_o). As already reviewed in the first chapter, field and laboratory evidences show that K_o increases with OCR in the swelling process. The greater the P_c, the greater the OCR and K_o at

Fig. 4-9 Relationship between swelling index, overconsolidation ratio and pre-consolidation pressure (P_c)



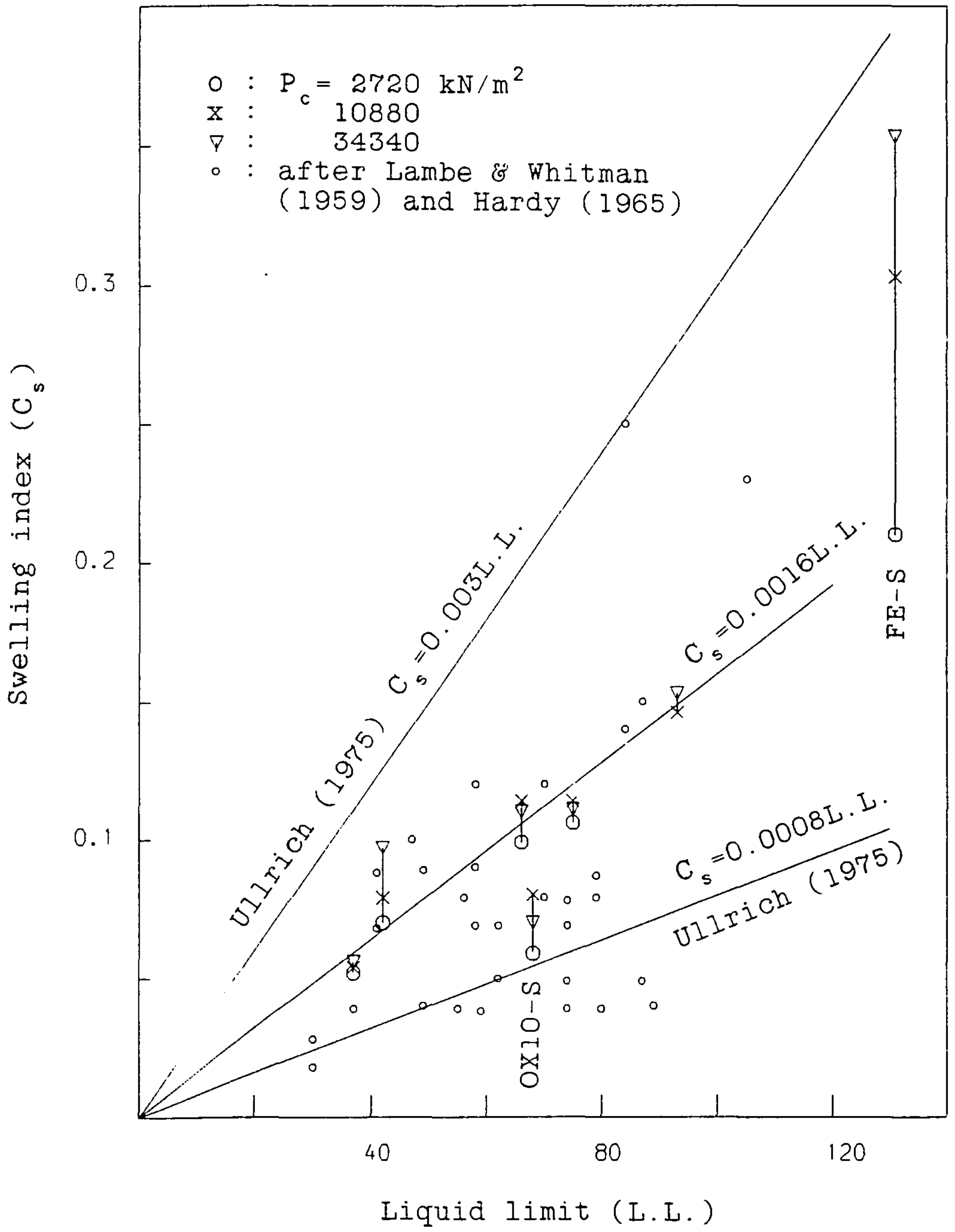
the same pressure. In the isotropic swelling tests conducted by Ullrich (1975) C_s always increases with OCR. In his one-dimensional swelling tests, C_s also increases with OCR if average stress is used instead of vertical stress. His swelling curves of the one-dimensional and isotropic tests are similar. Since K_o is unity in the isotropic tests, it does not seem to have a significant influence on C_s. In contradiction to this, Yudhbir (1969) found that the swelling curves were steeper in one-dimensional tests than in isotropic tests, and attributed the difference to the K_o effect. When K_o becomes greater during unloading, the friction between the sample and the ring could be significant (Leonards & Girault, 1961), even though the friction-reducing silicon grease was applied in all the consolidation-swelling tests of this project (Appendix C-1). Certainly this kind of friction would retard swelling to some extend and decrease C_s at high OCR values.

4-6-2 Swelling Index and Plasticity

All the average swelling indices (C_s) of the remoulded samples are plotted in Fig. 4-10 against liquid limit (L.L.). Also included are the data compiled by Lambe and Whitman (1959) and the range enclosed by two straight lines found by Ullrich (1975). Figure 4-10 shows that there is a general relationship between C_s and L.L. among those data from literature, but not as well correlated as between compression index and L.L. (see Section 4-3-3). However, the experimental data are scant and difficult to interpret because of unknown or different test conditions. All the C_s values of remoulded samples fall within the region given by Ullrich (1975), as shown in Fig. 4-10.

A close relationship is found between C_s and plasticity among five samples, as shown by the straight line in Fig. 4-10, expressed

Fig. 4-10 Relationship between swelling index and liquid limit in the remoulded samples



as:

$$C_s = 0.0016 \text{ L.L.} \qquad \text{4-13}$$

This line lies in the middle of the region given by Ullrich (1975). As shown in Fig. 4-10, the Fuller's Earth (L.L.=131) and Oxford Clay specimens (OX10-S, L.L.=68) are exceptions. The C_s values of the Fuller's Earth at three pre-consolidation pressures exhibit a considerably great range of values and are higher than is predicted by Equation 4-13. The Oxford Clay (OX10-S) seems to have smaller C_s values than the other Oxford Clay sample (OX19-S, L.L.=66), although both of them are generally similar in terms of mineralogy and plasticity (Sections 2-3 & 2-2). The explanation of this difference can probably be related to the work of Mesri *et al.* (1978). They found that the swelling amount immediately following sustained secondary swelling to be smaller than in tests without much secondary swelling. Since the consolidation-swelling test in the remoulded Oxford Clay (OX10-S) was designed to proceed for at least a logarithmic cycle of time after primary swelling or consolidation (Section 4-2), the smaller average C_s values for this sample conform with the claims of Mesri *et al.* (1978). This remoulded Oxford Clay also has a smaller C_c value than the trend given by the other samples, as shown in Fig. 4-3.

4-6-3 Swelling Indices of Undisturbed Samples

The average swelling indices (C_s) of undisturbed samples increase with increasing pre-consolidation pressure (P_c) or maximum reconsolidation pressure, even more so than those of their remoulded counterparts. This is also shown by the C_s values for the linear parts of swelling curves in Figs. 4-1-1 to -7. The large strain caused by compression in a pressure increment ratio of unity would destroy some weak diagenetic bonds (Terzaghi, 1941). When compression is greater than *in situ* P_c, the average C_s values increase even more. This is best demonstrated by the consistent increase in average C_s value from 10,880 to 34,340 kN/m^2 in London Clay, Fuller's Earth and Oxford Clay, whilst as discussed before, the average C_s values of remoulded samples usually increase less or even decrease within the same pressure range. The average C_s values of Lias Clay and Flockton mudstone remain the same, when the maximum compression increases from 10,880 to 34,340 kN/m^2. This means that their bonds are strong enough to resist compression. The undisturbed Fuller's Earth has an average C_s value (at a P_c value of 10,880 kN/m^2) which is four times bigger than that at 2,720 kN/m^2, and a C_s value from the linear portion of its swelling curve which is five times as great. Sensibly, this is most likely to be due to the cementing of the fabric (Section 2-3-4) which is easily destroyed by large strains induced when loading is beyond its P_c.

When compared with the remoulded samples within the same pressure range in Table 4-7, the undisturbed samples almost always have smaller average C_s values, except the Oxford Clay (OX10). The remoulded Oxford Clay (OX10-S) was tested under a different condition and has smaller average C_s values, as discussed in Section 4-6-2. The smaller C_s values of undisturbed samples have long been known, as explained in the first chapter of the thesis. The C_s values for the linear parts of the swelling curves in Figs. 4-1-1 to -7 also show the same trends as the average swelling indices do. The ratios of undisturbed to remoulded swelling index are 0.75 to 1.1 in the London Clays, 0.78 to 1.0 in the Oxford Clay (OX19) and 0.34 to 0.56 in the Lias Clay and Flockton mudstone. This indicates that the diagenetic bonds of the London and Oxford Clays appear to be too weak to bear large compressive strain, and those of the Lias Clay and Flockton mudstone are very strong. The ratios in the Fuller's Earth fall within a wide range of values (0.18 to 0.63) - from very small to medium. This shows that the Fuller's Earth has very strong bonds, but they are vulnerable to compressive strain. This order of strength of diagenetic bonds is the same as that postulated in Section 4-3-1, except for the Oxford Clays.

Diagenetic bonding has been taken for granted as the reason for the greater C_s values when undisturbed samples are reconsolidated to greater pressures, or for the greater C_s values in remoulded samples compared with undisturbed ones. However, other factors can also affect C_s, as discussed in Section 4-6-1. The difference in fabric between undisturbed and remoulded samples can have an important influence on C_s, particularly in the Fuller's Earth. The void ratio of the undisturbed Fuller's Earth at *in situ* P_c cannot be smaller than 2.2, as shown by the compression curve in Fig. 4-1-3. At the same pressure the remoulded void ratio is not greater than 2.0. The difference in void ratio is very large, corresponding to at least 7 per cent moisture content (or 70 mm^3/g void volume). As P_c increases and the void ratio decreases, the remoulded C_s increases. As a result of this, the undisturbed Fuller's Earth should have a smaller C_s value, when unloaded from its *in situ* P_c, than the corresponding remoulded samples within the same pressure range. That is to say, the increase in undisturbed C_s with P_c can be partly attributed to fabric change, especially the reduction of macro-pores after testing in the undisturbed Fuller's Earth (Section 3-3-2). Since there is less increase in remoulded C_s within the same pressure range, the increase in undisturbed C_s can still be partly ascribed to diagenetic bonds. The effect of void ratio on C_s does not played an important part in the London and Oxford Clays, since their undisturbed and remoulded virgin compression lines lie close to each other (Figs. 4-1-1, -2, -4 & -5). On the contrary, the Lias Clay and Flockton mudstone have much smaller void ratios than their remoulded counterparts within the whole pressure range (Figs. 4-1-6 & -7); thereby, diagenetic bonds seem to be the most reasonable factor for their smaller C_s values. In addition to fabric difference, the undisturbed and remoulded samples can also have different K_o conditions. When the undisturbed samples are placed in the cell, the K_o value is considered to be unity (see the detailed discussion in Section 5-3-2). This K_o value might be less or greater than the *in situ* K_o values in these overconsolidated samples, depending on their OCR values. When compressed beyond their *in situ* P_c values, the undisturbed samples resume a condition of normal consolidation. Hence, theoretically they should follow the increasing K_o pattern during subsequent unloading. Although there could be difference in K_o value among samples, the extent of its influence on primary swelling is still uncertain (Section 4-6-1).

4-6-4 **Recovered Strain Ratio**

As reviewed in Section 1-5-1, Bjerrum's (1967) concept of recoverable strain energy is useful in the examination of the swelling property of mudrocks. In this study the writer uses a ratio of swelling to compression index, C_s/C_c (called, 'the recovered strain ratio'), to represent the strain percentage recovered in the consolidation-swelling tests. The remoulded samples contain few bonds, so their recovered strain ratios can also be called 'the recoverable strain ratios'. A more plastic clay has a greater recoverable strain energy, as indicated by its higher C_s (Section 4-6-2). Whereas material with diagenetic bonds can only recover part of the recoverable strain energy in the swelling test, so it would have a recovered strain ratio smaller than its remoulded counterpart, in which most bonds are broken. Nevertheless, a highly plastic and bonded clay can still recover a large amount of strain energy during unloading, if the bonds are weak. Therefore, the extent of the diagenetic bonding effect on mudrocks of different plasticity can only be evaluated using a ratio as a criterion, but not as an absolute measure.

C_s/C_c values are presented in Table 4-8 for all the samples at three pre-consolidation pressures (P_c). No data are given for the undisturbed Flockton mudstone, since no C_c value is available (Section 4-3-3). The C_c values used are under a normal consolidation condition, listed in Table 4-3. The C_s values are the average ones cited in Table 4-7. No consistent relationship can be found between C_s/C_c and plasticity among the remoulded samples. Their C_s/C_c values vary from 0.22 to 0.38, comparable to the range, 0.1 to 0.4, compiled from the literature by Mesri *et al.* (1978). C_s/C_c always increases in the remoulded samples when P_c increases from 2,720 to 10,880 kN/m^2; whilst it remains almost constant in four samples and increases considerably in two samples, when P_c increases from 10,880 to 34,340 kN/m^2. Since C_c remains relatively constant within the pressure range of 2,720 to 10,880 kN/m^2, it is certain that recoverable strain increases when P_c increases. The Oxford Clay (OX10-S) is an exception again, with a decrease in C_s/C_c as P_c increases from 10,880 to 34,340 kN/m^2. This is possibly due to the different testing condition (Sections 4-2, 4-4-4 and 4-6-2). Hence, it is excluded in the following discussion.

The undisturbed C_s/C_c values always increase with P_c in all samples (Table 4-8). The greatest increase is in the Fuller's Earth. This trend is less consistent in the remoulded samples. It is probably implied, therefore, that the conversion of diagenetic bonds due to compressive strain in the undisturbed samples contributes to the recovered strain ratios because of the release of locked-in

Table 4-8 Recovered strain ratios of the samples

Sample	$P_c =$	C_s/C_c 2720 kN/m^2	C_s/C_c 10,880 kN/m^2	C_s/C_c 24,280 kN/m^2 or 34340
London Clay(LC)	U	0.24	0.28	0.36
	S	0.26	0.28	0.27
London Clay(LCW)	U	0.17	0.30	0.36
	S	--	0.33	0.34
Fuller's Earth(FE)	U	0.04	0.15	0.23
	S	0.23	0.33	0.38
Oxford Clay(OX10)	U	0.27	0.29	0.38
	S	0.22	0.30	0.26
Oxford Clay(OX19)	U	0.24	--	0.35
	S	0.28	0.32	0.31
Lias Clay(LI)	U	0.16	0.23	0.23
	S	0.25	0.26	0.27
Flockton mudstone (FM)	S	0.26	0.29	0.36

U : Undisturbed.

S : Remoulded.

C_s : average swelling index from Table 4-7.

C_c : average compression index from Table 4-3.

recoverable strain energy. When compared with remoulded ones, the undisturbed C_s/C_c values in the Fuller's Earth and Lias Clay are always smaller. The difference appears to be greater at lower P_c values in the Fuller's Earth. This demonstrates that the undisturbed Lias Clay and Fuller's Earth recovered a smaller percentage of strain in the tests than they would have if diagenetic bonds did not exist. Meanwhile, the bonds of the Fuller's Earth can be destroyed by compressive strain much more easily than those of the Lias Clay. On the contrary, the undisturbed C_s/C_c values become greater than their remoulded counterparts at P_c=34,340 kN/m^2 in the London and Oxford Clays. This probably means that, when compression exceeds *in situ* P_c, part of locked-in recoverable strain energy is released and so the recovered strain ratio increases. The bonds of the London and Oxford Clays are also vulnerable to large compression strain. All these postulations confirm what has already been claimed, based on other criteria in Sections 4-3-1 and 4-6-3.

4-7 General Discussions

The overall conclusion to be drawn from those results on the rate of swelling (Section 4-4) and secondary swelling (Section 4-5) is that swelling is of a progressive nature. The swelling rate in terms of volume change can be approximately predicted by Terzaghi's theory of swelling. The coefficient of swelling decreases with increasing overconsolidation ratio and drops by more than an order of magnitude below the corresponding coefficient of consolidation. The more plastic a clay, the smaller the coefficient of swelling. Secondary swelling proceeds to a considerable amount after the completion of primary swelling at high overconsolidation ratios. The ratio of secondary to primary swelling increases with overconsolidation ratio apparently without a limit. The amount of secondary swelling within a logarithmic cycle of time can be more than half that of primary swelling at an overconsolidation ratio of 500 in remoulded Oxford Clay. These characteristics exist in all the remoulded samples, regardless of their plasticity, and also in the undisturbed samples containing diagenetic bonds of different strength and forms.

The results on swelling index (Section 4-6) indicate that diagenetic bonding is another important factor in the swelling of undisturbed samples. Diagenetic bonds tend to reduce primary and secondary swelling and increase the coefficient of swelling. Locked-in recoverable strain energy can be released by partly destroying diagenetic bonds, no matter what their nature may be. In the laboratory weak or moderate bonds are progressively destroyed by increasing compressive strain, whereas in the field the breakdown of diagenetic bonds is usually time-dependent (Section 1-5).

Progressive or delayed softening of overconsolidated plastic clays or mudrocks and the resultant failure of slopes have commonly been attributed to the breakdown of diagenetic bonds and the release of locked-in recoverable strain energy (Section 1-5-1). Since the process of swelling is also progressive in nature, it should be considered before the role of diagenetic bonds can be evaluated. Terzaghi's theory of swelling has been applied to predict the rate of swelling in mudrocks (for example, along the Panama Canal; Lutton & Banks, 1970), and a slow rate of dissipation of excess negative pore pressure has been suspected to be the primary mechanism for the delayed failure phenomenon (for example, Vaughan & Walbancke, 1973). The reason is because of the dependence of shear strength on effective stress, as expressed as follows:

$$s = c' + \sigma' \tan\phi'$$

$$= c' + (\sigma-(u-\Delta u)) \tan\phi'$$

$$= c' + (\sigma-u+\Delta u) \tan\phi' \qquad \text{4-14}$$

in which s=shear strength, c'=effective cohesion, σ=total stress, σ'= effective stress, u=pore pressure, Δu=excess pore pressure (negative in swelling) and ϕ'= effective frictional angle. Because Δu decreases with time, so does the shear strength as swelling proceeds. The swelling in terms of volume change is even slower than the pore pressure dissipation (Mesri *et al.*, 1978). In addition to pore pressure dissipation, prolonged primary swelling with prominent secondary swelling would result in a significant increase in moisture content. So a further reduction of strength would take place because shear strength is closely related to moisture content (Lambe & Whitman, 1969). This is best demonstrated in Fig. 4-11, which displays the isochrones of void ratio in swelling and consolidation. The value of time is only relative because it depends on the length of drainage. In normal consolidation the isochrones are almost parallel, as shown by the lines, a-b and a'-b'. This is the same phenomenon as established by Bjerrum (1972) - see Fig. 4-12. Meanwhile, primary consolidation completes within 10 years. Figure 4-12 also shows that the strength of a normally-consolidated clay increases from s_d to s_o when the void ratio decreases from e_d to e_o within 3,000 years under a constant pressure, P_o. This has been confirmed in the laboratory tests conducted by Akai and Sano (1984). During swelling the increase in void ratio with time varies from low to high pressure. As shown by c-c' in Fig. 4-11, this increase at low pressure completes almost within a year and little swelling occurs from 1 to 1,000 years. In contrast, the increase in void ratio along d-d' at high pressure proceeds slowly, but largely and consistently, until the end of primary swelling (*c.* 50 years, much more than 10 years in consolidation), and then still persists from

Fig. 4-11 An example of time influence on swelling and consolidation (The derivation of isochrones is given in Appendix C-3. The depth is based on a submerged unit weight of 10 kN/m^2/m and a water table on the ground surface)

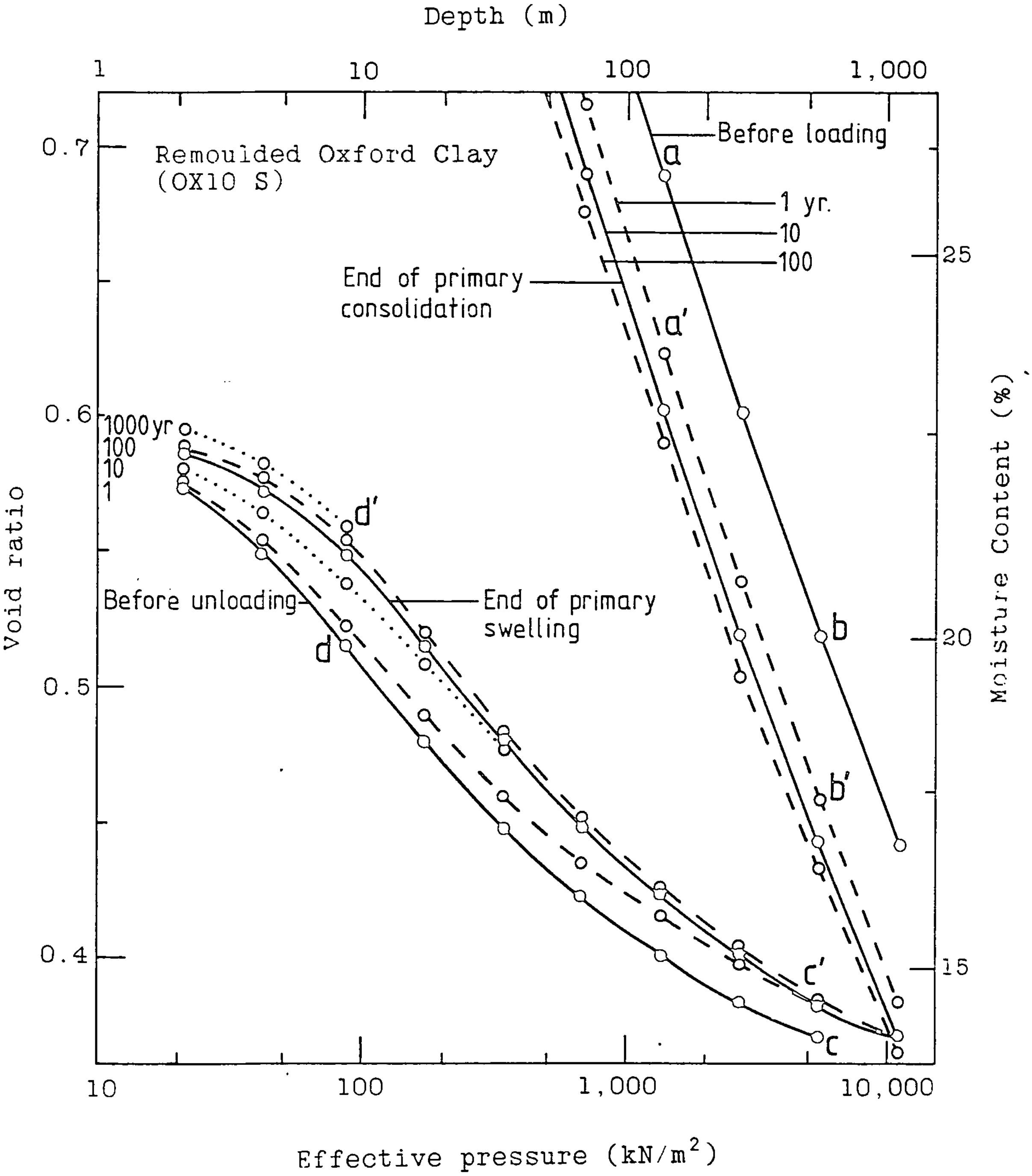
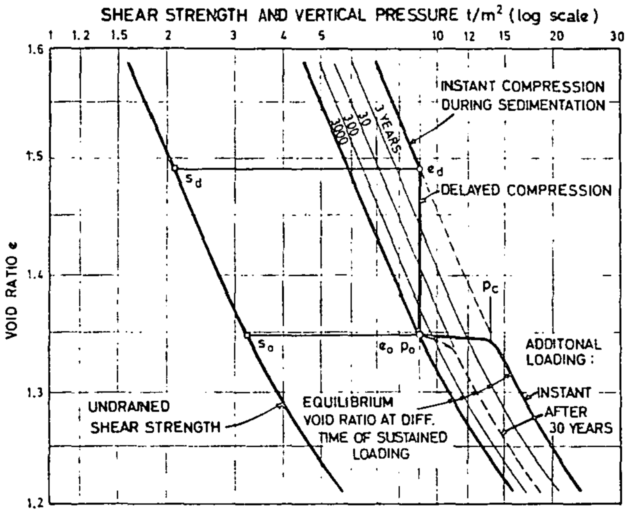


Fig. 4-12 Geological history of normally consolidated clays (after Bjerrum, 1967a)



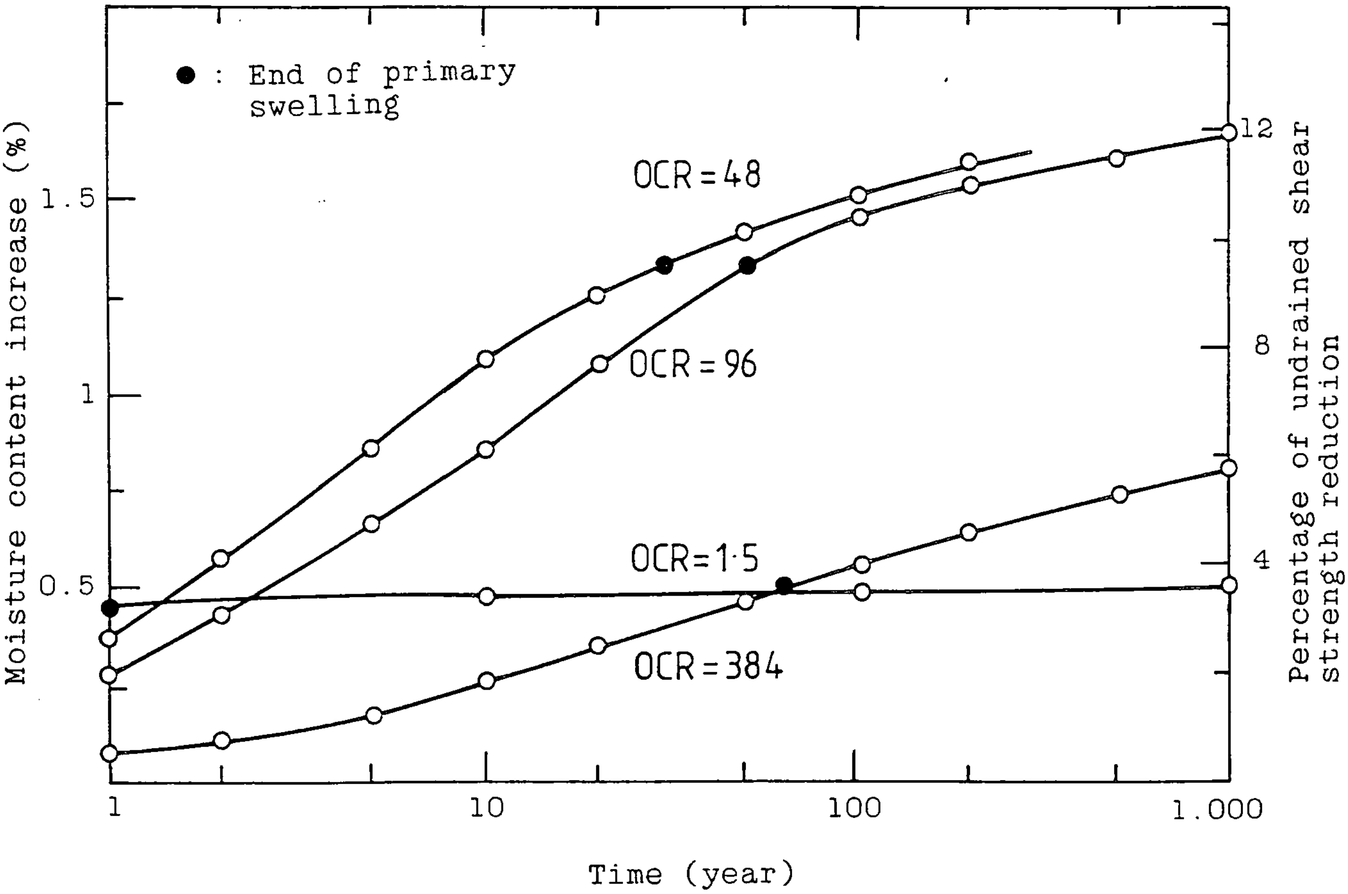
100 to 1,000 years. This figure can be considered as a miniature of the geological history of Bearpaw Shale in Fig. 1-8.

Mudrocks of lower plasticity, like the Lias clay and Flockton mudstone investigated, have a less absolute amount of secondary swelling because of smaller primary swelling and so the softening effect is less, even though the ratio of secondary to primary swelling can be quite large at high overconsolidation ratios. Heavily-overconsolidated clays of high plasticity, but with weak diagenetic bonds, like the two London Clay specimens, can exhibit a long swelling process, owing to their very small coefficients of swelling (0.03 to 0.06 m^2/yr. at OCR=96, compared to the coefficients of consolidation, 0.16 to 0.32 m^2/yr. at OCR=1). Because of greater swelling indices the amount of secondary swelling can be very high. Meanwhile, the development of secondary swelling is even slower. This is best illustrated by an example (Remoulded Oxford Clay OX10-S) in Fig. 4-13, which shows the increase in moisture content with time. The most significant increase occurs at high OCR (for instance, *c.* 1.2% increase from 1 to 100 years at OCR=48); whilst at a very high OCR value of 384 there is only an increase of *c.* 0.5% from 1 to 100 years. In terms of percentage of undrained shear strength reduction, it is about 8 per cent from 1 to 100 years at OCR=48 or 96, but less than 4 per cent at OCR=384 and almost no reduction at OCR=1.5. The pressure decrement ratio is unity in this example. If a higher ratio (a common case in excavation) or more plastic clay is involved, the moisture content increase is certainly greater. That is to say, this kind of softening can be occurring over a very long period of time and, as a result, the considerable strength reduction involved will lead to failure of slopes or foundations. The opinion of Calabresi and Scarpelli (1985) is that swelling seems to contribute to the decrease in shear strength with time, from the peak to what is called

Fig. 4-13 An example of time influence on moisture content increase and strength reduction in swelling

Sample: Remoulded Oxford Clay (OX10-S)
P_c : 10,880 kN/m^2
Length of drainage= 1 m

The undrained shear strength is based on the data of Burland *et al.* (1978).
The calculation is given in Appendix C-3.



the fully-softened strength, through the reduction of true cohesion. It is true, nevertheless, that diagenetic bonds increase the coefficient of swelling and reduce the amount of primary and secondary swelling. Sensibly, the progressive softening of heavily-overconsolidated plastic clays or mudrocks is controlled by the combined effect of breakdown of diagenetic bonds and progressive swelling. The latter includes the dissipation of negative pore pressures and primary and secondary swelling in volume change.

The nature of diagenetic bonds has not been clear from the literature. Cementation is almost omni-present in sediments, and could be very effective in reducing swelling, such as in the Fuller's Earth investigated here. Mechanical adhesion due to large pressures in depth has also been suggested (for example, Bjerrum, 1967). This type of strong (quasi-metamorphic) bonding of clay minerals can be expected in the highly-indurated Lias Clay and Flockton mudstone (Section 3-2-2). Slaking may not be effective enough to destroy all of them (Section 3-6). The most well-known bonds in soil mechanics must be the 'solid bonds' of adsorbed water layers between clay particles by Terzaghi (1941). This water is very viscous so that there is a threshold value of shear force below which flow does not occur (Low, 1961). The gradual development of solid bonds can have a strong effect on consolidation by increasing the resistance of clay against further volume change for an increase in load. A quasi-pre-consolidation pressure has usually been observed to increase the actual previous maximum consolidation pressure (Leonards & Ramiah, 1960). If the pressure increment is large enough (say, 10), the bonds are very much less effective. The weak diagenetic bonds of the London and Oxford Clays might belong to this category. The last layer of adsorbed water is not driven off until 6,000 to 10,000 m in depth (Section 1-4-1), which is greater than what all the samples have experienced. Therefore, this type of bond would also exist in other undisturbed samples. Though most of the natural diagenetic bonds were destroyed by slaking the sample tested, the solid bonds of adsorbed water layers would be generated in the remoulded samples during secondary consolidation (Leonards & Ramiah, 1960). In the remoulded Oxford Clay (OX10-S) with sustained consolidation and swelling, this kind of bonding effect is considered to be well confirmed by its decreased compression and swelling indices and greater coefficients of consolidation and swelling due to the gradual breakdown of bonds. So a delayed swelling can develop, according to Mitchell's (1976) opinion. However, the time period (24 hours) of each loading step in the remoulded samples is insignificant relative to the geological time scale to which undisturbed mudrocks are subject.

4-8 Summary

1. Seven undisturbed samples and their remoulded counterparts were tested in the modified oedometers with a maximum pressure of 24,280 or 34,340 kN/m^2 under one-dimensional consolidation-swelling conditions.
2. The pre-consolidation pressures of the samples were estimated, ranging from 2.400 to 50,000 kN/m^2. The *in situ* overconsolidation ratios (OCR) also show considerable variation.
3. The coefficients of consolidation and the compression indices of remoulded samples under normal consolidation conditions are closely related to their liquid limits. The undisturbed samples have higher coefficients of consolidation and smaller compression indices in comparison with remoulded types. The Fuller's Earth is an exception, having a greater average compression index, probably because of its highly open and cemented, but easily-destroyed,

structure in the undisturbed condition.

4. All the measured swelling rate curves were analysed, using the square root of time fitting method, and compared with Terzaghi's theoretical curve on a swelling percentage versus logarithm of time factor plot. In general, Terzaghi's theory of swelling approximately predicts the shape of swelling rate curves. The swelling of more plastic samples tends to fit better to the theory. Swelling proceeds faster at low OCR than is predicted by the Terzaghi theory, but is slower at high OCR, probably due to the prominence of secondary swelling.
5. The difference between measured swelling rate curves and Terzaghi's is more clearly illustrated by comparing the two coefficients of swelling computed from 50 and 90 per cent primary swelling. The swelling process of Fuller's Earth approaches Terzaghi's curve at low OCR (c. 6 to 10), those of Lias Clay and Flockton mudstone do at OCR values higher than 100. Other samples lie between these two extremes.
6. The coefficients of swelling of the samples consistently decrease with increasing OCR, and become much smaller than the coefficients of consolidation at high OCR values. The undisturbed samples invariably have greater coefficients of swelling at high OCR than their remoulded counterparts.
7. The coefficient of swelling is also a function of plasticity - a smaller coefficient of swelling being found at a higher liquid limit (under similar OCR values).
8. Secondary swelling proceeds like secondary consolidation after 100 per cent primary swelling, but its amount, expressed as secondary swelling index or in terms of strain, increases with OCR and reaches an almost constant value at high OCR. The ratio of secondary to primary swelling, or secondary swelling to swelling

index, also increases with OCR, but does not show any signs of having attained a maximum value. This results in some swelling rate curves having no inflection point on the semi-logarithm plot.

9. Swelling index increases with OCR immediately after consolidation, then remains fairly constant within a given pressure range, and then decreases until the minimum pressure during unloading. Swelling index is also influenced by pre-consolidation pressure in remoulded samples. This could be associated with the change in fabric.
10. A linear relationship between swelling index and liquid limit is found (C_s = 0.0016 L.L.) for five remoulded samples. The Fuller's Earth is the exception, exhibiting a wide range of larger swelling indices at three different pre-consolidation pressures. The swelling and consolidation processes are sensitive to testing conditions. Sustained secondary swelling and consolidation cause a decrease in the swelling and compression indices and increase the coefficients of swelling and consolidation in one remoulded sample (OX10-S).
11. The undisturbed samples have smaller swelling indices than the remoulded, due to their diagenetic bonding. Based on the ratios of undisturbed to remoulded swelling index and also the relative order of undisturbed and remoulded compression curves, the undisturbed samples can be placed, according to their strength of diagenetic bonds. in an order of:

    Fuller's Earth > Flockton mudstone & Lias Clay ≫ (Oxford Clays > London Clays)

    The strong bonds in the Fuller's Earth are of the nature of a cement (probably carbonate) and are very vulnerable to compressive strain.
12. The ratio of swelling to compression index, C_s/C_c, is used to

represent the strain percentage recovered in the consolidation -swelling test. The C_s/C_c ratios of the remoulded samples range from 0.22 to 0.38; no consistent relationship is found between C_s/C_c and plasticity. The analysis, based on this parameter, confirms the order of strength of diagenetic bonds, judged from other evidences.

13. Swelling is principally of a progressive nature in heavily-overconsolidated clays and mudrocks, regardless of their plasticity and diagenetic bonds. Progressive failure in these rocks can be ascribed to the combined effects of prolonged primary swelling process (including pore pressure dissipation and moisture content increase) with prominent secondary swelling, together with the breakdown of diagenetic bonds.
14. The diagenetic bonds are suspected to be due to: (a) carbonate-cementing, (b) mechanical adhesion and (c) viscous adsorbed-water-layers between clay particles.

CHAPTER 5 SWELLING PRESSURE AND PHYSICO-CHEMICAL SWELLING

As reviewed in the first chapter, swelling is conventionally analysed by means of either a mechanical or physico-chemical model (Section 1-6). The former has been discussed in the fourth chapter. The latter model is included in this chapter.

Experiments were carried out to evaluate the effect of pore water concentration on swelling pressure and degree of swelling in the undisturbed samples, using a specially-designed swell cell. Remoulded Fuller's Earth was transformed into a Na-form for consolidation-swelling test considerations, in order to investigate the effect of this monovalent cation on swelling. The modified oedometers (see Chapter 4) were also used to test some undisturbed and remoulded samples with a non-polar liquid, n-decane, as pore fluid, *i.e.* to inhibit osmotic swelling.

The results of swelling pressure measurements are discussed first, by considering the physico-chemical model and the stress release concept. Examination is then made of the influence of physico-chemical force on effective stress and the application of double-layer theory in swelling. Finally, the replacing effect of n-decane on void ratio and swelling is presented.

5-1 Double-layer Theory

The influencing factors and general assumptions in the double-layer theory have been discussed in Section 1-6. A convenient formulation of the theory was given by Bolt (1956) as follows (Figs. 5-1 & 1-9):

$$v\ (\beta C_o)^{1/2}\ (x_o+d) = 2\ (C_o/C_c)^{1/2} \circ \int_{\phi=0}^{\pi/2} \left(d\phi/(1-(C_o/C_c)^2\ \mathrm{Sin}^2\phi)^{1/2}\right) \qquad \text{------} \qquad 5\text{-}1$$

where v = the cation valence,

β = $8\pi F^2/1000\varepsilon RT$, about 10^{15}cm/mmole for water at 20°C (F= Faraday's constant, ε= dielectric constant of pore fluid, R= gas constant, T= temperature in Kelvins),

d = half the distance between clay platelets,

x_o= the distance between clay surface and imaginary plane at which potential becomes infinity,

= $4/v\beta\Gamma$ (Γ: surface charge density of clay in milli-equivalent/cm^2), being approximately 1/vÅ for illite, 2/vÅ for kaolinite, 4/vÅ for smectite),

C_o= concentration in the pore fluid in mmole/cm^3,

C_c= cation concentration in the midplane between clay platelets.

ϕ = the electric potential.

Swelling pressure is governed by the Van't Hoff equation:

$$P_s = 2\,n\,K\,T\,(\text{Cosh } u - 1) \quad \text{------------------------------} \tag{5-2}$$

in which P_s= swelling pressure,

n = molar concentration of ions in pore fluid,

K = Boltzmann constant,

T = temperature in Kelvins,

u = the midplane potential function.

Equation 5-2 can be expressed in terms of midplane cation and pore fluid concentrations as follows (Bolt, 1956):

$$P_s = R\,T\,C_o\,(C_c/C_o + C_o/C_c - 2) \quad \text{------------------------} \tag{5-3}$$

In practice, it is necessary to express d by means of the following equation:

$$e = r_w\,G_s\,A_s\,d \quad \text{--} \tag{5-4}$$

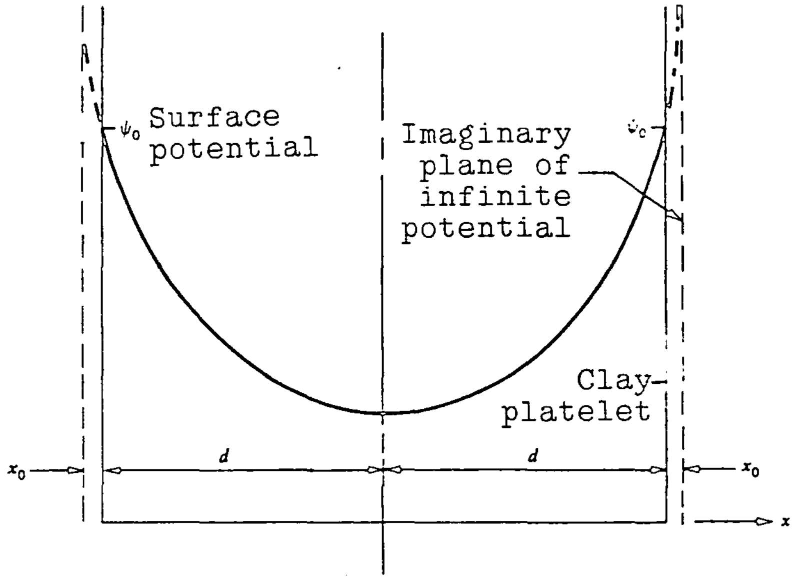
where e = the void ratio of the clay,

r_w= the unit weight of the pore fluid,

G_s= the specific gravity of the clay,

A_s= the surface area of the clay.

Fig. 5-1 Potential distribution for interacting double-layers from parallel clay platelets (after Mitchell. 1976)



To calculate theoretical curves of void ratio versus pressure, combinations of $v(\beta C_o)^{1/2}$ (x_o+d) and $\log(P_s/RTC_o)$ that satisfy Equations 5-1 and -3 have been tabulated by Bolt (1956).

Sridharan and Jayadeva (1982) show that according to Equation 5-1, half the distance between clay platelets and the dielectric constant are related for two pore fluids by:

$$d_1/\varepsilon_1^{1/2} = d_2/\varepsilon_2^{1/2} \quad\text{------------------------------------} \quad 5\text{-}5$$

5-2 Effective Stress Concept

The effective stress concept, proposed by Terzaghi in 1923, is one of the most essential in soil mechanics. The effective stress (σ') is equal to the total stress (σ) minus the pore pressure (u):

$$\sigma' = \sigma - u \quad\text{--} \quad 5\text{-}6$$

It is the effective stress that governs the behaviour of soils, notably compression and strength. Equation 5-6 ignores both repulsive and attractive forces of an electrical nature in clays. The repulsive force between clay platelets is primarily attributed to the interaction between double-layers (Fig. 5-1), described in the previous section. The principal contribution to the attractive force comes from van der Waals' force, although many other forces have been suggested (van Olphen, 1963a). Attractive forces are relatively small in comparison with the repulsive force within the range of external loadings involved in the field and the laboratory tests. Sridharan and Venkatappa Rao (1973) combined all those forces and extended the conventional effective stress as follows:

$$\sigma' = \sigma - u_w - u_a - R + A \quad\text{--------------------------------} \quad 5\text{-}7$$

where σ' = effective stress,

σ = total stress,

u_w = pore water pressure,

u_a = pore air pressure,

R,A= total interparticle repulsion, attractive forces divided by total interparticle area.

If the soil is fully saturated, Equation 5-7 can be simplified as:

$$\sigma' = \sigma - u - (R-A) \qquad \text{5-8}$$

in which R-A represents the component of the effective stress associated with physico-chemical influence. It is to be noted that when R-A is negligible, for example, in sands, the conventional and the extended effective stresses are the same. For clays and mudrocks, as demonstrated by Morgenstern and Balasubramonian (1980), R-A could be approximated theoretically from the double-layer theory using the equations in the previous section.

5-3 Swelling Pressure

5-3-1 Experimental Methods

Several different approaches have long been adopted in the measurement of swelling pressure. For unsaturated samples, the osmotic pressure measurement can be combined with the conventional oedometer test (Kassiff & Ben-Shalom, 1971). For saturated samples, swelling pressure measurements can be grouped into (a) by oedometers, and (b) by triaxial cells. Conventional and modified oedometers with a one-dimensional condition have been used by most investigators (Skempton, 1961; Kassiff & Baker, 1969; Agarwal & Sharma, 1973; Madsen, 1979; Morgenstern & Balasubramonian, 1980), and are also recommended by the International Society for Rock Mechanics (1979). Franklin (1984) used a so-called 'ring swell cell', but with undefined lateral expansion. Skempton (1961) measured the excess pore pressure, equivalent to the swelling pressure, of the samples in a triaxial cell under a constant cell pressure with no volume change.

Yong and Warkentin (1975) comment that 'the dependence of swelling pressure on volume change makes a precise measurement of swelling pressure difficult'. They considered that an ordinary oedometer allowed too much volume expansion and underestimated the swelling pressure at any void ratio. In order to reduce the necessary volume expansion in the measurement of swelling pressure, a rigid swell cell was manufactured with a semi-rigid load cell (Appendix C-2-1). The inevitable vertical displacement was found to be not more than 0.01 mm, which is comparable with that of Madsen's (1979) cell. The measuring procedure is given in Appendix C-2-2. All of the swelling pressures reached the maximum within about 10 hours, as shown in Fig. 5-2. The same phenomenon was also found by Borgesson (1985). This kind of measurement was not done on the Lias Clay and Flockton mudstone, since they were too brittle to be fitted into the swell cell. Swelling pressures were also measured in the modified oedometers at the beginning of consolidation-swelling tests (Appendix C-1-2). Half the estimated effective overburden pressure was applied in the tests before water was poured into the cells (Appendices C-1-2(b) & C-2). Pile (1980) also used this procedure in the measurement of swelling pressure. The reason for this is to reduce the effect of any possible disturbance in the preparation of the specimens, particularly on the surfaces, due to the brittle character of the samples. This is also an indication of the difficulty of determining swelling pressure. In other words, the accuracy of this kind of measurement depends very much on the technique used in the sample preparation.

All the swelling pressures, measured in the swell cell and oedometers, are presented in Table 5-1. It is noted that the swelling pressures measured in the modified oedometers are 0 to 50 per cent less than in the swell cell. This verifies that the swell cell is more suitable in the measurement of swelling pressure.

Fig. 5-2 Development of swelling pressures in the swell cell (with the distilled water bath)

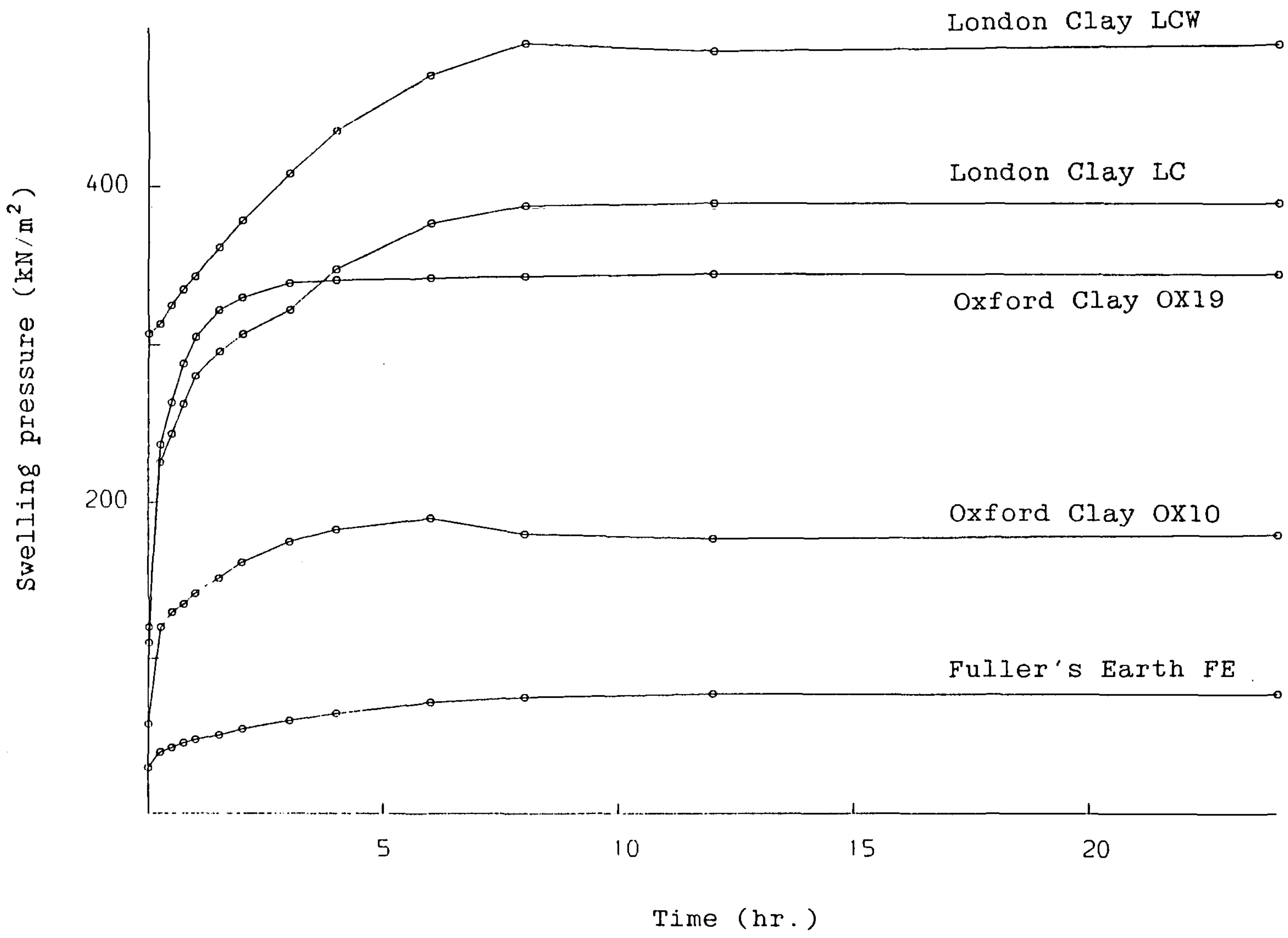


Table 5-1 Swelling pressures (P_s, kN/m^2) and K values of the samples

Sample	Overburden pressure * (kN/m^2)	P_s (by the swell cell) distilled water	Pore water	P_s (by the modified oedometer)
London Clay (LC)	191-250	390 K=1.8-2.6	393 K=1.9-2.6	204
London Clay (LCW)	573-763	489 K=0.5-0.8	472 K=0.4-0.7	361
Fuller's (FE) Earth	49-65	77.5 K=1.5-2.3	75.5 K=1.3-1.9	76.5
Oxford Clay (OX10)	98-134	180 K=1.5-2.3	182 K=1.5-2.3	173
Oxford Clay (OX19)	186-250	345 K=1.6-2.3	347 K=1.6-2.3	314
Lias Clay (LI)	615-807	--	--	1020 K=1.4-2.0
Flockton (FM) mudstone	4830-6320	--	--	3620 K=0.4-0.6

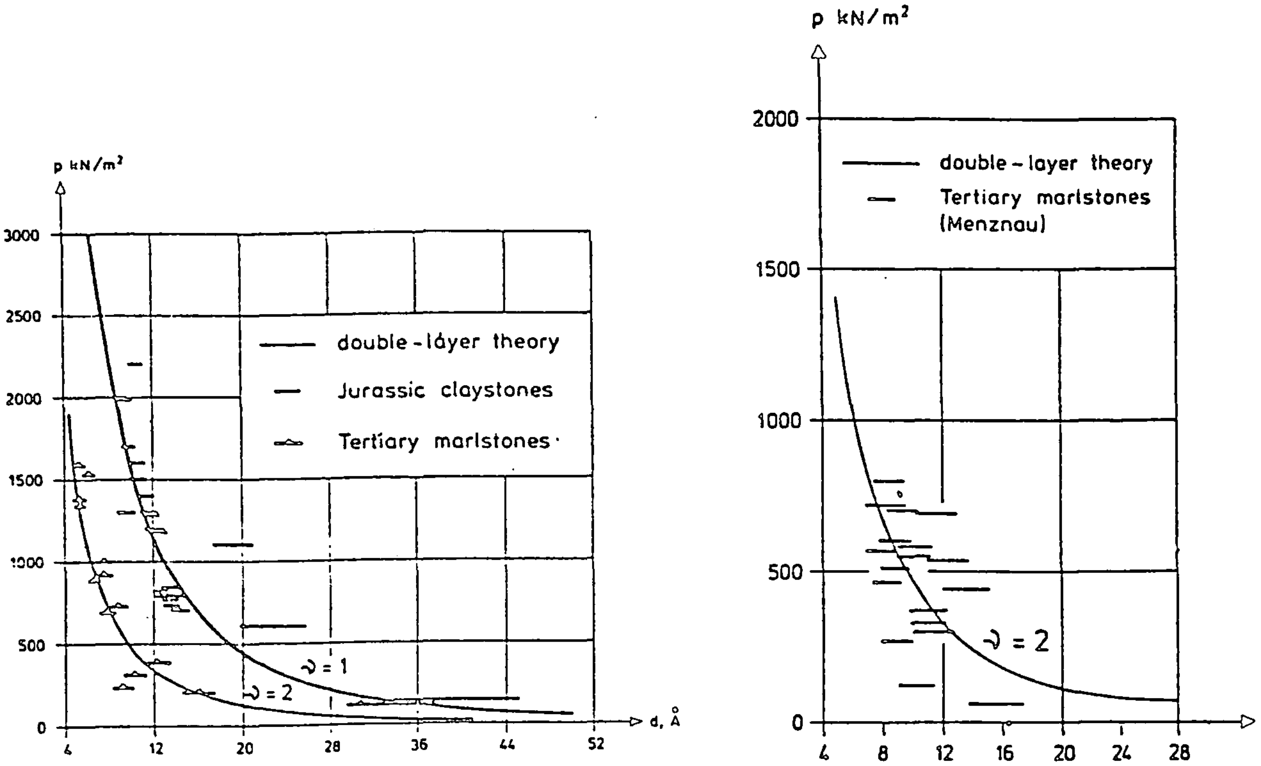
* Based on a submerged unit weight, 9.81-12.8 kN/m^2/m.

5-3-2 Swelling Pressure and Physico-chemical Force

According to the double-layer theory, swelling pressure is related to the moisture content or void ratio by Equations 5-1 to -4. Madsen (1979) found that the swelling pressures measured in mudrocks agreed well with what the theory predicted (Fig. 5-3). In this study, however, the question of double-layer (or osmotic) swelling is envisaged in a different way from Madsen because of the following reasons.

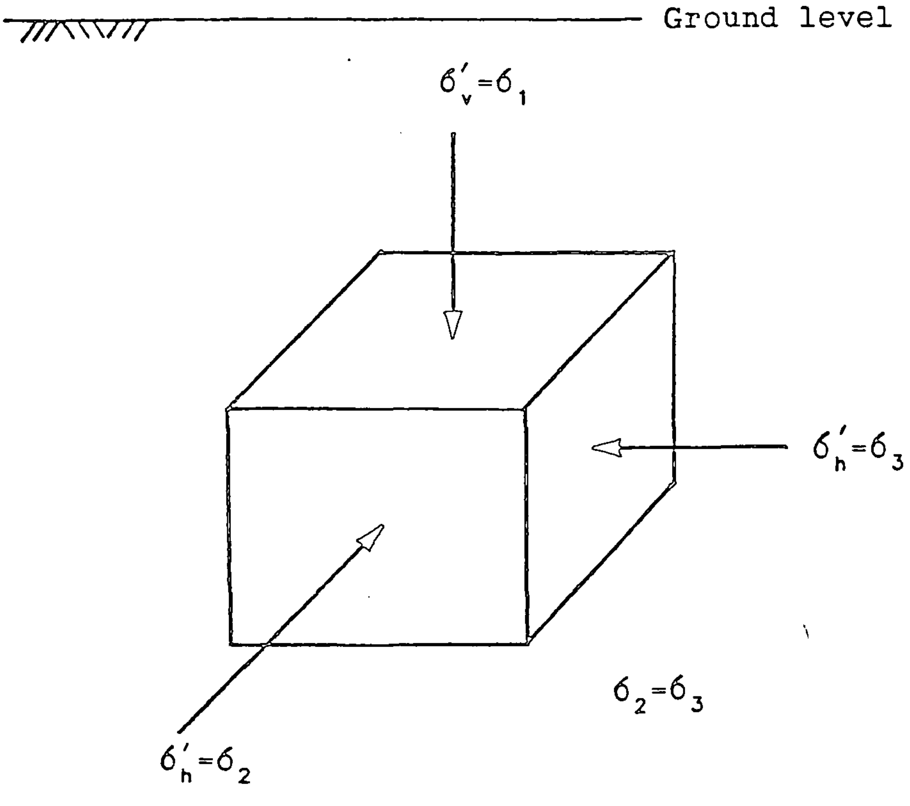
In Equation 5-4 it is assumed that particles are of infinite extent and are equidistant throughout the sample. As found in the analysis of pore size distribution (Section 3-3), the pore sizes of the samples range widely from less than 37.5 Å to over 10,000 Å in radius. However, the actual extent of double-layer influence is normally limited up to *c.* 400 Å. Meanwhile an overall non-parallel orientation exists in most of the samples (Sections 3-4 & 3-5), except in tactoids (Section 1-4-4) and this should limit osmotic swelling (Yong & Warkentin, 1975). Even in the undisturbed Lias Clay and Flockton mudstone of the highest preferred orientation, undulating alignment of clay minerals dominates the fabric. Thin smectite particles in the Fuller's Earth appear to be curved, differing from the ideal condition. Defects on clay surfaces also exist, for example, the terraced surface postulated for illite by Bolt and Miller (1955). As a result of these, an estimate of the actual distance between clay minerals would seem to be impractical. At best, an 'effective' half spacing, d, between clay surfaces (Fig. 5-1) can be implied by Equation 5-4. In addition the intracrystalline space in expandable clay minerals becomes a fixed distance in the case of divalent exchangeable cations, *i.e.* the water adsorbed is of fixed volume. The term 'dead volume' has usually been used to describe that space not affected by the double-

Fig. 5-3 Madsen's (1979) measured and calculated swelling pressures as a function of the half spacing (d) between clay platelets



Note: ν = valence.

Fig. 5-4 Diagram of stress in the ground



layer repulsive force (*e.g.* Yong & Warkentin, 1975). The concept of dead volume has been applied in the estimation of volume change with pressure by Klausner and Shainberg (1971) and Nagaraj and Srinivasa Murthy (1986a,b). The nature of the naturally occurring exchangeable cations implies that only some intracrystalline swelling should occur in the samples studied (Sections 2-5 & 2-6). For this reason external surface areas were measured (Section 3-2), instead of total surface areas. This can then be applied in Equation 5-4 as the 'effective' surface area so as to obtain the equivalent 'effective' void ratio.

From the swelling pressures listed in Table 5-1, the half spacings between clay surfaces were calculated according to Equations 5-1 and 5-3 and are expressed as x_o+d in Table 5-2. Also given are the effective void ratios, derived according to Equation 5-4, using the average external surface areas in Table 3-1. The measured void ratios given in Tables C-1 and C-3 are also quoted, together with the calculated equivalent 'average' half spacings, based on the total surface areas in Table 3-1. The difference between effective and measured void ratios is displayed as dead volume in percentage of measured void ratio in Table 5-2. Part of the intracrystalline space in the samples studied is expandable because monovalent exchangeable cations are also present (Sections 2-5 & 2-6). However, no allowance can be given for these in the dead volume calculations.

It is demonstrated in Table 5-2 that the x_o+d values from the swelling pressures measured in the oedometers (designated as OD) are the highest and their equivalent dead volumes are smaller than the other test results, simply because of their lower swelling pressures (Table 5-1). The x_o+d values calculated from swelling pressures range from 8 to 43 Å. A d value less than 10 Å would seem illogical, because this would entail squeezing water from the strongly bonded

Table 5-2 Effective half spacings (d) and void ratios and dead volumes of the undisturbed samples

Sample		x_o+d (Å)	Effective void ratio	Measured void ratio	Average d (Å)	Dead volume(%)
London Clay (LC)	SC-D*	17	0.268	0.706	25	62
	SC-P	12	0.189	0.706	25	73
	OD	21	0.332	0.709	26	53
London Clay (LCW)	SC-D	20	0.301	0.741	20	59
	SC-P	17	0.256	0.741	20	65
	OD	22	0.332	0.756	21	56
Fuller's Earth (FE)	SC-D	31	0.908	2.400	43	62
	SC-P	33	0.967	2.400	43	60
	OD	43	1.260	2.401	43	48
Oxford Clay (OX10)	SC-D	32	0.490	0.542	23	10
	SC-P	32	0.490	0.542	23	10
	OD	33	0.505	0.551	24	8
Oxford Clay (OX19)	SC-D	22	0.328	0.623	28	47
	SC-P	22	0.328	0.623	28	47
	OD	26	0.387	0.644	29	40
Lias Clay (LI)	OD	15	0.076	0.332	39	73
Flockton mudstone(FM)	OD	8	0.024	0.125	11	81

* SC: Test in the swell cell.
D: With distilled water bath.
P: With reconstituted pore water bath.
OD: Test in the modified oedometer.

layer (Fig. 1-9) adjacent to the mineral face. Water from this 10 Å wide film (3 molecules) can only be removed at room temperature by a pressure greater than 120 MN/m^2 (van Olphen, 1963b). The average d values calculated from the total void ratios range from 11 to 43 Å. All of these x_o+d and average d values are beyond or close to the smallest pore entrance radius (37.5 Å) in the pore size analysis (Section 3-3). Judging from the pore size distributions in the samples (Figs. 3-3-1 to -7), the effective half spacings of the samples seem to be only of a small proportion.

Except in the Oxford Clay (OX10), the calculated dead volumes range from 40 to 81 per cent. The highest values belong to the Lias Clay and Flockton mudstone, even when based on oedometer swelling pressures. There is a contradiction between the two Oxford Clay samples. The specimens from OX10 have a much lower dead volume than OX19, even when allowing for similar mineralogical and chemical compositions, plasticity, moisture contents and fabrics (Chapters 2 & 3). Since a lower swelling pressure was measured in OX10, a higher x_o+d value and a lower dead volume is calculated. This may indicate that the swelling pressures measured in the samples studied are a function not only of moisture content or void ratio, as could be expected in the double-layer theory, but also of the *in situ* stress condition, as discussed in the next section.

5-3-3 **Relation between Swelling Pressure and *in situ* Stress**

Swelling pressure can be envisaged as an indication of the *in situ* stress condition. During the sampling operation a sample has been subjected to stress release which sets up a negative pore pressure. The magnitude of this can be formulated as follows (G.N. Smith, 1978):

$$\Delta u = -(\sigma'_h + A(\sigma'_v - \sigma'_h)) \qquad K = \sigma'_h/\sigma'_v$$

$$= -\sigma'_v\,(K + A(1-K))$$

or $$= -\sigma'_v\,(A + K(1-A)) \qquad \text{5-9}$$

in which Δu is the negative pore water (suction) pressure, σ'_v and σ'_h are *in situ* effective vertical and horizontal stresses, A is Skempton's pore pressure parameter and K the stress ratio of σ'_h to σ'_v. K is not the rock mechanics convention of total stress. It is the soil mechanics convention and therefore effective stress. Under one-dimensional conditions the stress ratio is customarily expressed as K_o. For an ideal elastic material A equals 0.33 and for clays it varies between -0.1 and 0.3 (Broms, 1980). Since A and 1-A are usually greater than zero, Δu is less than σ'_v if K is less than unity (for normally consolidated and slightly overconsolidated clays). It is greater than σ'_v if K is greater than unity (for heavily overconsolidated clays). Skempton and Sowa (1963) found that overconsolidated clays (OCR=2.1 to 13.8) behaved almost exactly as an elastic material with A=0.3. For heavily overconsolidated clays, therefore, Equation 5-8 will then become:

$$\Delta u = -\sigma'_v\,(1+2K)/3$$

or $$= -(\sigma'_v + 2\sigma'_h)/3 \qquad \text{5-10}$$

That is, the absolute value of the negative pore pressure is equal to the average *in situ* effective stress (Fig. 5-4).

In the measurement of swelling pressure by the writer, the horizontal confining pressure was not measured, so values of K are unknown. Theoretically, samples have a K value of unity after sampling, confirmed by Skempton and Sowa (1963). During the one-dimensional swelling tests, Kassiff and Baker (1969) found an average K_o value of 1.0, ranging from 0.72 to 1.15, in compacted soils. If this (K_o=1) also applies to the tests in this project, then the measured vertical pressure with no volume change is equal to the absolute value of the excess negative pore pressure and also the swelling pressure, according to Equation 5-9.

The K values of samples, calculated from swelling pressure according to Equation 5-10, are presented in Table 5-1. The effective vertical stress (or overburden pressure) is estimated by assuming an average submerged unit weight of 9.81 to 12.8 kN/m^2. It is shown in Table 5-1 that the London (LC), Oxford and Lias clays and Fuller's Earth may all have K values greater than unity, as indicated by their high overconsolidation ratios (Table 4-1). The K values of London Clay (LCW) and Flockton mudstone are considerably less than unity, which conforms with their low overconsolidation ratios (Table 4-1).

Mechanical disturbance or moisture loss or gain during sampling, transportation and preparation for tests cannot be ignored in the evaluation of swelling pressure. The ratio of the measured swelling pressure to the ideal one, which is deduced from Equation 5-8 or 5-9, has been used to assess the degree of disturbance (Broms, 1980). Mechanical disturbance and moisture gain tend to decrease the swelling pressure measured and the reverse is true for moisture loss. The low K value for London Clay (LCW) could be due partly to a moisture gain when it was recovered from depth (Section 2-1). A mechanical disturbance during preparation for the test most likely occurred in Flockton mudstone specimens because of their brittle nature (Appendix C-1-2).

5-4 Effect of Pore Water Chemistry on Swelling

5-4-1 Experimental Methods

The remoulded Fuller's Earth was transformed to a Na-saturated form and tested in the modified oedometer. The procedure is given in Appendix C-1-2(f). The purpose of this test is to investigate the influence of exchangeable cation species on the swelling properties of Fuller's Earth.

The swell cell, designed to measure swelling pressure, was also used to measure swelling amounts of undisturbed samples in a strain-controlled condition. The procedure is given in Appendix C-2-2. The pore waters used in the samples (the chemical compositions of which were found by the squeezing method in Section 2-6) were reconstituted using chloride salts. All the cell water compositions were analysed after testing and are given in Table C-4.

5-4-2 Swelling of Na-saturated Fuller's Earth

The consolidation-swelling testing result of Na-saturated Fuller's Earth is given in Table C-1-8. Its compression index, C_c= 2.93, and swelling indices, C_s=1.35 when P_c=2,720 kN/m^2 and C_s=1.52 when P_c=10,880 kN/m^2, are very high. The recovered strain ratios, C_s/C_c, are about 0.5, greater than those of all the other samples in Table 4-8. Bolt (1956) considers that C_s/C_c is indicative of the relative importance of the physico-chemical swelling forces in soils. The greater the C_s/C_c value, the more important the physico-chemical swelling. It is implied, therefore, that the swelling of Na-saturated Fuller's Earth is closer to the physico-chemical model. This agrees with the general conclusion made in the literature (*e.g.* Mitchell, 1973). Nevertheless, a C_s/C_c value of 0.5 is still far away from unity, a value which a pure, fine clay and other colloids should have theoretically (Bolt, 1956). Unrecovered strain during a consolidation-swelling test appears to be an indicator of dead volume, since the double-layer theory predicts the same amount of compression and swelling. The recovered strain ratios of other samples in Table 4-8 are always much less than 0.5, probably an indication of the large dead volumes in Table 5-2.

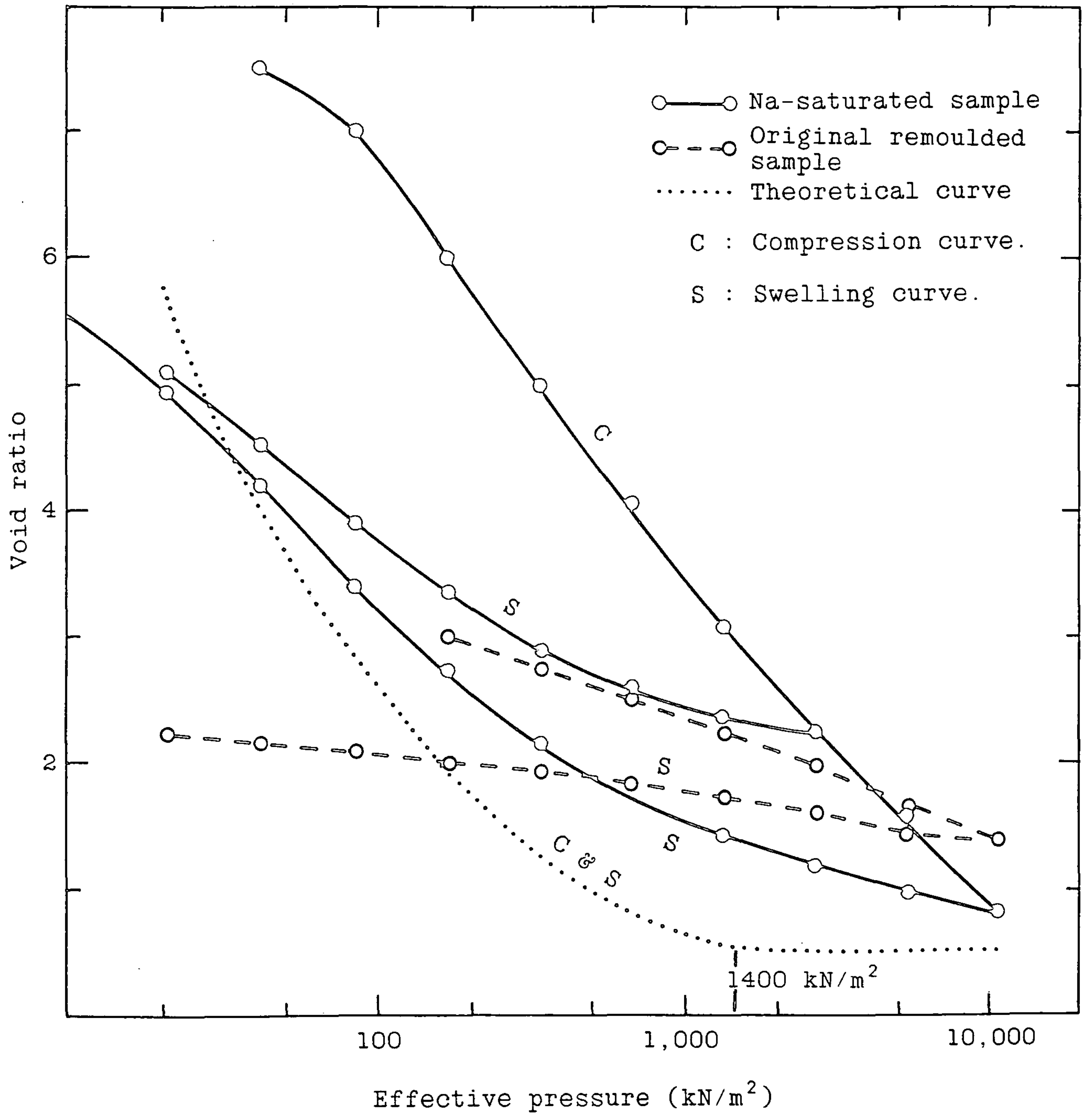
The compression and swelling curves of the Na-saturated Fuller's

Earth are shown in Fig. 5-5, together with those of the original remoulded sample for comparison. Also included is a theoretical curve for the Na-saturated Fuller's Earth with a total surface area of 200 m^2/g (Table 3-1). Half spacings, smaller than 10 Å at a pressure of c. 1,400 kN/m^2, equivalent to a void ratio of 0.55, should change little with pressure, as already postulated in Section 5-3-2. The deformation observed beyond 1,400 kN/m^2 cannot be explained by the double-layer theory. The measured compression curve and most of the swelling curve lie far above the theoretical one in Fig. 5-2, probably indicating the existence of a large dead volume. As discussed in Section 4-6, C_s would be greater if the effect of K_o is considered during unloading. Meanwhile, secondary swelling becomes significant at a high overconsolidation ratio (Section 4-5), but is not included in the C_s calculation. However, the double-layer theory does not differentiate secondary from primary swelling.

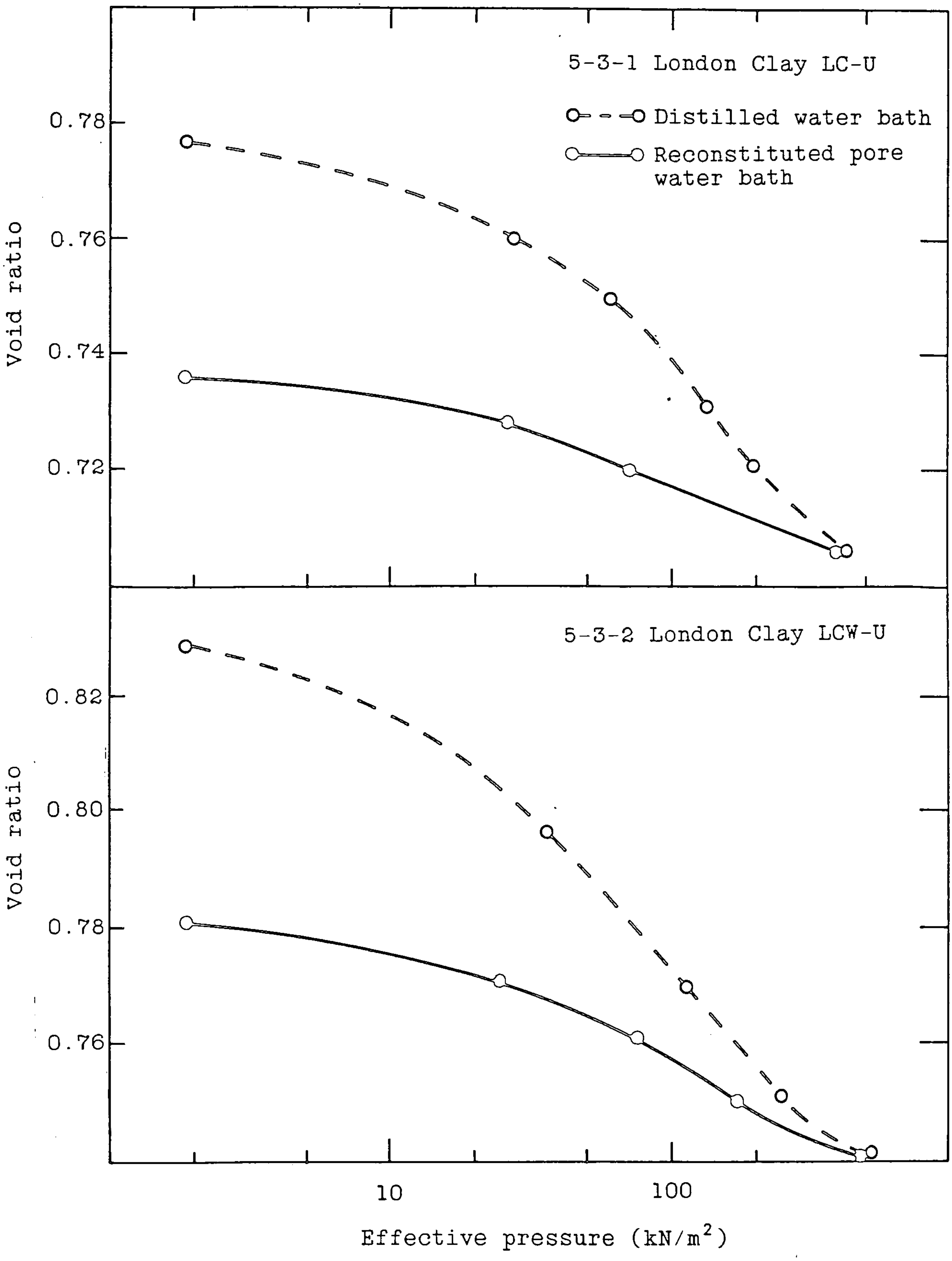
5-4-3 **Physico-chemical Forces in the Swell Cell**

The experimental results for five undisturbed samples tested in the swell cell are given in Table C-2. Their swelling curves are shown in Figs. 5-6-1 to -5. It is shown clearly that all the swelling amounts in the distilled water bath exceed those in the reconstituted pore water bath. This conforms qualitatively with the modified effective stress concept in which allowance is made for the repulsive force, R, (*i.e.* the physico-chemical component) (Section 5-2). The average swelling indices of the samples were calculated according to Equation 4-12 and are given in Table 5-3. It is shown that all the average swelling indices using the distilled water are greater than with reconstituted pore waters. Compared with those in Table 4-7, the average swelling indices obtained in the swell cell tests are always smaller, even if the cell water concentrations in

Fig. 5-5 Compression and swelling curves of the Na-saturated remoulded Fuller's Earth



Figs. 5-6-1 and 5-6-2 Swelling curves of the undisturbed London Clays in the swell cell



Figs. 5-6-3, -4 and -5 Swelling curves of the undisturbed Fuller's Earth and Oxford Clays in the swell cell

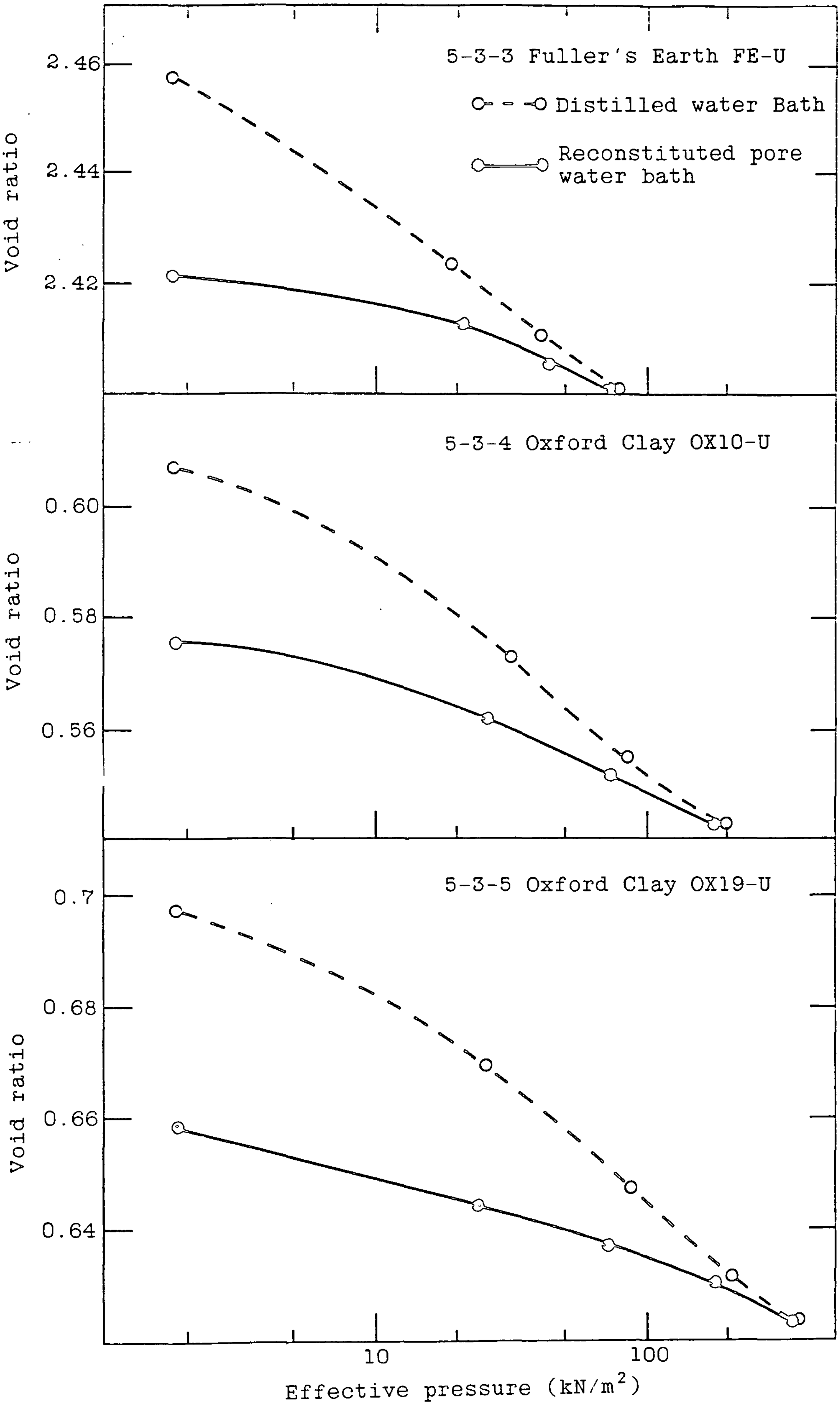


Table 5-3 Average swelling indices of the undisturbed samples in the swell cell

Sample		Swelling index * Distilled Water	Swelling index * Pore Water
London Clay	LC-U	0.030	0.013
London Clay	LCW-U	0.037	0.017
Fuller's Earth	FE-U	0.035	0.013
Oxford Clay	OX10-U	0.032	0.017
Oxford Clay	OX19-U	0.032	0.015

* Average value between swelling pressure and 1.86 kN/m^2, based on Equation 4-12.

Table 5-4 Physico-chemical forces (R-A, in kN/m^2) in the undisturbed samples

Sample	x_o+d * (Å)	R-A ** measured	R-A calculated
London Clay (LC)	16.9	19	270
	24.2	127	190
	28.8	117	128
	42.1	59.8	59.3
London Clay (LCW)	19.3	33	203
	26.4	84	242
	38.9	82	108
Fuller's Earth (FE)	30.3	3.9	6.1
	44.6	15.2	20.1
	61.5	0	4.9
Oxford Clay (OX10)	31.0	14	196
	44.4	29.4	85.4
	72.1	26.3	31.9
Oxford Clay (OX19)	21.0	20	367
	27.6	34	204
	40.6	72.3	87.3
	65.6	25.6	25.6

* Derived from the equivalent pressure in the test with distilled water bath.

** Measured at the equivalent pressure (Table C-3) which is based on the test with distilled water bath.

the modified oedometers and swell cell are generally similar (Table C-4). This is probably because the compressive pressures used were much smaller than the pre-consolidation pressures to which the samples had been subjected so the diagenetic bonds would be little disturbed, as discussed in detail in Section 4-6-3. As reviewed in Section 1-4-2, many mudrocks at depth are associated with water of high salinity, so the dilution which occurs due to the percolation of fresh water could increase swelling when mudrocks are exposed to near -surface.

In order to check whether the double-layer theory can quantitatively predict the magnitude of physico-chemical force difference, R-A, in the samples studied, a theoretical analysis is carried out below.

In the application of double-layer theory the most uncertain component is the half spacing, d, between clay platelets. Morgenstern and Balasubramonian (1980) derived the d values according to Equation 5-4, using external surface areas. The void ratios include the intracrystalline space in expandable clays, so total surface areas should be used instead. In this study, a different approach is adopted. A half spacing is calculated according to the double-layer theory for each pressure in the test with the distilled water bath. Then a pressure value is obtained at the same half spacing for the cation concentration in the reconstituted pore water bath. According to Equation 5-8, the pressure difference at the same half spacing or void ratio is the physico-chemical force, R-A, owing to the difference in pore water chemistry. An example of calculation is given in Appendix C-4. The results are given in Table 5-4, together with the measured values. It is clearly shown that the double-layer theory tends to overestimate R-A, especially at small half spacings, in the London and Oxford Clays. The difference can become negligible at greater spacings.

The pore size distributions, shown in Section 3-3-2, of four samples after the free swelling tests indicate that in comparison with the samples before testing, there is an increase in pore volume in the macro- (>1,000 Å in radius) and micro-pore (<200 Å) regions, but the increase is greater in the former. As the long-range repulsive force does not extend beyond *c*. 400 Å, the volume increase in the macro-pore region is most probably due to mechanical force, instead. All the calculated effective half spacings (Table 5-4) are smaller than, or close to, the experimental limit, 37.5 Å, in the pore size analysis (Section 3-3-1). Nevertheless, the existence of physico-chemical swelling is implied by the increase in micro-pore volume.

5-5 Effect of a Non-polar Liquid on Swelling

5-5-1 Experimental Method

In order to examine the physico-chemical effect, a non-polar organic liquid, n-decane ($CH_3(CH_2)_8CH_3$), was used to substitute for water in four remoulded samples. N-decane is relatively less volatile (boiling point=174°C) and has a negligible dielectric constant, 1.991 at 20°C (Weast, 1980). The total contents of n-decane and water, left in the specimens after the consolidation-swelling tests, were determined at 105°C as for the moisture contents. The moisture content was measured separately, using $CaCl_2$ to absorb water coming out from the sample at 105°C. The void ratios of the specimens were calculated according to the following equation:

$$e = (w_d\ G_s\ /\ 0.730) + (w\ G_s) \qquad \text{5-11}$$

in which w_d and w are the n-decane and water contents, respectively, 0.730 g/cm^3 the density of n-decane at 20°C and G_s the specific gravity of the solid. One consolidation-swelling test was done with

London Clay (LCW), mixing sample powders with n-decane (Appendix C-1-2(d)). It was found that the slurry appeared non-plastic and the resultant fabric would be quite different from that using water. Hence, another four tests were done, using slurries of sample powders and water. These slurries were first consolidated in the pore fluid squeezer and in the modified oedometers. After the sample was consolidated to 10,880 kN/m^2, the pore water was replaced by n-decane. This test was also done in the undisturbed London (LCW-U) and Oxford (OX10-U) Clays. The replacing method and all the other details are given in Appendix C-1-2(c,e). In the replacement, acetone was used as an intermediate agent, because acetone is highly volatile and miscible with water and the replacement becomes more efficient and complete. Acetone was also used for the same purpose by Sridharan and Venkatappa Rao (1973).

In the tests, a pressure decrement or increment ratio of two or more was used during reconsolidation or swelling because the measurement was not sensitive enough to determine the end of primary consolidation or swelling when the consolidation or swelling amount was small. During virgin consolidation, however, a pressure increment of unity was used, as applied in the tests for the remoulded samples in Chapter 4. Each pressure increment or decrement lasted for 24 hours or until the end of primary consolidation or swelling, the determination of which has been described in Section 4-4-1.

5-5-2 Experimental Result and Discussion

The experimental results are given in Table C-2. The resultant effect of the replacement by n-decane on the internal (or intracrystalline) spacing of the expandable clay minerals in the London Clay (LCW) and Fuller's Earth was checked by X-ray diffractometry (Section 2-3). It was found that the smectites after replacement still had the same structure as without replacement. The moisture contents left in the samples after replacement and testing range from 0.4 to 4.9 per cent (Table C-2). The highest value is for the Fuller's Earth, which has expandable smectite as the major constituent (Table 2-4).

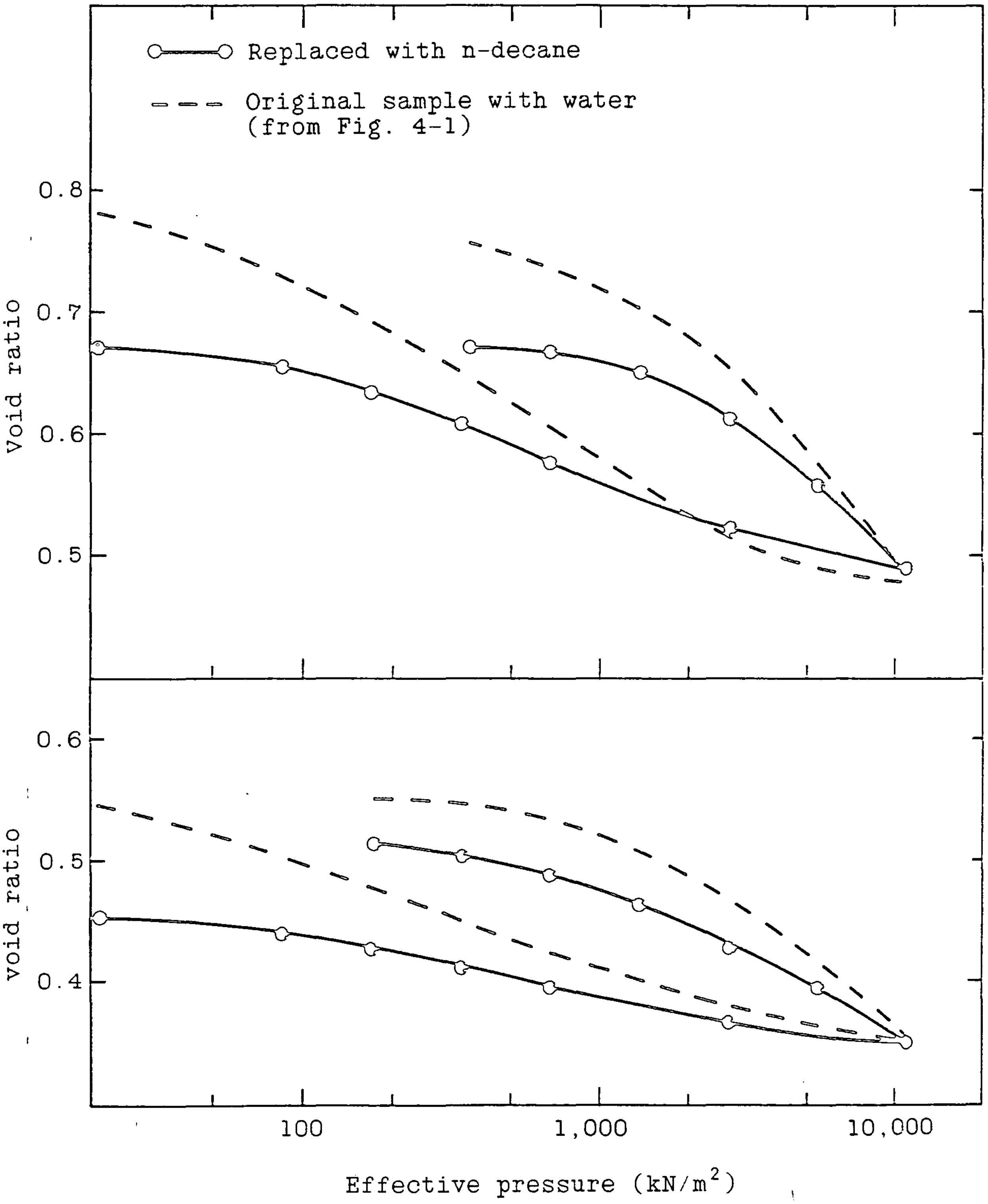
The compression and swelling curves of the undisturbed and remoulded samples are shown in Figs. 5-7-1 to -6. Also included in Figs. 5-7-1 and -2 are the compression and swelling curves of the original undisturbed London (LCW-U) and Oxford (OX10-U) Clays (from Figs. 4-1-2 & -4) for comparison. The compression curve of the London Clay (LCW-S), remoulded with n-decane, lies far above that with water (Fig. 5-7-3), indicating the unsuitability of this preparation technique.

All the recompression curves of remoulded samples immediately after the replacement of pore water by n-decane drop below the swelling curves before the replacement (Figs. 5-7-3 to -6). This is a proof of the collapse (or suppression) of double-layers. The same phenomenon is also shown by the undisturbed London and Oxford Clays in Figs. 5-7-1 and -2. No previous work has been conducted on undisturbed specimens in this way as far as the writer is aware.

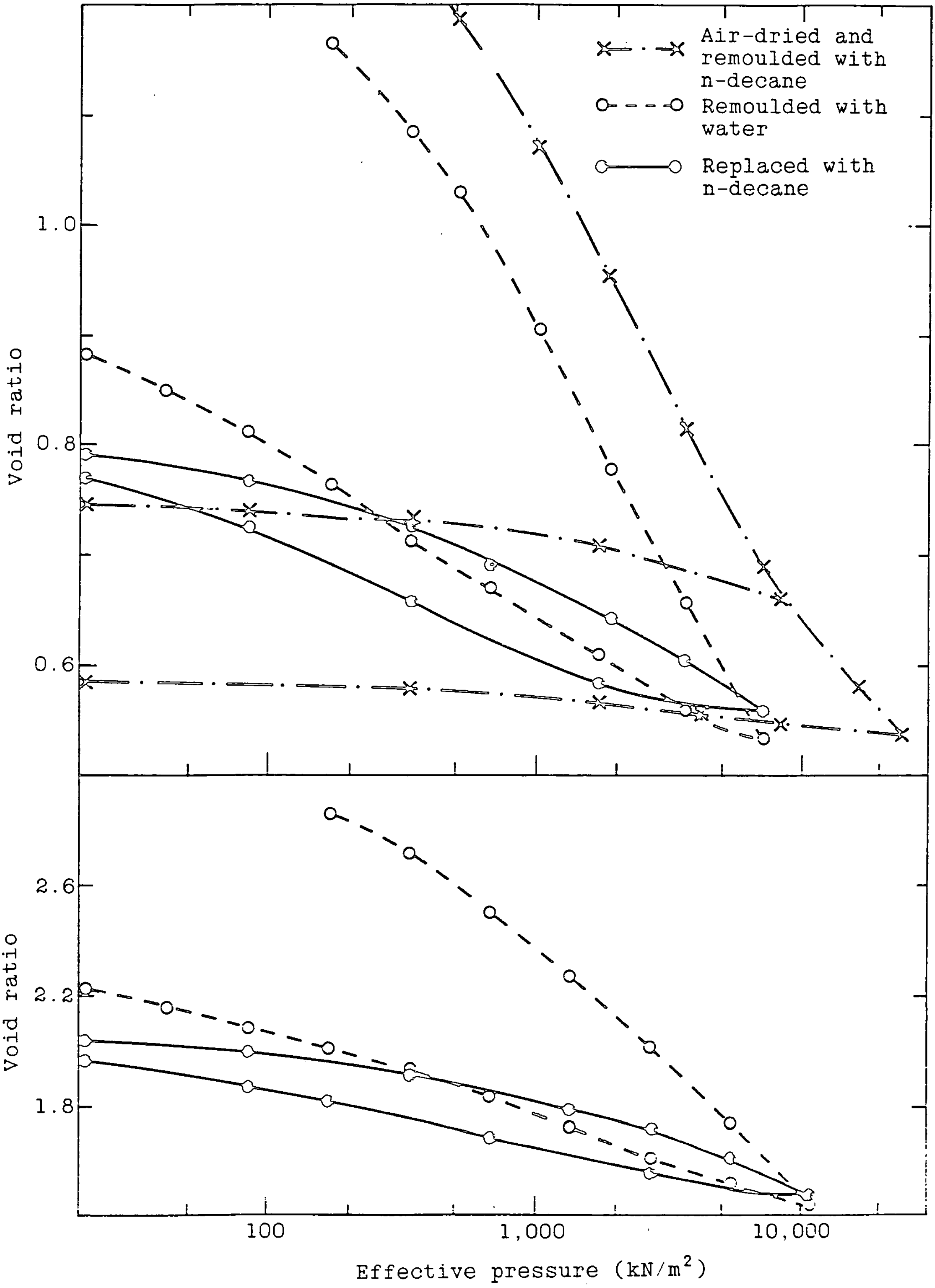
The reduction in void ratio due to the n-decane replacement was derived at the swelling pressure for each undisturbed sample and at 21.2 kN/m^2 for each remoulded sample, and is given in Table 5-5. This value can be used to evaluate the relative degree of the influence of non-polar fluid on suppressing double-layers. As shown in Table 5-5, the void ratio reductions of the remoulded samples range widely from 0.006 to 0.188, and are in an order of:

Fuller's Earth > London Clay (LCW-S) > Oxford Clay (OX19-S)
> Lias Clay

Figs. 5-7-1(Top) and 5-7-2(Bottom) Compression and swelling curves of the undisturbed London Clay LCW-U(Top) and Oxford Clay OX10-U(Bottom) with n-decane and water as pore fluids



Figs. 5-7-3(Top) and 5-7-4(Bottom) Compression and swelling curves of the remoulded London Clay LCW-S(Top) and Fuller's Earth(Bottom) with n-decane and water as pore fluids



Figs. 5-7-5(Top) and 5-7-6(Bottom) Compression and swelling curves of the remoulded Oxford Clay OX19-S(Top) and Lias Clay (Bottom) with n-decane and water as pore fluids

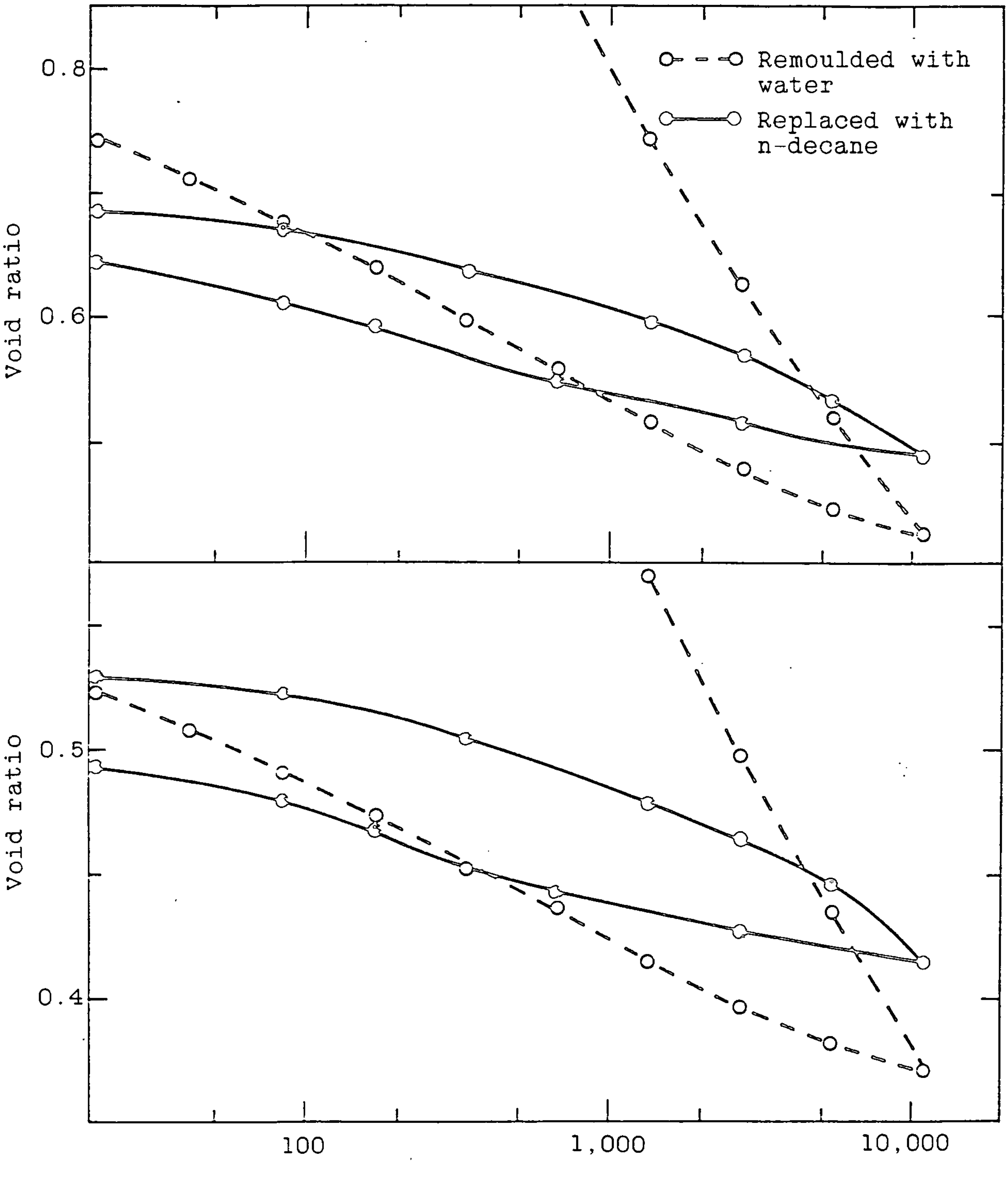


Table 5-5 Void ratio reductions of the samples due to the replacement of pore water by n-decane

Sample		Void ratio reduction *
London Clay	LCW-U	0.085
	LCW-S	0.098
Fuller's Earth	FE-S	0.188
Oxford Clay	OX10-U	0.035
	OX19-S	0.065
Lias Clay	LI-S	0.006

U: Undisturbed. S: Remoulded.
* Measured at the swelling pressure for the undisturbed sample and at 21.2 kN/m^2 for the remoulded sample.

Table 5-6 Average swelling indices of the samples with n-decane and water as pore fluids

Sample		Swelling index * n-decane (1)	pore water (2)	Percentage mechanical swelling (1)/(2)	Physico-chemical swelling (2)-(1)
London Clay	LCW-U	0.068	0.113 ***	60	0.045
	LCW-S**	0.017 0.022	--		
	LCW-S	0.084	0.139	60	0.055
Fuller's Earth	FE-S	0.180	0.289	62	0.109
Oxford Clay	OX10-U	0.038	0.070 ***	54	0.032
	OX19-S	0.057	0.117	49	0.060
Lias Clay	LI-S	0.029	0.055	53	0.026

U: Undisturbed. S: Remoulded.
* Average value between maximum pressure and 21.2 kN/m^2, based on Equation 4-12.
** Air-dried sample powders remoulded with n-decane.
*** From Table 4-7 (P_c=10,880 kN/m^2).

This order agrees with the expandable clay mineral (smectite and mixed-layer clays) content and plasticity (Tables 2-2 & 2-4), and also with the total and internal surface area values (Table 3-1). This latter agreement probably indicates that the n-decane replacement decreased the internal spacing of expandable clay minerals in the London and Oxford Clays and Fuller's Earth, although it did not destroy this spacing completely, as found by the X-ray diffraction analysis. The two undisturbed samples, London (LCW-U) and Oxford (OX10-U) Clays, have smaller void ratio reductions than their remoulded counterparts (Table 5-5); but, the void ratios are at different pressure levels, so no comparison can be made. Since the friction angle of particles in n-decane is about 10 degrees greater than in water (Sridharan & Venkatappa Rao, 1973), this might be the reason why all the recompression curves of remoulded samples lie above the original compression and swelling curves when compression reaches the maximum (Figs. 5-7-3 to -6).

The average swelling indices from pre-consolidation pressure to 21.2 kN/m^2 of the samples before and after the replacement of pore fluid are given in Table 5-6, together with the average swelling index of the undisturbed London and Oxford Clays within the same pressure range from Table 4-7. The average swelling indices of the London Clay (LCW-S) remoulded with n-decane are much smaller than that of the same sample remoulded with water and replaced by n-decane. Olson and Mesri (1970) conducted similar tests by remoulding kaolinite, illite and smectite with carcinogenic carbon tetrachloride, which has a dielectric constant of 2.28, at a similar level to that of n-decane. Their average swelling indices within a pressure range of c. 43,000 to 43 kN/m^2 are in a small range of 0.03 to 0.05. These values are greater than those of the London Clay remoulded with n-decane. A possible cause is the higher pressure used in their tests, which usually causes a greater swelling index, as found in Section 4-6-1.

As shown in Table 5-6, the undisturbed London and Oxford Clays replaced by n-decane have an average swelling index smaller than their remoulded counterpart, probably due to the difference in fabric and the diagenetic bonds in the undisturbed samples, as discussed in Section 4-6-3. All the average swelling indices of the undisturbed and remoulded samples with n-decane as pore fluid are much less than with pore water. This certainly shows the influence of dielectric constant of pore fluid on swelling, as demonstrated in Equation 5-5. The average swelling indices of the samples, remoulded with water and replaced by n-decane, range from 0.029 to 0.180 (Table 5-6). These values are generally greater than 0.01 to 0.03 of sands of equant particles (Olson & Mesri, 1970). The same fabric can be assumed before and after the replacement of pore fluid. Meanwhile, the internal spacing of expandable clay minerals in the samples remained constant during swelling because no water was available and n-decane is non-polar. As a result of these, the swelling in n-decane is due to mechanical force. *e.g.* particle sliding, bending, rolling and crushing (Mitchell. 1976). Therefore, high elasticity of clay particles is implied. especially in the Fuller's Earth which contains a substantial amount of smectite. This is somewhat different from the postulation of Mesri and Olson (1971) that mechanical swelling is a minor component of swelling in montmorillonite. In conclusion a possible reason for this difference is that they used pure montmorillonite and mixed air-dried powders with organic liquid, and so the resultant specimen had a different fabric from a sample mixed with water. The order of average swelling indices of the four remoulded samples are the same as that of their void ratio reductions.

In terms of percentage the mechanical swelling, implied by the swelling index with n-decane as pore fluid, ranges from 49 to 62 in the remoulded samples, and is in the same range for the undisturbed samples, as shown in Table 5-6. However, particles have greater shear resistance in n-decane than in water, as mentioned before. Thereby, the mechanical swelling percentage in the samples would be greater in water than is implied in Table 5-6. The swelling index given in Table 5-6 has been plotted against liquid limit in Fig. 5-8. As found in Section 4-6-2, the total swelling has a close relationship with liquid limit. It is clearly shown that the mechanical swelling components of London, Oxford and Lias Clays are about half the total. Since the London, Oxford and Lias Clays cover a wide range of plasticity and clay mineral mixtures (smectite - mixed-layer clays - illite - kaolinite; Table 2-4), the two linear relationships between total and mechanical swelling indices and liquid limit in Fig. 5-8 probably apply to most natural clayey sediments. Both the total and mechanical swelling index of Fuller's Earth (65 per cent smectite) fall outside the trend, although the mechanical swelling component falls within a similar percentage range as other samples.

Sridharan and Venkatappa Rao (1973) also carried out swelling tests on three samples (kaolinite, montmorillonite and black cotton soil), remoulded with water and non-polar liquids and also replaced with other pore fluids. Their results are displayed as an average swelling index in Table 5-7. The average swelling index of kaolinite in carbon tetrachloride (CCl_4) is 53 per cent of that in water, conforming with the values in Table 5-6. On the contrary, the average swelling indices of montmorillonite and black cotton soil in non-polar liquids are only 29 and 11 per cent of those in water, respectively. Their swelling indices in non-polar liquids are much

Fig. 5-8 Relationship between total and mechanical swelling indices and liquid limit in the remoulded samples (Equation C_s=0.0016L.L. was derived in Fig. 4-10, and Equation C_s=0.0008L.L. represents 50 per cent of total swelling.)

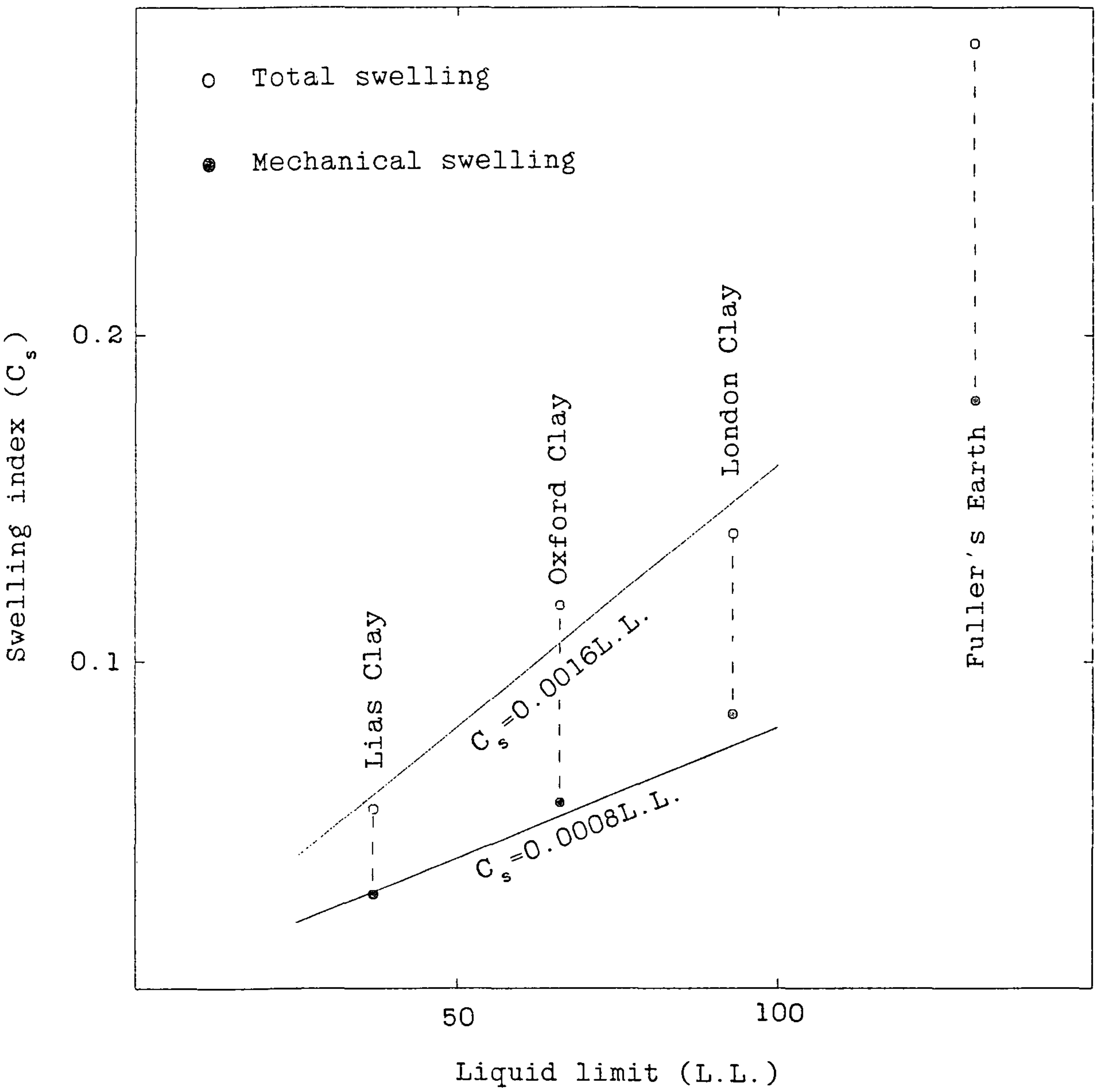


Table 5-7 Sridharan and Venkatappa Rao's (1973) experimental results on swelling in water and non-polar liquids

Sample	Liquid limit	Clay size fraction (%)	SWELLING INDEX *			
			Remoulded with water	Replaced by CCl_4	Remoulded with CCl_4	Replaced by water
Kaolinite	49	54	0.095	--	0.050	--
Montmorillonite	305	100	0.959	--	0.028**	--
Black cotton soil (mainly smectite)	101	29	0.223	0.026-0.033	0.024	0.062-0.090

* Average values between 800 and 6.26 kN/m^2.

** Remoulded with non-polar n-Heptane, instead.

smaller than that of kaolinite, although according to the mechanical model, the reverse should be the case since montmorillonite (smectite) and black cotton soil are finer-grained and more plastic than kaolinite (Table 5-7). This result could possibly be due to the aggregation caused by remoulding with non-polar liquid, as mentioned earlier in the text. When remoulded with water and then replaced by CCl_4, the black cotton soil shows 12 to 15 per cent mechanical swelling, much less than the values in Table 5-6. However, when remoulded with CCl_4 and then replaced by water, the percentage increases up to 27 to 39 per cent. The pressure applied by them, however, is much smaller than in this study and this affects swelling index to a great extent, especially in smectite-rich samples (Section 4-6-1).

The difference between the swelling indices determined with pore water and with n-decane as pore fluid is probably a measure of the degree of physico-chemical swelling. It ranges from 0.026 to 0.109 in the remoulded samples, as shown in Table 5-6 and by the length of the broken lines in Fig. 5-8. The Fuller's Earth has the greatest physico-chemical swelling, whilst the Lias Clay has the smallest. The remoulded London Clay has a slightly smaller physico-chemical swelling index than the remoulded Oxford Clay, although the former contains a greater amount of expandable clay minerals (Section 2-3). Again, the two undisturbed samples have smaller physico-chemical swelling indices than their remoulded counterparts (see Table 5-6).

5-6 Summary

1. The swelling pressures of samples were measured in the swell cell and modified oedometers. The values obtained in the swell cell are greater than in the modified oedometers. This indicates that the stiff swell cell is more suitable for the measurement of

swelling pressure.

2. Using the values of swelling pressures, the effective half spacings and void ratios, average half spacings and dead volumes of samples are derived from double-layer theory. It is found that the 'effective' void ratios represent only a small proportion of the total, suggesting that dead volumes are large.
3. Swelling pressure would seem to have some dependency on the *in situ* stress condition. The *in situ* K values of the samples were estimated, ranging from 0.4 to 2.6, the lowest of which are in the Flockton mudstone and London Clay (LCW). These two samples also have the smallest overconsolidation ratios.
4. Na-saturated remoulded Fuller's Earth has much higher compression and swelling indices and also a greater C_s/C_c ratio, than the natural Ca-rich variety. This indicates the greater physico-chemical swelling influence of the Na (monovalent) cation.
5. All the swelling indices of undisturbed samples in the distilled water bath are greater than those in the pore water bath. This shows the role of ion concentration in influencing the degree of swelling, *i.e.* low cation concentrations enhance physico-chemical swelling.
6. The physico-chemical forces of five undisturbed samples were measured and also calculated from the double-layer theory. The comparison shows that the theory in general tends to overestimate the physico-chemical forces.
7. Almost non-polar n-decane was used to replace water in the samples in order to examine physico-chemical swelling. The void ratio reductions determined for remoulded samples due to the n-decane replacement range widely from 0.006 to 0.188 at 21 kN/m^2, and are in the order of:

   Fuller's Earth > London Clay > Oxford Clay > Lias Clay

This order agrees with the smectite content, plasticity and total and internal surface areas.

8. The average swelling indices of the samples remoulded with water and replaced by n-decane, indicate that the mechanical swelling component ranges from 0.029 to 0.180 (49 to 62 as a percentage). There is a linear relationship between mechanical swelling indices and liquid limit for the remoulded London, Oxford and Lias Clays. Smectite-rich Fuller's Earth does not follow this linear trend.

CHAPTER 6 GENERAL SUMMARY AND CONCLUSIONS

Since Terzaghi published the theory of consolidation, the compression and rate of consolidation have been investigated in detail on clays. Relatively little research has been carried out on swelling, especially on natural undisturbed materials. As has been indicated in this study, undisturbed mudrocks can not be reproduced in the laboratory, in terms of fabric and diagenetic bonds. In this study seven heavily-overconsolidated clays and mudstones, undisturbed and remoulded (by slaking), have been tested.

The rate of swelling, in terms of volume change and negative pore pressure dissipation, has recently attracted a few researchers (Section 1-7), because it has been suspected to be one of the factors responsible for the progressive/delayed slope failure in mudrocks. On the other hand, the mechanism of swelling has been controversial for a long time (Section 1-6). In particular, the physico-chemical behaviour of clays has been claimed by some investigators to be predictable by means of the double-layer theory. Whilst others have considered that natural clay assemblages behave rather differently in comparison with pure, fine clay minerals. In this study the experimental program has primarily been directed to explore the rate and mechanism of swelling.

Three groups of sample characterisation have been carried out: (a) plasticity classification and mineralogy by X-ray diffractometry and fluorescence analyses, (b) exchangeable cations and geochemistry of pore fluid, produced by high-pressure squeezing and saturation extraction, (c) fabric, including particle size, surface area, pore size, and preferred orientation. Also, micro- and macroscopic features by scanning electron microscopy and X-ray radiography. The general properties of the samples are summarized in Table 6-1. The

Table 6-1 Summary of the properties of the samples studied

Sample	Geologic age	Clay Mineralogy (% in weight)					Plasticity		Cation exchange capacity	External surface area
		K	I	ML	S	Ch*	L.L.	Classification		
London Clay (LC)	Eocene	28	14	3	15	--	75	CV	20 meq/g	57 m^2/g
London Clay (LCW)	Eocene	25	15	6	18	--	93	CE	25	55
Fuller's Earth (FE)	Lower Cretaceous	--	--	--	65	--	131	CE	65	105
Oxford Clay (OX10)	Upper Jurassic	22	10	28	--	--	68	CH	19	58
Oxford Clay (OX19)	Upper Jurassic	25	11	28	--	--	66	CH	19	56
Lias Clay (LI)	Lower Jurassic	8	43	7	--	5	37	CI-MI	12	19**
Flockton mudstone (FM)	Carboniferous	20	32	8	--	8	42	CI	11	11**

* K= Kaolinite, I= Illite, ML= expandable mixed-layer clays, S= Smectite, Ch= Chlorite.

** For undisturbed specimens.

samples cover a wide spectrum of stratigraphic age, from Carboniferous to Eocene. They contain 60 to 80 per cent of clay minerals, in which smectite and expandable mixed-layer clays are from 0 to 65 and 28 per cent, respectively. In terms of Atterberg limits, they range from extremely-high to medium plasticity. The over-all activities of London and Oxford Clays and Fuller's Earth are similar to that of illite; whilst the Lias Clay and Flockton mudstone have similar activities to kaolinite. The cation exchange capacity ranges from 9.9 to 75 meq/100g. Since the samples cover a wide range of properties, the experimental results are regarded as being applicable to mudrocks in general. Based on the content of expandable clays (smectite and mixed-layer clays of a illite-smectite type), plasticity and cation exchange capacity, the samples fall into the order of:

Fuller's Earth > London Clay (LCW > LC) > Oxford Clay > Lias Clay & Flockton mudstone (from high to lower values)

The measured external surface areas, indicative of particle size and controlled mainly by clay-size fraction, of the samples range from 10 to 107 m^2/g. It has been revealed in the study that the internal surface areas of the samples conform with the contents of expandable clay minerals. The pore size analysis has shown that the samples have a wide range of pore sizes, which have been classified into macro- (> 1,000 Å in radius), medium- (200-1,000 Å) and micro-pores (<200 Å). In general the pore size distributions are polymodal on a semi-logarithmic plot, whilst the remoulded samples more commonly have a bimodal pattern. The X-ray diffraction analysis has shown a preferred orientation developed in the direction normal to the loading axis in most samples; whilst in scanning electron microscopic photographs only the undisturbed Lias Clay and Flockton mudstone samples have an apparent preferred orientation, albeit with undulating appearance. It has been clearly indicated by X-ray radiography that the undisturbed samples, except the Fuller's Earth, contain fissures, but the remoulded samples are macroscopically homogeneous.

The measured swelling rate curves have been analysed, using the square root of time fitting method. Those curves for the undisturbed samples are believed to be the first systematic experimental results available in the literature.

The swelling process has commonly been considered to be opposite to the consolidation process. The analysis presented in this thesis has shown, however, that there are some distinct phenomena in swelling. In general, swelling proceeds faster at a low overconsolidation ratio (OCR) than is predicted by Terzaghi's theory of swelling, but it is slower at high OCR values, probably due to the prominence of secondary swelling. The swelling of more plastic samples approaches Terzaghi's theoretical curve at lower OCR's, particularly for the Fuller's Earth. The coefficient of swelling consistently decreases with increasing OCR, and becomes much smaller than the coefficient of consolidation at high OCR. In one remoulded Oxford Clay, secondary swelling increases with OCR and reaches an almost constant value at high OCR ($C_{\alpha s}$=0.5-0.7x10^{-2}). The ratio of secondary to primary swelling also increases with OCR, ranging from 5 to 60 per cent, which is also a function of pre-consolidation pressure (P_c), but does not show any signs of having attained a maximum value. These phenomena have commonly been confirmed by the measured swelling rate curves of other samples.

Progressive slope failure in mudrocks has been ascribed by Bjerrum (1967) to the breakdown of diagenetic bonds and then later, by others (*e.g.* Lutton & Banks, 1970), to the slow dissipation of excess negative pore pressures. Based on the prolonged primary swelling process and prominent secondary swelling, it is postulated that swelling in terms of volume increase is principally of a progressive nature in heavily-overconsolidated clays and mudstones, regardless of their plasticity and diagenetic bonds. Moisture content increase and strength reduction have been demonstrated to be significant in the swelling process (Section 4-7). As a result, the progressive softening and failure phenomenon in heavily-overconsolidated plastic clays and mudstones can be ascribed to the combined effects of the progressive swelling process (including negative pore pressure dissipation) and the breakdown of diagenetic bonds.

The locked-in recoverable strain energy is important in the swelling of mudrocks (Section 1-5). When compared with remoulded samples (containing no diagenetic bonds), the smaller swelling in undisturbed samples has usually been ascribed to the diagenetic bonds which restrict the release of locked-in strain energy. However, other factors can also affect swelling, particularly the fabric. Diagenesis tends to reduce the macro-pore volume which is unrecoverable, especially in the highly-indurated mudstones. Recoverable strain energy or recovered strain ratio increases with pre-consolidation pressure (P_c) in remoulded samples; meanwhile, an unrecoverable macro-pore volume decrease occurs with increasing P_c. In other words, the locked-in recoverable strain energy or potential swelling is believed to be less than is indicated by the recovered strain ratios of remoulded samples, especially in the Fuller's Earth and the indurated Lias Clay and Flockton mudstone. Different orientation would also seem to affect swelling, particularly in undisturbed Lias Clay and Flockton mudstone, which have a greater preferred orientation. The dependence of swelling on fabric has also been found in compacted clays (*e.g.* Parcher & Liu, 1965). The ratio, K_o, of horizontal to vertical effective stress at rest might be another influential factor, as has been claimed by many investigators. A high K_o value can promote swelling through particle sliding at contact points, although no shear failure plane has been found in the present work by X-ray radiography. From the information on secondary swelling, however, its role is uncertain, as discussed in Section 4-5. Further work is needed to understand the extent of the K_o-effect on swelling.

The strength and nature of diagenetic bonds have been discussed. The criteria used include: (a) the relative positions of compression curves, (b) swelling index, (c) recovered strain ratio (C_s/C_c) and (d) fabrics. Cementing is almost omni-present in natural sediments. In particular, the carbonate cement in the Fuller's Earth is very strong in terms of restricting swelling, but vulnerable to large compressive strain because of its open fabric. Bonds of a viscous-adsorbed-water-type could also exist in all the aged sediments. They could be the major type of bonds in the London and Oxford Clays, appearing to be weak in strength and also vulnerable to compression. Mechanical adhesion (cold welds) most probably occurs in indurated mudrocks, like the Lias Clay and Flockton mudstone, which show an increase in surface area after slaking. This type of bond is very strong against compression and swelling.

The coefficients of swelling and consolidation and indices of swelling and compression have generally been found in the present work to correlate with the plasticity of remoulded samples. The result suggests that these parameters, especially those of swelling, depend very much on testing conditions. This might be the reason why no consistent relationship between C_s and L.L. has been found by other investigators. Sustained secondary consolidation and swelling cause a decrease in consolidation and swelling indices and an increase in coefficients of consolidation and swelling. A new linear relationship has been established between swelling index and liquid limit, $C_s = 0.0016$ L.L., within a L.L. range of 37 to 93 in the remoulded samples. Diagenetic bonding generally increases the coefficients of consolidation and swelling, and decreases compression and swelling indices. That is to say, the swelling proceeds faster in undisturbed samples than is predicted by remoulded samples. In contrast, the average compression index of undisturbed specimens is greater than the remoulded one in the Fuller's Earth, probably because of its very open fabric in the undisturbed state.

There are two traditional explanations for the generation of swelling pressures: (a) they are due to the repulsive force between clay platelets, which can be calculated from the double-layer theory (for example, Madsen, 1979); that is, swelling pressure is a function of the half spacing, d, between clay platelets or moisture content and surface area; (b) they are due to stress release during sampling (for example, Skempton & Sowa, 1963); that is, it is an indication of the *in situ* stress condition.

The double-layer theory has been used by many investigators to explain or predict the pressure - volume change behaviour of clays. The assumed parallel orientation of clays in the theory is, however, far different from the real arrangement of particles in natural sediments, as has been found by the X-ray diffraction analysis and scanning electron microscopy. Pore size analysis has shown that macro-pores form a large dead space that under a practical pressure range the repulsive force cannot operate within. Dead volume decreases with increasing P_c, as implied by the increase in swelling index with P_c (Table 4-7). In the calculation of d values most investigators have used Equation 5-4; p196 this kind of approach ignores the dead space and is considered by the writer to be unrealistic. In this study the d values have been calculated from the equivalent swelling pressures according to the double-layer theory. The results indicate that the calculated d values are much smaller than the average d values obtained from the moisture contents and surface areas. This is another confirmation of large dead volumes in natural materials.

Rather differently, swelling pressure has also been considered to be an average value of *in situ* effective vertical and horizontal stresses (Equation 5-9), p256. Since the moisture content and the pressure acting on a sample taken from depth must be in equilibrium if there is no disturbance after sampling, the stress release concept is more logical and realistic. The close link between ratios of horizontal to vertical effective pressures and overconsolidation ratios tends to be in favour of this.

It has been found that the double-layer theory can be used to explain the effects of dilution on the determination of exchangeable cations. Also, the influence of applied pressure and sample thickness on the composition of pore water extracted with the pore fluid squeezer is considered in terms of double-layer theory. Dilution changes cation ratios on the exchangeable sites since the soluble salts content increases with increase in water content. It has been demonstrated in Section 2-6 that because of the physico-chemical behaviour.clay minerals act as a semi-permeable membrane, and this results in a less concentrated pore fluid under high pressure and also in smaller mono-/di-valent cation ratios.

The modified effective stress concept has been used to account for the influence of the physico-chemical force, R-A, on volume change, mainly in respect to the change in pore water chemistry. Morgenstern and Balasubramonian (1980) demonstrated that the double-layer theory could be used to predict R-A values. However, their analysis was based on some incorrect assumptions, as discussed in

Section 5-4. In this study the theoretical calculation has suggested that the double-layer theory tends to overestimate R-A values. Nevertheless, the results have shown that a lower cation concentration in pore water increases swelling.

It is beyond doubt that the large void ratios in clays are partly due to long-range repulsive forces, as has been demonstrated by the large compression and swelling indices of remoulded Na-saturated Fuller's Earth and the void ratio reductions in the replacement of pore water by non-polar n-decane. These results have also revealed the dependence of void ratio reduction on mineralogical composition. Nevertheless, fabric or void ratio also depends on the geochemical environment during deposition in the field, or on the preparation method in the laboratory (Section 1-4-4). The decrease in macro-pore volume with increasing P_c can be accounted for by either the mechanical or physico-chemical model of swelling. The physico-chemical model can also be applied to explain the increasing swelling index with P_c due to the increase in preferred orientation, *i.e.* parallel platelet orientation being conducive to double-layer swelling.

In differentiating mechanical from physico-chemical swelling, fabric differences between samples remoulded with fluids of different dielectric constants have not been considered in detail by other investigators (*e.g.* Olson & Mesri, 1970). In this study the replacement of pore water by n-decane has been conducted for two undisturbed samples. and also for four remoulded samples after consolidation. The fabric before and after replacement should be very similar; consequently, the results are more reliable. The mechanical model, considering particle bending and sliding, has been supported by the swelling with non-polar n-decane as pore fluid. Also in support of the mechanical model, of swelling is the greater volume increase in macro-pores than in micro-pores in the undisturbed samples after the free swelling tests in the swell cell. Mechanical swelling has been postulated to comprise not less than 49 to 62 per cent of total swelling in the undisturbed and remoulded samples. The only similar experimental information available in the literature is given by Sridharan and Venkatappa Rao (1973). Their results tend to indicate a smaller percentage of mechanical swelling in a smectite-rich soil, but their experiment was done at lower pressures, which affect swelling to a great extent.

In conclusion, factors affecting swelling include time, diagenetic bonds, fabric, mineralogy, pore fluid chemistry and stress history. Mechanical and physico-chemical swelling must occur simultaneously, both of which depend very much on fabric. Those factors are usually interdependent. In particular, fabric is a function of clay mineralogy and depositional geochemistry, and also pre-consolidation pressure. Furthermore, the diagenetic bonds modify fabric, especially in indurated mudrocks.

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APPENDIX A MINERALOGY AND GEOCHEMISTRY

A-1 X-ray Diffractometry

1. Air-dried samples were gently powdered in an agate mortar, until no grittiness was felt. Then 0.225 grams of sample powder were mixed with 0.025 grams of boehmite, which is used as an internal standard. The mixtures were smear-mounted on glass slides using acetone as the liquid medium.
2. An X-ray trace was produced with a Philips PW1130 X-ray Diffractometer using iron-filtered cobalt K_α radiation, with the divergent, scatter and recieving slits of 0.5°, 0.1° and 0.5°, respectively. All the samples were run at a scanning speed of 0.5° of 2θ per minute, covering a range of 2 to 50° of 2θ.
3. The sample slides were then placed in a sealed vessel containing ethylene glycol for 3 days. After glycolation the slides were run again, using the same conditions, from 2° to 20° of 2θ.
4. The slides were heated at 550°C for an hour and then placed in a desiccator to be cooled down. They were also run in the same conditions.
5. A polar planimeter was used to measure the peak areas after a suitable base line had been inserted. The peak heights and the widths at half heights were also measured for clay minerals.
6. Separate slides were also prepared using distilled water as the liquid medium, instead of acetone, to make clays perfectly oriented on the glass slides. All the slides were run in the same conditions as in (2) from 2° to 30° of 2θ before and after glycolation and also after being heated at 300°C for half an hour.

A-2 Determination of Exchangeable Cations and Soluble Salts

1. About 0.4 grams of sample powder, which passed a B.S. 200 mesh

after being gently ground, was weighed and placed in a plastic stoppered bottle. Two bottles were needed for each sample.

2. 40 millilitres of either 0.5M barium chloride (adjusted to pH=7 with $Ba(OH)_2$) or distilled water were added to the bottles, and the mixtures were mechanically shaken for half an hour and then left overnight.
3. The suspensions were centrifuged at 12,000 g for 20 minutes until the resulting liquors became clear, at which stage they were decanted into plastic stoppered bottles.
4. Analysis of Na, K, Ca and Mg ions was carried out by atomic absorption spectrometry on these solutions in the Chemistry Department of this University. An Orion Research specific ion electrode was used to measure the concentrations of chloride in these solutions. Sulphate concentrations were measured by means of a barium per-chlorate (0.01M) titration with the indicator Sulphonazo III.
5. Calculations

X_1, X_2 ppm: parts per million of cations in the solutions treated with $BaCl_2$ and distilled water, respectively.

Y_1, Y_2 g : grams of sample powder treated with $BaCl_2$ and distilled water, respectively, after the moisture weight was subtracted.

Exchangeable cations (meq/100g)

$=(X_1/Y_1 - X_2/Y_2) \times 10^{-6} \times 40(\mathrm{ml}) \times 100(\mathrm{g}) / (\text{cation meq.wt.})$

Soluble salts (meq/100g)

$=X_2 \times 10^{-6} \times 40(\mathrm{ml}) \times 100(\mathrm{g}) / (Y_2 \times \text{cation meq.wt.})$

Calculated pore fluid concentration (ppm)

$=X_2 \times 40(\mathrm{ml}) / (Y_2 \times \textit{in situ}\ \text{m.c.})$

A-3 Pore Fluid Squeezing

A-3-1 Apparatus

1. A pore fluid squeezer (Fig. A-1) was constructed with highly corrosion-resistant stainless steel 316 S16. The filter was a sintered stainless steel porous disc with 7 µm pores, 32.5 mm in diameter and 3 mm thick, which was cleaned with HCl, HNO_3 and boiling water.
2. A load was applied from a large shear box machine (referred to later as a static system) or from a hydraulic loading machine (Avery-Denison Ltd.)
3. Pore fluid was collected in a plastic container, sealed with silicon grease to prevent evaporation.

A-3-2 Procedure

1. For the static loading system, samples of *c*. 150 grams were placed in the squeezer. A load was exerted by steps within an hour to reach the designated pressure and then left to operate for 3-7 days. Silicon grease was applied to seal possible air passage. Finally pore fluid was removed from the bottom of the squeezer and weighed and then stored in a stoppered plastic bottle.
2. For the hydraulic loading system, samples of *c*. 15 grams were used and the load increased up to the designated pressure in minutes and then left for 15 minutes. The resultant pellets had a thickness of *c*. 7 mm. This procedure was repeated until 8-10 millilitres of pore fluid were obtained. The pore fluid was weighed and stored as before.
3. All the pore fluids produced were analysed as in A-2.

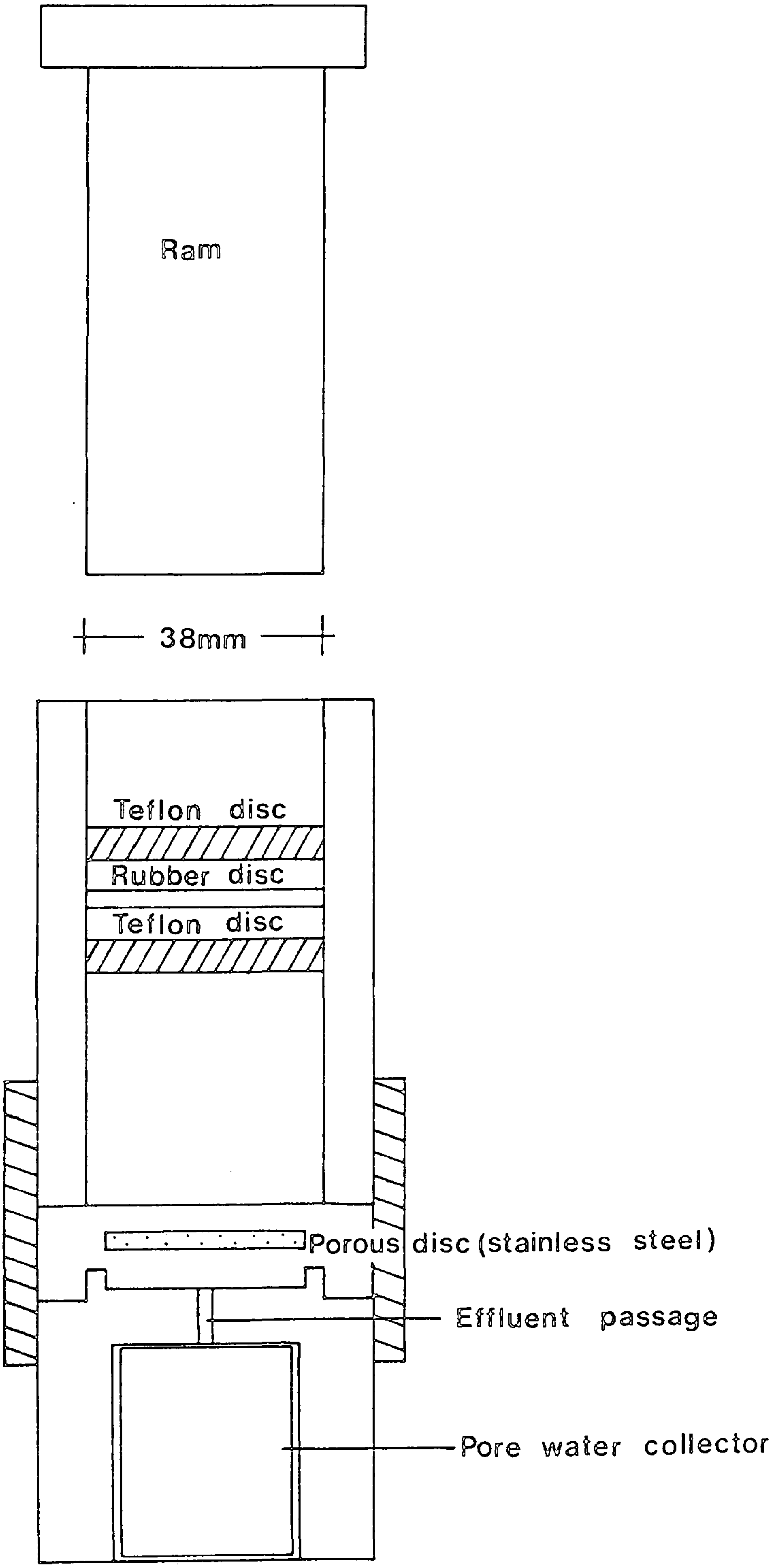
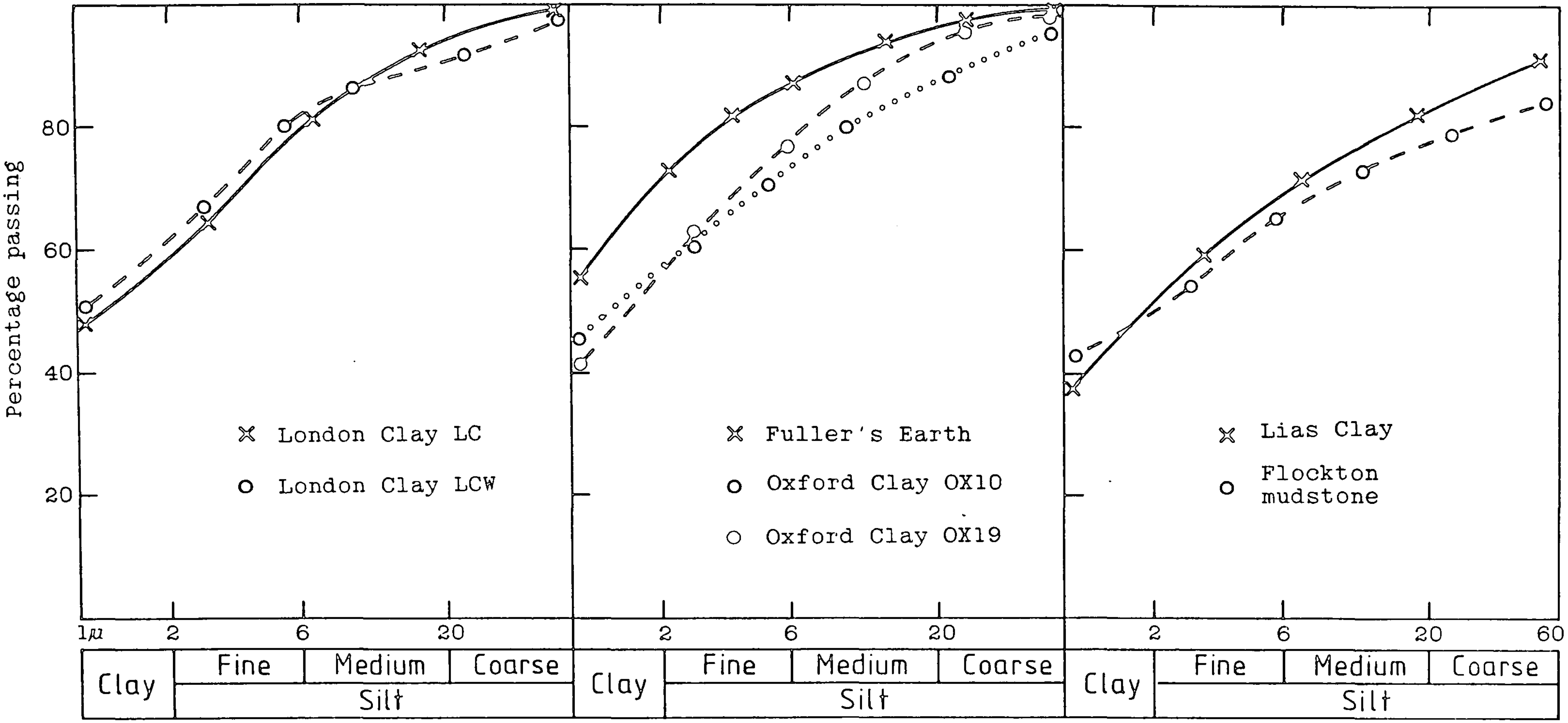


Fig. A-1 Pore fluid squeezer (scale 1:1)

Fig. A-2 Particle size distributions of the samples



APPENDIX B ANALYSES OF FABRIC

B-1 Freeze-drying

1. Samples, including the undisturbed and those after the free swelling and the consolidation-swelling tests (Appendix C), were cut by a sharp knife into sticks (*c*. 3 x 5 x 10 mm) and then immersed in a liquid nitrogen bath.
2. Frozen samples were transferred to a freeze-drier (Edwards EF4 Modulyo) in the Zoology Department of this University. The chamber temperature was maintained at -60°C and a vacuum pressure was applied for 4 hours.
3. After being dried, samples were stored in a desiccator and were ready for the analyses of surface area and pore size distribution.

B-2 Surface Area Measurement

B-2-1 Procedure

1. Freeze-dried specimens were weighed and de-aired in the sample cell at 300°C in a nitrogen stream for 2 hours.
2. After being de-aired, the sample cell was transferred to the running station of a continuous flow areameter (Quanta Chrome Co.) in the Ceramics Department of Leeds University.
3. The flow controller was set to a relative pressure, 0.1, of nitrogen. Then the sample cell was immersed in a liquid nitrogen bath and adsorption peaks were maintained between 0.15 and 0.25 by adjusting the attenuation factor.
4. After adsorption was completed, the liquid nitrogen bath was removed and the sample cell was warmed up to room temperature in a water bath. the desorption peak value was then noted and also the desorption signal area.
5. An appropriate amount of calibration gas was injected into a septum and the calibration signal area was noted.

6. The flow controller was then set to the next relative pressures, 0.2 and 0.3, and Steps 3-5 were repeated.
7. After testing the specimen was weighed again. The room temperature and the barometric pressure were also noted.

B-2-2 Example of Calculation

Sample: FE-S24

Sample weight, W = 0.1049 g

Barometric pressure, P_a = 754 mm Hg

Room temperature, T_a = 20°C = 293°K

Experimental result:

P/P_o	V_c(ml)	S_s	S_c	V_a(ml)	V(ml)	$1/V(1-P/P_o)$
0.1	4	1183	1073	4.41	4.08	0.272
0.2	4	604	522	4.63	4.28	0.292
0.3	4	660	508	5.20	4.81	0.297

P/P_o : Relative pressure.

V_c : Calibration volume.

S_s : Sample signal area.

S_c : Calibration signal area.

V_a : desorption volume at the ambient condition)= $S_s \times V_c/S_c$

V : desorption volume at STP, $V = V_a(P_a/T_a)(T_o/P_o)$

(T_o=273°K, P_o=760 mm Hg)

On the plot of $1/V(1-P/P_o)$ versus P/P_o in Fig. B-1, the best-fit straight line, derived by the least square method, has the parameters (see equation 3-1):

Slope, $S = (C-1)/V_m \times C = 0.131$

Intercept, $I = 1/V_m \times C = 0.261$

Therefore, the volume, V_m, of the adsorbate monolayer is:

$V_m = 1/(S+I) = 2.55$ (ml)

According to Equation 3-2, the surface area, A_s, is:

Fig. B-1 An example of the plot of $1/V'(1-P/P_o)$ versus P/P_o

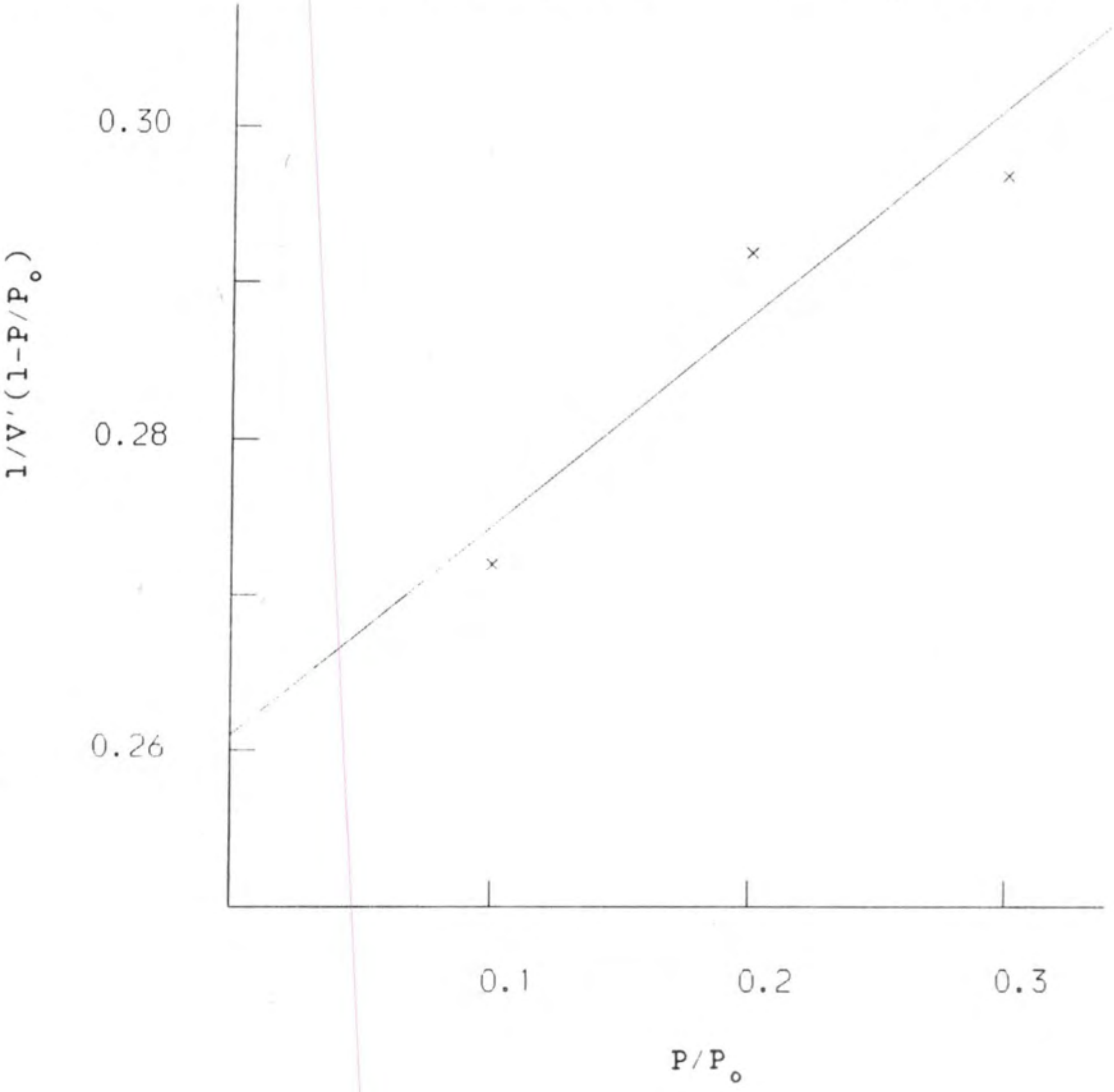
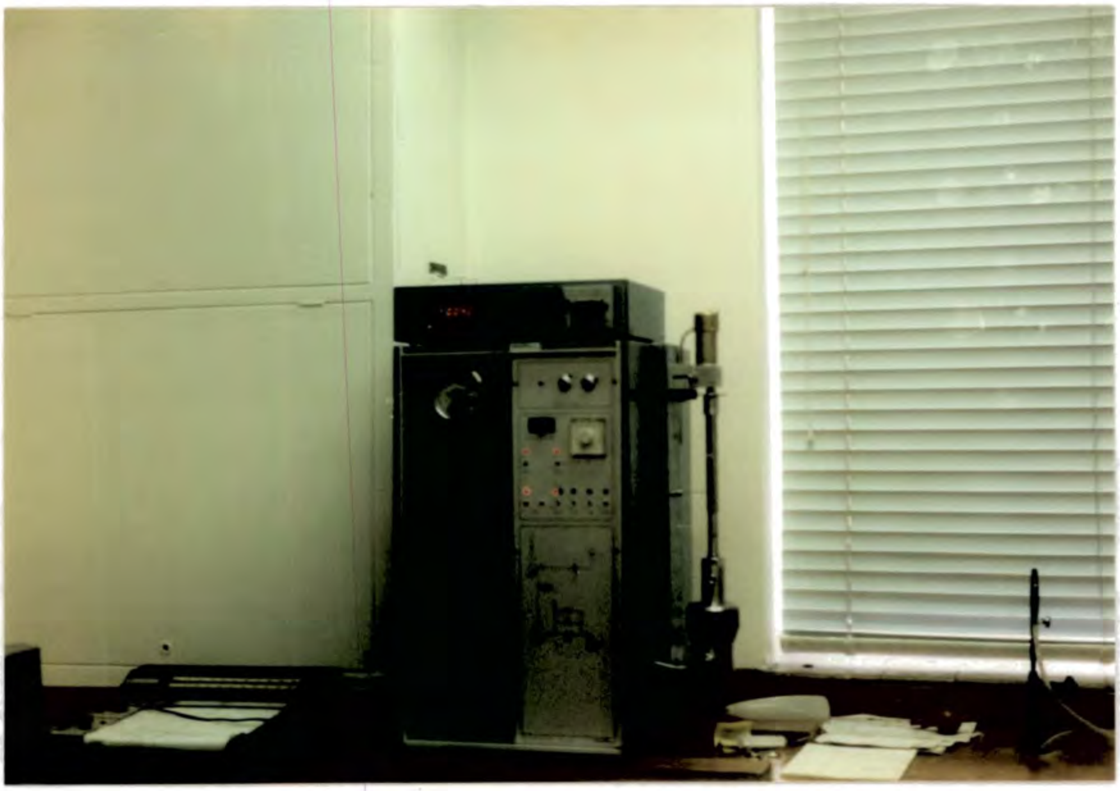


Fig. B-2 Mercury porosimeter



$$
\begin{aligned}
A_s &= N \text{ x } A_a \ (V_m/V_o) \ / \ W \\
&= 6.02 \text{ x } 10^{-3} \text{ x } 16.2\text{x}10^{-20}(\text{m}^2) \text{ x } 2.55\text{x}10^{-6}(\text{m}^3) / \\
&\quad (22.4\text{x}10^{-3}(\text{m}^3) \text{ x } 0.1049 \ (\text{g})) \\
&= 106 \ (\text{m}^2/\text{g})
\end{aligned}
$$

B-3 Pore Size Analysis

1. Freeze-dried specimens of about 0.2-2 grams were weighed and placed in a dilatometer with a suitable bore size, and then evacuated at a vacuum pressure for 30 minutes, and afterwards the dilatometer was filled with clean mercury.
2. The dilatometer was then attached to a mercury porosimeter (Carlo Erba Strumentazione, Milan), as shown in Fig. B-2, with a maximum pressure of 2,000 kg/cm^2. The porosimeter uses a programmable delay system holding up the pump for the time necessary for the mercury to completely penetrate all pores. In this study three minutes was found to be enough.
3. Pressure was increased by small steps up to 2,000 kg/cm^2 and the amount of mercury penetrating pores was recorded, together with pressure values, by a micro-computer (Fig. B-2).
4. Density was measured by the mercury displacement method for all freeze-dried samples.

B-4 Preferred Orientation Analysis

1. Sample preparation: The undisturbed samples and some samples after the consolidation-swelling tests were cut to strips, approximately 10 mm wide by 20 mm long in directions parallel to and at the right angle to the vertical direction. After being air-dried, strips were ground flat with a medium abrasive first and then with a very fine abrasive, using paraffin as the lubricant.
2. X-ray diffraction: The polished strips were analysed in a Philips

PW1130 X-ray diffractometer as for the mineralogy. The peak heights of the kaolinite 001 and 020 reflections, the illite 002 and 110 reflections and the smectite 001 and 020 reflections were measured.

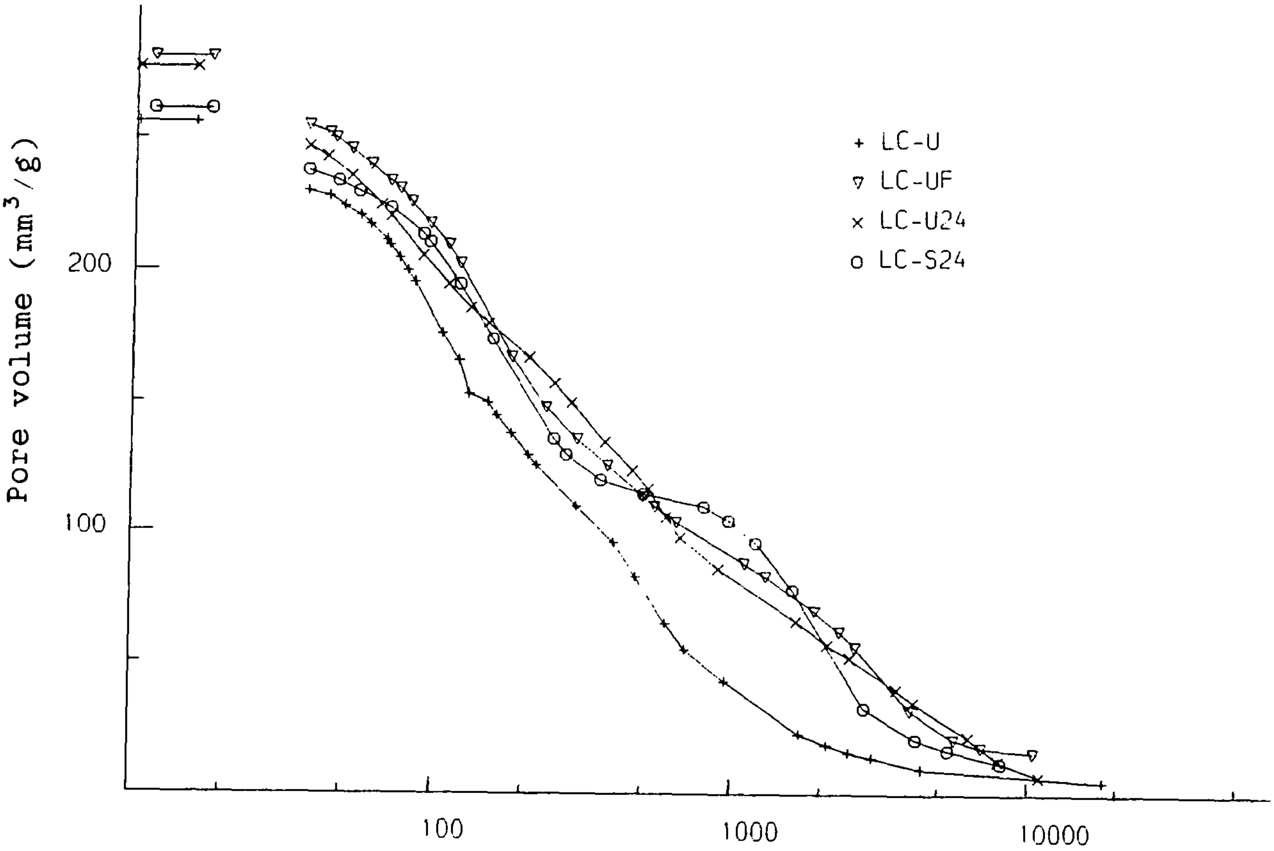
3. Fully-oriented specimen: Sample powders were mixed with distilled water in a beaker and stirred. A glass slide was placed at the bottom of the beaker about one minute after stirring. Then the solution was evaporated at 60°C in an oven until it dried out.
4. Random specimen: Sample powders were poured into an aluminium holder, commonly used in XRD analysis. The powders were pressed as little as possible to prevent any undesirable orientation.
5. Both the fully-oriented and random specimens were X-rayed as before.

B-5 Scanning Electron Microscopy (SEM)

Sample preparation:

1. Freeze-dried specimens, stored in a desiccator, were broken in a designated direction, parallel or perpendicular to the loading axis.
2. Sellotape was used to clean loose material on the exposed surfaces, and then specimens were attached to the SEM stands.
3. Specimens were kept in the desiccator again. Experience shows that the samples adsorbs enough moisture in air to delay or even prevent SEM examination.
4. Gold coatings were applied before SEM examination started.

Figs. B-3-1(Top) and B-3-2(Bottom) Cumulative pore size distributions of the London Clay



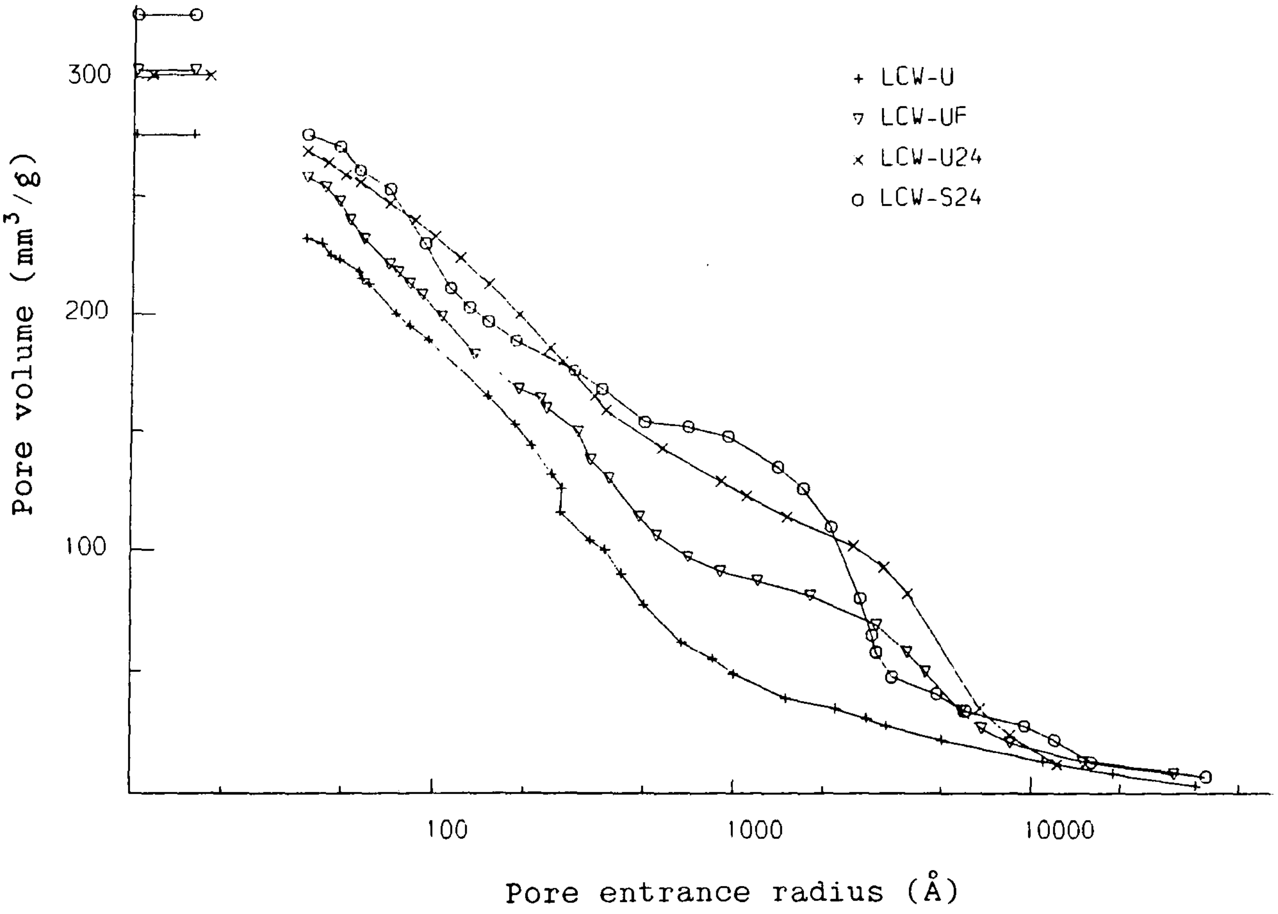
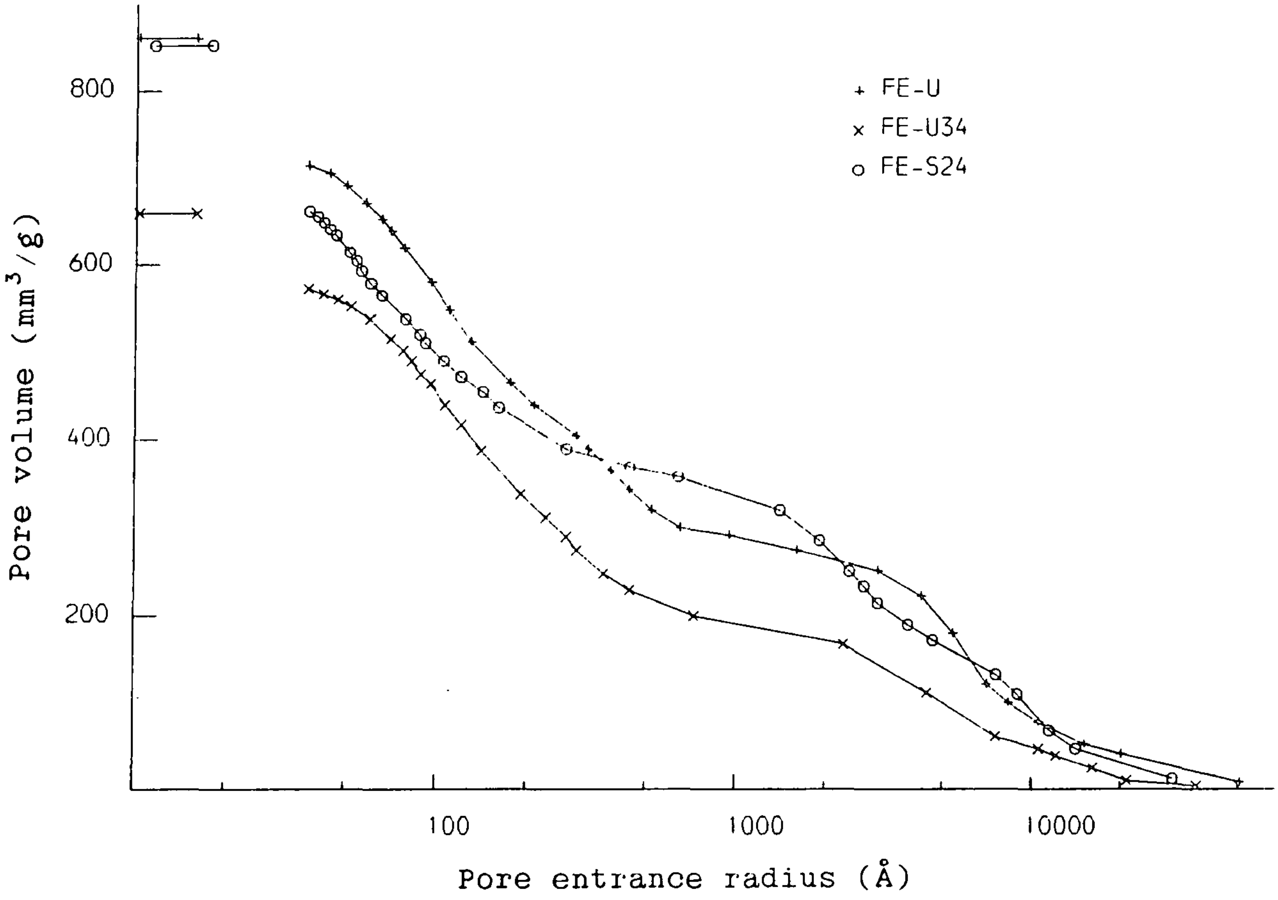
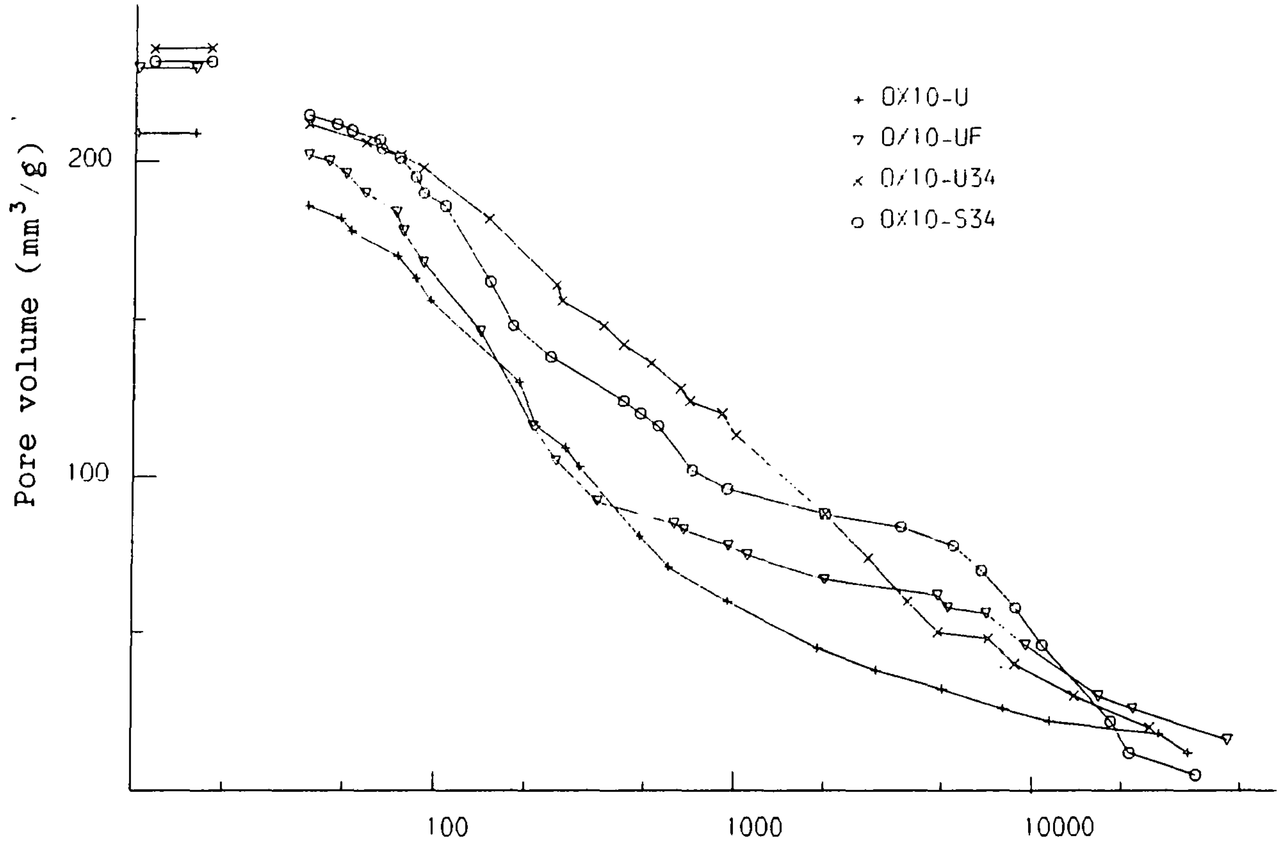
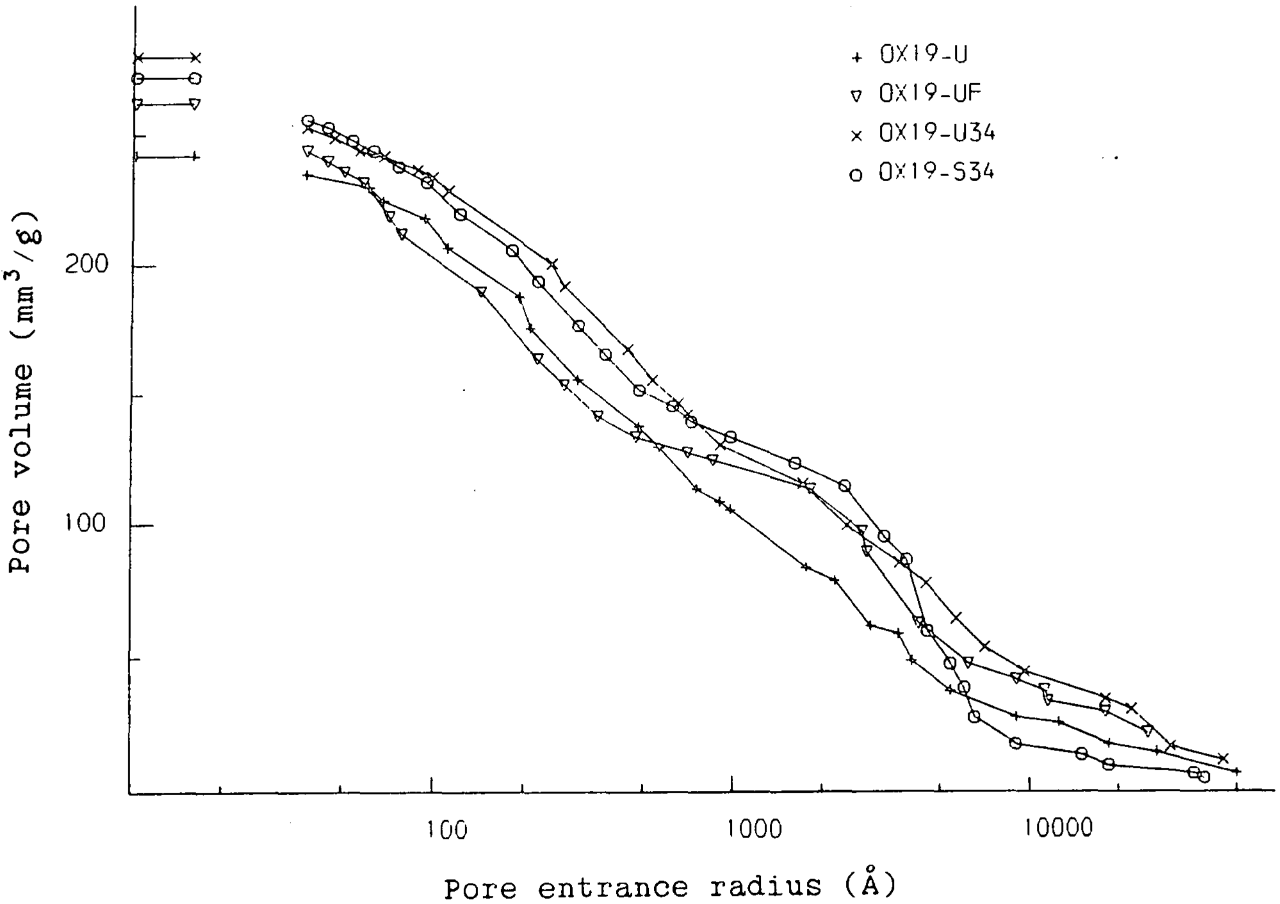


Fig. B-3-3 Cumulative pore size distributions of the Fuller's Earth

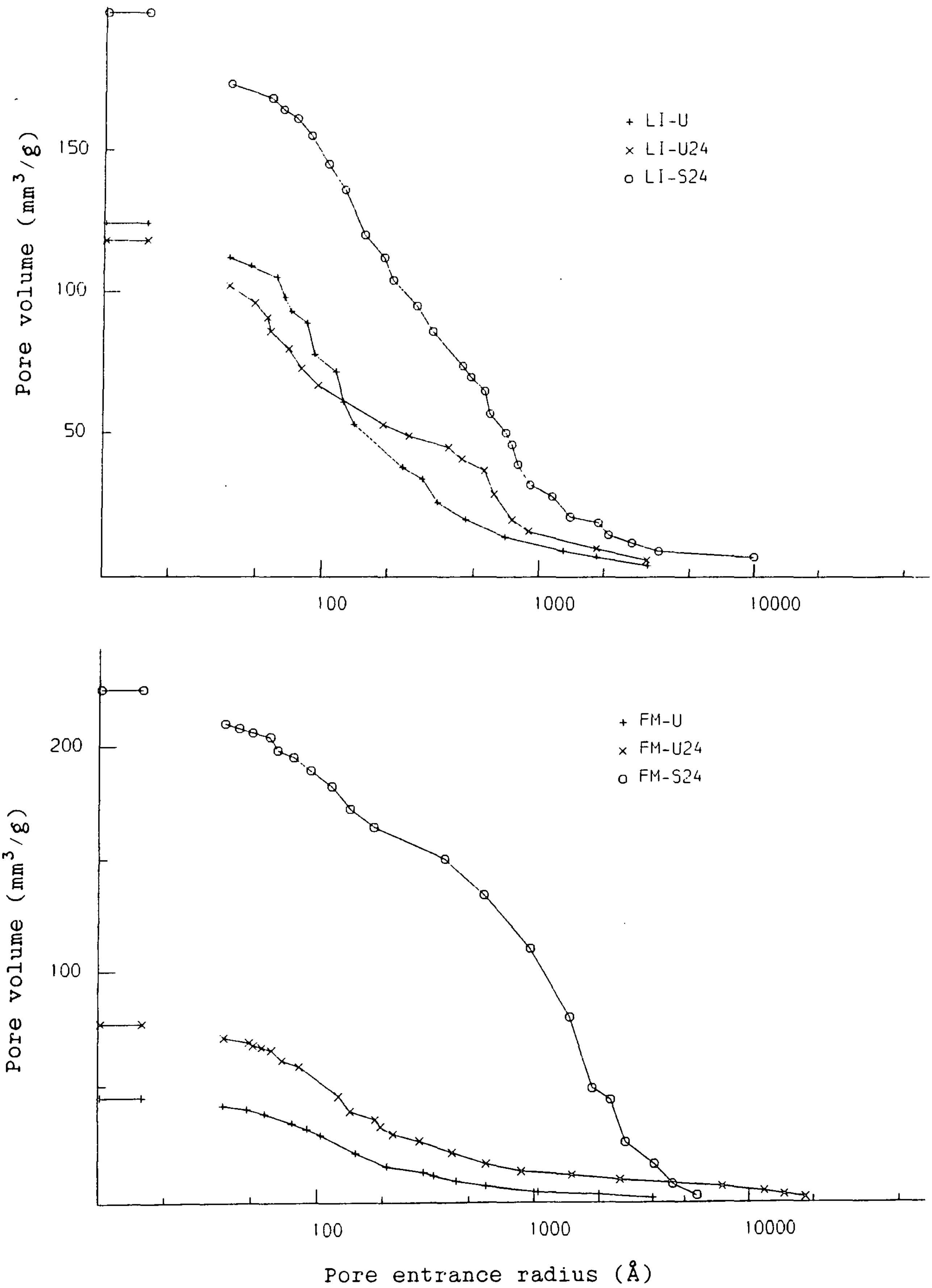


Figs. B-3-4(Top) and B-3-5(Bottom) Cumulative pore size distributions of the Oxford Clay





Figs. B-3-6(Top) and B-3-7(Bottom) Cumulative pore size distributions of the Lias Clay and Flockton mudstone



APPENDIX C CONSOLIDATION AND SWELLING

C-1 Tests in Modified Oedometers

C-1-1 Apparatus

1. Two modified fixed-ring oedometers were constructed, using highly corrosion-resistant stainless steel 316 S16 (Fig. C-1). The ring has a diameter of 38 mm and a height of 15.2 mm, and a thickness of either 2 or 3 mm to accommodate 24,280 or 34,340 kN/m^2 pressures.
2. The filters used above and beneath specimens are made up of the same material as in the pore fluid squeezer (Appendix A-4). All the filters used in this project were cleaned regularly with HCl, HNO_3 and boiling water.
3. Load was applied with the normal oedometer system (up to 10,880 kN/m^2) as well as with the level system of a large shear box machine (4,160-34,340 kN/m^2).
4. The displacement was monitored by dial gauges reading to 0.002 mm and also by L.V.D.T. transducers with a 0.001 mm sensitivity connected to the laboratory data logger.
5. The total thickness of the ring and the cell was 12 mm, this being considered sufficiently robust to maintain a condition of one-dimensional consolidation and swelling.
6. The cell and reservoirs were covered by paper or plastic film during tests to minimize air pollution and cell fluid evaporation.

C-1-2 Procedures

(a) For Undisturbed Samples

1. Softer samples were cut into a suitable dimension and pressed into the rings. For the brittle Flockton mudstone and Lias Clay, samples were sawed into a suitable size and then ground to fit the

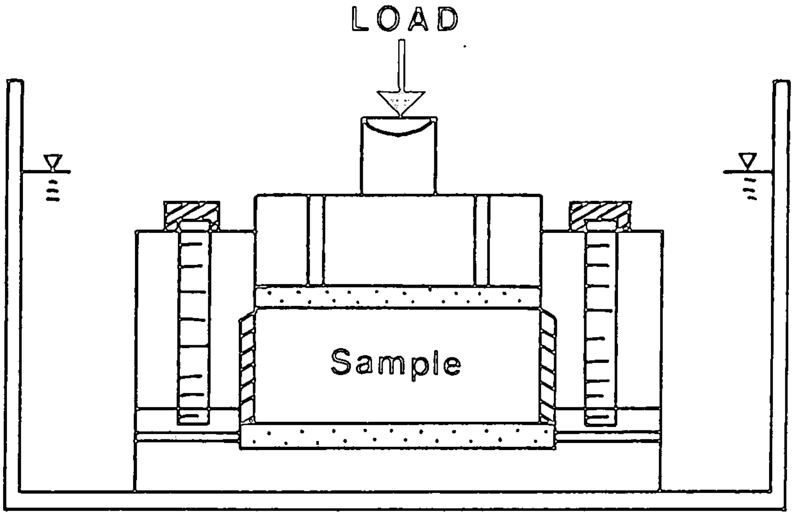


Fig. C-1 Modified oedometer (scale 1:1)

rings. Silicon grease was applied on the inside surface of the rings to reduce the side friction to a minimum. All the samples have almost horizontal fissility so that the resultant specimens had the fissility normal to the loading axis.

2. The apparatus was assembled and half the estimated effective overburden pressure (see Table 5-1) was exerted first.
3. After the displacement stopped, the cell was flooded with deionized water and load was applied gradually to maintain no displacement. After the maximum pressure was reached, the readings of the dial gauge and the transducer were recorded and the maximum pressure was taken to be the swelling pressure.
4. Afterwards, pressure was increased by an increment ratio of about unity up to pressures of 2,720, 10,880 kN/m^2 and the maximum pressure (24,280 or 34,340 kN/m^2). It was then decreased by the same ratio down to the minimum (1.47 or 1.72 kN/m^2). For some samples, a pressure decrement ratio of two or more was used. For consolidation each pressure increment was maintained for 24 hours; whereas for swelling each decrement was kept in operation either for 24 hours or until the process had reached 100 per cent primary swelling, based on the estimation by the square root of time fitting method. For recompression each pressure increment was maintained until the consolidation had reached 100 per cent primary swelling in order to reduce the testing period.
5. The cell water was collected at the end of each test for a chemical analysis of Na, K, Ca and Mg by atomic adsorption spectrometry.
6. The thickness and the weight of the specimen were measured and the moisture content determined.

(b) For Remoulded Samples

1. Each sample was immersed in distilled water and air-dried repeatedly (referred to as slaking in the text) for a period ranging from a week to a month, and then completely disintegrated by gently pressing in a mortar. The disintegrated samples were also used in the determination of the Atterberg limits.
2. The disintegrated samples were then mixed with distilled water to be like slurries, having a liquidity index of *c*. 1.5, and then left in sealed beakers overnight.
3. The slurries were carefully placed in the pore fluid squeezer (see Appendix A-3), and it was ensured that little air was left in the slurries. Consolidation was carried out in the squeezer by steps, up to *c*. 100 kN/m^2.
4. The consolidated slurries were then removed from the squeezer to the modified oedometers and tested as in the normal procedure for the undisturbed samples.

(c) For the Undisturbed Samples Replaced by n-decane

1. Samples were set in the rings as in (a).
2. Then the samples were placed in a beaker containing acetone. Vacuum pressure was applied with a gradual addition of n-decane into the beaker for a week. The samples were always kept immersed completely in the liquids.
3. The samples containing n-decane were reconsolidated to 10,880 kN/m^2 and unloaded to the minimum pressure, using a pressure decrement ratio of about two.

(d) For the Remoulded Sample Mixed with n-decane

1. The disintegrated samples from (b) were air-dried and mixed with acetone and then air-dried again.
2. Slurries were made by adding n-decane to the treated samples and

left in sealed beakers overnight as well.

3. The slurries were then tested as in the normal procedure for the remoulded samples.

(e) For the Samples Remoulded with Water and Replaced by n-decane

1. The samples were prepared as in (b) and consolidated up to 10,880 kN/m^2.
2. And then the samples were treated and tested as in (c).
3. The thickness of specimens were measured using a micrometer before the replacement of pore fluid and also after the test.

(f) For the Remoulded Na-saturated Fuller's Earth Sample

1. The disintegrated Fuller's Earth sample was first washed with distilled water, and then a 1M NaCl solution was added and the mixtures centrifuged three times.
2. The resultant slurries were mechanically shaken for an hour.
3. The Na-saturated slurries were then tested as for the normal remoulded samples.

C-2 Tests in the Swell Cell

C-2-1 Apparatus

1. The swell cell is shown in Fig. C-2. The material used to manufacture the swell cell is the same as for the modified oedometers. The ring has a diameter of 74 mm and a height of 30 mm. The total thickness of the ring and its holder is 5 mm and this is considered thick enough to maintain a condition of one-dimensional swelling (the greatest swelling pressure measured with this cell is 489 kN/m^2).
2. The porous discs used were made of corundum, 5 mm thick.
3. The weight of the loading plate and the upper porous disc is 816

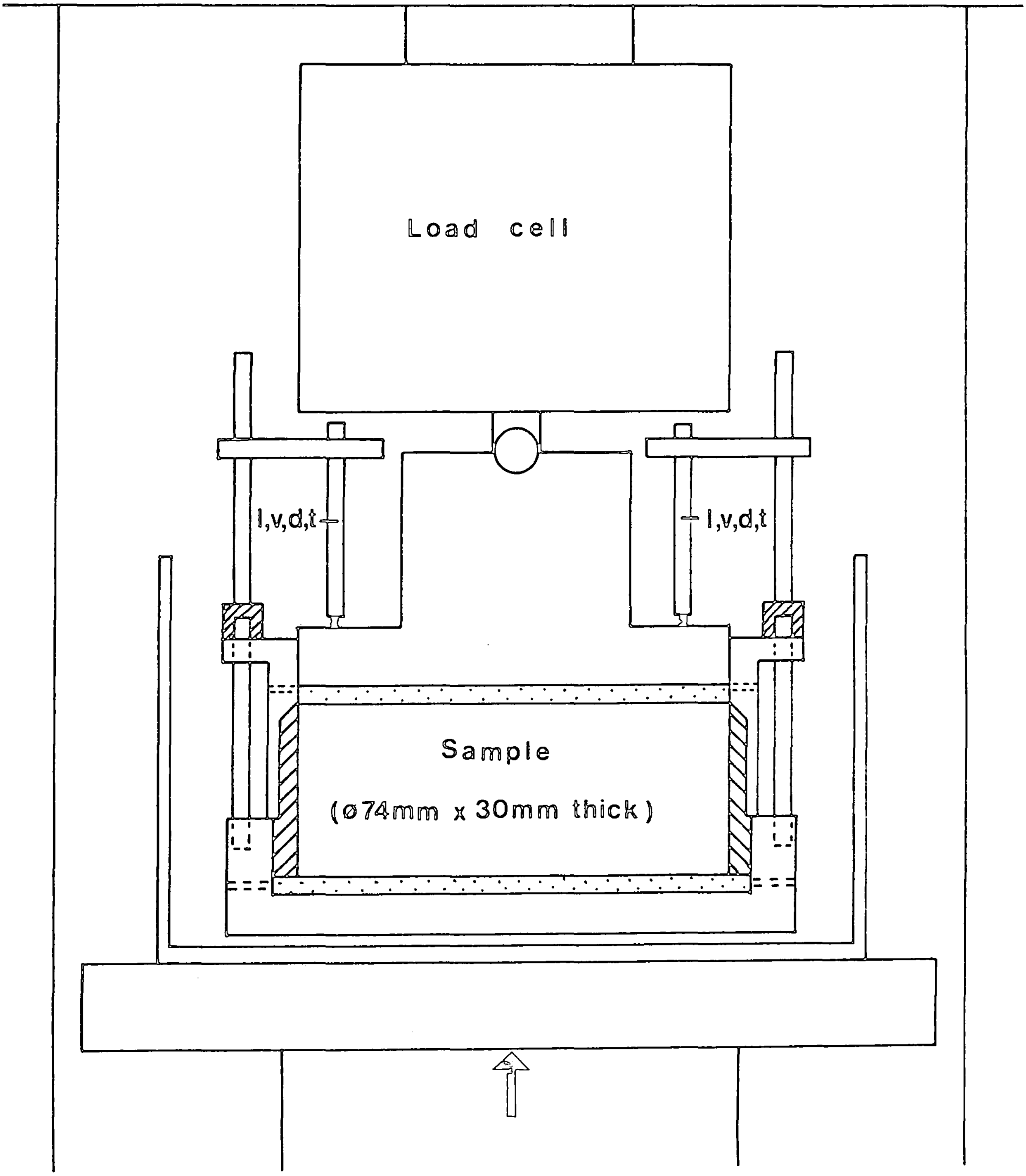


Fig. C-2 Swell Cell (scale 1:1)

grams, equivalent to 1.86 kN/m^2. The load cell against which swelling is measured (Fig. C-2) has a capacity of 20 kN and a sensitivity of 0.015 kN (3.5 kN/m^2).

4. Displacement is monitored by two L.V.D.T. transducers with a maximum displacement of 5 mm and a sensitivity of 0.001 mm. The readings of the load cell and the L.V.D.T. transducers were recorded by the laboratory data logger.

C-2-2 Procedure

1. Samples were cut into a suitable dimension and pressed into the ring. Silicon grease was applied on the inside surface of the ring.
2. The apparatus was assembled and half the estimated effective overburden pressure (see Table 5-1) was applied to the specimen.
3. After the displacement stopped, the readings of the load cell and the transducers were recorded, and then the cell was flooded with distilled water first. The piston was adjusted regularly to maintain zero specimen swelling. Ten hours was found to be sufficient to reach a maximum swelling pressure; however, 24 hours was allowed before the next step.
4. The cell water was replaced with a reconstituted pore fluid (Na, K, Ca and Mg-chloride), the composition of which was obtained in Appendix A-3. Then Step 3 was carried out again. Actually very little displacement was found in this step.
5. The piston was lowered through small distance to allow specimens to swell and left for 24 hours to reach equilibrium between pressure and displacement.
6. After pressure was reduced to the minimum (1.86 kN/m^2), reconsolidation was carried out by steps to reach the original sample thickness. Then the cell water was replaced with distilled

water again and Step 5 repeated.

7. After pressure was reduced to the minimum again, the cell water was collected for chemical analysis of Na, K, Ca and Mg by atomic adsorption spectrometry. The thickness and weight of the specimen were measured and the moisture content determined.

C-3 Calculation in Figures 4-11 and 4-13

Sample : Remoulded Oxford Clay OX10-S

P_c=10,880 kN/m^2,

t= time in year,

T_v= time factor,

H= length of drainage = 1 m,

C_{vs}= coefficient of swelling, given in Table C-1-4,

Δe= void ratio increase at time t,

e_o, e_p= void ratios at the beginning of each unloading and at the end of primary swelling, respectively, from Table C-1-4,

SP= swelling percentage,

Δw= moisture content increase at time t,

G_s= specific gravity of the sample.

From Equation 4-6, the time is calculated as:

$$t = T_v H^2 / c_{vs}$$

$$= T_v / c_{vs} \qquad \text{C-1}$$

The increases in void ratio and moisture content are as follows:

$$\Delta e = (e_p - e_o) \times SP\% \qquad \text{C-2}$$

$$\Delta w = \Delta e / G_s \qquad \text{C-3}$$

From the measured swelling rate curves, some examples of which are given in Fig. 4-5-9, T_v and SP are obtained. And then t, Δe and $\Delta \omega$ are calculated from Equations C-1 to -3. The isochrones of void ratio in consolidation are derived from the same procedure.

C-4 An Example of R-A Calculation

Sample: London Clay LC-U (see the definition of the symbols in section 5-1)

(1) In the distilled water bath

$C_o = 2.66\text{x}10^{-4}\text{M} = 2.66\text{x}10^{-7}\text{mmole/cm}^3$ (from Table C-4)

$v = 1.5$ (calculated according to the concentrations of mono- and di-valent cations)

At $P_s = 412\ \text{kN/m}^2$ (Table C-3)
$\quad = 4.07$ atm

$\log P_s/RTC_o = \log(4.07/82.056 \text{ x } 293 \text{ x } 2.66\text{x}10^{-7}$
$\quad = 2.804$

According to Bolt's (1956) table on the relationship between $\log P_s/RTC_o$ and $v(\beta C_o)^{1/2}(x_o+d)$, the latter is then derived by interpolation:

$v(\beta C_o)^{1/2}(x_o+d) = 0.131$

$x_o+d = 0.131/1.5(10^{15} \text{ x } 2.66\text{x}10^{-4})^{1/2}$
$\quad = 16.9\text{x}10^{-8}$ cm = 16.9 A

(2) In the reconstituted pore water bath

$C_o = 3.07\text{x}10^{-2}$ M = $3.07\text{x}10^{-5}$ mole/cm^3

$v = 1.8$

Using the x_o+d value in (1), the following value is calculated:

$v(\beta C_o)^{1/2}(x_o+d) = 1.8(10^{15} \text{ x } 3.07\text{x}10^{-2})^{1/2} \text{ x } 16.9\text{x}10^{-8}$
$\quad = 1.685$

By interpolation (the same procedure as in (1)), the equivalent $\log P_s/RTC_o$ value is derived:

$\log P_s/RTC_o = 0.278$

$P_s/RTC_o = 1.897$

$P_s = 82.056 \text{ x } 293 \text{ x } 3.07\text{x}10^{-5} \text{ x } 1.897$
$\quad = 1.400$ atm.
$\quad = 142\ \text{kN/m}^2$

The physico-chemical force difference, R-A, is:

$R\text{-}A = P_{s(1)} - P_{s(2)} = 412 - 142 = 270\ \text{kN/m}^2$

Table C-1 Results of the consolidation-swelling tests of the undisturbed (U) and remoulded (S) samples in the modified oedometers

C-1-1 London Clay LC

LC-U Initial mc.=25.2% Final m.c.=27.7%

Pressure (kN/m^2)	Void ratio	c_v/c_s (m^2/yr) (t_{50})	(t_{90})
204	0.709		
680	0.685		
1360	0.663		
2720	0.627	0.798	0.511
1360	0.634	0.603	0.431
680	0.652	0.332	0.249
340	0.674	0.170	0.186
170	0.697	0.0854	0.0878
85.0	0.730	0.0578	0.0625
42.5	0.764	0.0501	0.0583
21.2	0.796		
42.5	0.790		
85.0	0.776		
170	0.760		
340	0.737		
680	0.712		
1360	0.676		
2720	0.626		
5440	0.569		0.321
10880	0.491	0.709	0.602
5440	0.498	0.381	0.340
2720	0.520	0.232	0.211
1360	0.549	0.118	0.0978
680	0.584	0.0651	0.0637
340	0.625	0.0503	0.0492
170	0.671	0.0310	0.0343
85.0	0.714	0.0202	0.0231
42.5	0.750	0.0146	0.0155
21.2	0.749		
42.5	0.770		
85.0	0.757		
170	0.741		
340	0.718		
680	0.686		
1360	0.659		
2720	0.613		
4160	0.575		
8280	0.504		0.334
16290	0.428		0.306
24280	0.374	0.529	0.420
16290	0.386	0.392	0.332
8280	0.415	0.210	0.183
4160	0.450	0.104	0.0957
1360	0.517	0.0633	0.0601
680	0.558	0.0477	0.0472
340	0.602	0.0282	0.0291
170	0.648	0.0193	0.0219
85.0	0.689	0.0140	0.0161
42.5	0.724	0.0104	0.0115
21.2	0.740	0.00921	0.00918
1.72	0.749		

LC-S Final m.c.=26.1%

Pressure (kN/m^2)	Void ratio	c_v/c_s (m^2/yr) (t_{50})	(t_{90})
170	1.213		0.193
340	1.089		0.218
680	0.955		0.289
1360	0.826		0.252
2720	0.705	0.587	0.451
1360	0.730	0.256	0.206
680	0.766	0.171	0.147
340	0.808	0.104	0.100
170	0.848	0.0637	0.0725
85.0	0.886	0.0536	0.0596
42.5	0.910	0.0251	0.0256
21.2	0.928		
42.5	0.947		
85.0	0.940		
170	0.912		
340	0.868		
680	0.817		
1360	0.758		
2720	0.689		0.242
5440	0.586		0.219
10880	0.476	0.306	0.249
5440	0.503	0.165	0.147
2720	0.543	0.107	0.0993
1360	0.585	0.0744	0.0732
680	0.629	0.0612	0.0605
340	0.671	0.0401	0.0388
170	0.712	0.0297	0.0322
85.0	0.743	0.0132	0.0202
42.5	0.770	0.0118	0.0116
21.2	0.784		
42.5	0.784		
85.0	0.769		
170	0.750		
340	0.725		
680	0.696		
1360	0.655		
2720	0.613		
4160	0.574		
8280	0.502		
16290	0.405		0.217
24280	0.342	0.394	0.309
16290	0.358	0.272	0.207
8280	0.396	0.136	0.117
4160	0.437	0.0795	0.0703
1360	0.507	0.0530	0.0486
680	0.549	0.0448	0.0426
340	0.588	0.0292	0.0319
170	0.622	0.0164	0.0121
85.0	0.649	0.0122	0.0104
42.5	0.668	0.00908	0.0114
21.2	0.683	0.00773	0.00987
1.72	0.707		

Table C-1-2 London Clay LCW

LCW-U Initial m.c.=27.3% Final m.c.=30.1%

Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})
361	0.756		
680	0.734		
1360	0.705		
2720	0.656	0.482	0.339
1360	0.667	0.285	0.172
680	0.688	0.193	0.148
340	0.712	0.0922	0.0805
170	0.741	0.0419	0.0457
85.0	0.765	0.0267	0.0301
42.5	0.783	0.0218	0.0250
21.2	0.794		
42.5	0.804		
85.0	0.791		
170	0.773		
340	0.744		
680	0.714		
1360	0.683		
2720	0.652		
5440	0.574		0.154
10880	0.476	0.411	0.329
5440	0.490	0.192	0.168
2720	0.516	0.129	0.112
1360	0.561	0.0711	0.0648
680	0.606	0.0509	0.0487
340	0.649	0.0324	0.0323
170	0.689	0.0221	0.0247
85.0	0.724	0.0158	0.0171
42.5	0.761	0.00917	0.00940
21.2	0.781		
42.5	0.778		
85.0	0.759		
170	0.734		
340	0.703		
680	0.674		
1360	0.640		
2720	0.597		
4160	0.561		
8280	0.486		0.167
16290	0.403		0.144
24280	0.344	0.311	0.263
16290	0.355	0.195	0.152
8280	0.391	0.124	0.101
4160	0.434	0.0650	0.0592
1360	0.522	0.0416	0.0408
680	0.573	0.0302	0.0311
340	0.618	0.0206	0.0214
170	0.667	0.0135	0.0150
85.0	0.708	0.00850	0.00944
42.5	0.745	0.00722	0.00765
21.2	0.763	0.00571	0.00594
1.72	0.791		

LCW-S Final m.c.=32.6%

Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})
510	1.051		0.155
1020	0.887		0.156
1870	0.762		0.134
3570	0.642		0.126
7140	0.521	0.270	0.223
3570	0.549	0.130	0.117
1700	0.594	0.0675	0.0694
680	0.659	0.0489	0.0536
340	0.705	0.0306	0.0517
170	0.752	0.0213	0.0268
85.0	0.801	0.0161	0.0201
42.5	0.852	0.0112	0.0134
21.2	0.890		
42.5	0.895		
85.0	0.860		
170	0.826		
340	0.780		
680	0.738		
1360	0.686		
2720	0.621		
4160	0.567		0.120
10220	0.449		0.100
24280	0.309	???	???
16290	0.322	???	???
8280	0.355	???	???
4160	0.402	0.0464	0.0495
2040	0.445	0.0385	0.0426
1020	0.494	0.0322	0.0394
510	0.542	0.0207	0.0232
255	0.588	0.0149	0.0158
85.0	0.669	0.00757	0.00810
42.5	0.726	0.00665	0.00773
21.2	0.776	0.00407	0.00624
1.72	0.867		

Table C-1-3 Fuller's Earth FE

FE-U Initial m.c.=80.2% Final m.c.=66.1%

Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})
76.5	2.401		
170	2.381		
340	2.353		
680	2.312	0.412	0.339
340	2.324	0.217	0.256
85.0	2.350	0.0905	0.0976
21.2	2.367		
85.0	2.369		
340	2.338		
680	2.309		
1360	2.259		
2720	2.126		0.0854
5440	1.856		0.0741
10880	1.577	0.208	0.170
5440	1.621	0.106	0.0867
2720	1.680	0.0855	0.0624
1360	1.741	0.0435	0.0429
680	1.797	0.0244	0.0249
340	1.851	0.0183	0.0191
170	1.891	0.0147	0.0157
85.0	1.925	0.00949	0.0104
42.5	1.957	0.00864	0.00949
21.2	1.975		
42.5	2.082		
85.0	1.987		
170	1.969		
340	1.930		
680	1.881		
1360	1.828		
2720	1.769		
4160	1.725		
8280	1.609		
16290	1.381		0.0613
34340	1.073	0.0817	0.0681
16290	1.142	0.0337	0.0334
4160	1.317	0.0203	0.0209
2040	1.429	0.0155	0.0165
1020	1.517	0.0138	0.0143
510	1.584	0.0126	0.0137
255	1.641	0.00867	0.0102
170	1.670	0.00792	0.00949
85.0	1.717	0.00710	0.00807
42.5	1.751	0.00628	0.00697
21.2	1.784	0.00561	0.00605
1.47	1.888		

FE-S Final m.c.=85.2%

Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})
170	2.990		0.0795
340	2.767		0.0713
680	2.514		0.0527
1360	2.242		0.0432
2720	1.972	0.0965	0.0886
1360	2.029	0.0539	0.0580
680	2.105	0.0341	0.0344
340	2.166	0.0141	0.0147
170	2.224	0.00965	0.00968
85.0	2.287	0.00429	0.00442
42.5	2.351	0.00413	0.00421
21.2	2.415		
42.5	2.381		
85.0	2.331		
170	2.275		
340	2.209		
680	2.124		
1360	2.012		
2720	1.898		0.0325
5440	1.651		0.0297
10880	1.406	0.0793	0.0752
5440	1.494	0.0354	0.0335
2720	1.602	0.0204	0.0201
1360	1.719	0.0144	0.0146
680	1.830	0.0108	0.0119
340	1.932	0.00722	0.00798
170	2.019	0.00580	0.00591
85.0	2.091	0.00533	0.00429
42.5	2.164	0.00370	0.00382
21.2	2.227		
42.5	2.161		
85.0	2.127		
170	2.068		
340	1.990		
680	1.908		
1360	1.801		
2720	1.666		
4160	1.566		
8280	1.402		
16290	1.247		0.0214
24280	1.081	0.0391	0.0385
16290	1.144	0.0243	0.0243
8280	1.285	0.0175	0.0166
4160	1.438	0.0126	0.0132
2720	1.532	0.0108	0.0114
1360	1.665	0.00946	0.00987
680	1.792	0.00726	0.00771
340	1.898	0.00577	0.00596
170	1.976	0.00432	0.00442
85.0	2.058	0.00356	0.00371
42.5	2.120	0.00323	0.00317
21.2	2.161	0.00255	0.00272
1.72	2.236		

Table C-1-4 Oxford Clay OX10

OX10-U	Initial	Final		OX10-S	Final		
	m.c.=18.9%	m.c.=23.6%			m.c.=23.2%		
Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})	$C_\alpha/C_{\alpha s}$
85.0				0.926		0.254	
170				0.856		0.334	0.0090
173	0.551						
340	0.544			0.774			0.0128
680	0.532			0.690		0.470	0.0115
1360	0.506			0.602		0.624	0.0109
2720	0.465	2.20	1.58	0.519	1.94	1.61	0.0106
1360	0.473	0.801	0.634	0.529	0.930	0.801	0.0010
680	0.486	0.372	0.344	0.547	0.426	0.378	0.0019
340	0.507	0.180	0.170	0.570	0.220	0.217	0.0020
170	0.531	0.141	0.133	0.591	0.114	0.112	0.0045
85.0	0.557	0.0960	0.0973	0.614	0.0583	0.0583	0.0045
42.5	0.580	0.0481	0.0522	0.634	0.0385	0.0382	0.0048
21.2	0.602			0.644			0.0047
42.5	0.610			0.665			
85.0	0.594			0.651			
170	0.576			0.635			
340	0.551			0.616			
680	0.518			0.595			
1360	0.492			0.567			
2720	0.459			0.503		0.574	
5440	0.414			0.443		0.628	0.0087
10880	0.354	3.15	1.77	0.371	1.83	1.55	0.0098
5440	0.363	0.763	0.678	0.383	0.675	0.552	0.0008
2720	0.380	0.432	0.375	0.401	0.360	0.322	0.0020
1360	0.402	0.263	0.240	0.423	0.187	0.173	0.0024
680	0.423	0.169	0.135	0.448	0.101	0.0981	0.0042
340	0.449	0.0952	0.0766	0.480	0.0612	0.0580	0.0038
170	0.475	0.0631	0.0633	0.515	0.0337	0.0328	0.0065
85.0	0.502	0.0394	0.0429	0.550	0.0281	0.0278	0.0075
42.5	0.528	0.0292	0.0294	0.573	0.0220	0.0213	0.0072
21.2	0.544			0.586			0.0068
42.5	0.563			0.612			
85.0	0.550			0.595			
170	0.532			0.574			
340	0.511			0.553			
680	0.479			0.527			
1360	0.449			0.498			
2720	0.417			0.460			
4160	0.396			0.432			
8280	0.356		0.512	0.385			
16290	0.312		0.452	0.321		0.635	
34340	0.233	1.80	1.31	0.235	1.80	1.54	0.0091
16290	0.258	0.760	0.618	0.248	0.628	0.559	0.0008
8280	0.282	0.391	0.280	0.267	0.320	0.301	0.0010
4160	0.307	0.222	0.201	0.289	0.119	0.108	0.0014
2720	0.319	0.134	0.137				
1360	0.344	0.106	0.108	0.322	0.0681	0.0659	0.0020
680	0.373	0.0738	0.0719	0.350	0.0394	0.0495	0.0041
340	0.404	0.0479	0.0473	0.377	0.0295	0.0302	0.0065
170	0.438	0.0325	0.0297	0.404	0.0200	0.0198	0.0055
85.0	0.471	0.0241	0.0277	0.429	0.0150	0.0150	0.0063
42.5	0.505	0.0154	0.0160	0.447	0.00634	0.00609	0.0068
21.2	0.531	0.0121	0.0130	0.459	0.00574	0.00599	0.0068
1.47	0.600			0.478			

Table C-1-5 Oxford Clay OX19

OX19-U Initial m.c.=21.3% Final m.c.=28.0%

Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})
314	0.644		
680	0.630		
1360	0.593		
2720	0.551	0.747	0.523
1360	0.564	0.250	0.190
680	0.590	0.132	0.122
340	0.618	0.0672	0.0637
170	0.645	0.0638	0.0643
85.0	0.677	0.0581	0.0595
42.5	0.697	0.0442	0.0492
21.2	0.713		
42.5	0.719		
85.0	0.704		
170	0.681		
340	0.643		
680	0.617		
1360	0.586		
2720	0.551		
4160	0.525		
8280	0.469		0.341
16290	0.390		0.295
34340	0.286	0.207	0.130
16290	0.314	0.191	0.126
8280	0.348	0.126	0.114
4160	0.388	0.0997	0.104
2040	0.420	0.0861	0.0848
1020	0.457	0.0561	0.0577
510	0.495	0.0448	0.0514
255	0.534	0.0308	0.0366
85.0	0.591	0.0186	0.0252
42.5	0.626	0.0135	0.0199
21.2	0.647	0.00981	0.0137
1.47	0.720		

OX19-S Final m.c.=27.2%

Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})
170	1.078		0.301
340	0.975		0.238
680	0.850		0.263
1360	0.737		0.293
2720	0.635	1.01	0.672
1360	0.652	0.337	0.292
680	0.679	0.184	0.174
340	0.715	0.104	0.0896
170	0.755	0.0577	0.0590
85.0	0.792	0.0391	0.0404
42.5	0.824	0.0311	0.0397
21.2	0.844		
42.5	0.858		
85.0	0.849		
170	0.818		
340	0.771		
680	0.722		
1360	0.671		
2720	0.610		0.337
5440	0.530		0.305
10880	0.443	0.609	0.523
5440	0.462	0.284	0.239
2720	0.493	0.154	0.132
1360	0.528	0.0990	0.0851
680	0.566	0.0599	0.0568
340	0.606	0.0476	0.0476
170	0.647	0.0313	0.0331
85.0	0.687	0.0158	0.0141
42.5	0.723	0.00915	0.00747
21.2	0.752		
42.5	0.751		
85.0	0.737		
170	0.719		
340	0.671		
680	0.620		
1360	0.571		
2720	0.521		
4160	0.491		
8280	0.428		
16290	0.378		0.288
34340	0.276	0.334	0.391
16290	0.299	0.222	0.226
8280	0.329	0.135	0.121
4160	0.363	0.0669	0.0646
1360	0.428	0.0483	0.0448
680	0.466	0.0341	0.0382
340	0.507	0.0305	0.0311
170	0.543	0.0168	0.0183
85.0	0.579	0.0154	0.0186
42.5	0.607	0.0131	0.0141
21.2	0.630	0.00599	0.00706
1.47	0.714		

Table C-1-6 Lias Clay LI

LI-U Initial m.c.=12.2% Final m.c.=11.8%

Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})
1020	0.332		
2720	0.306	8.86?	6.18?
1360	0.311	6.12	3.69
340	0.326	2.88	2.76
85.0	0.341	2.01	1.89
21.2	0.351		
85.0	0.349		
340	0.336		
680	0.325		
2720	0.302		
5440	0.281		
10880	0.254	4.64	2.41
2720	0.274	2.25	1.47
680	0.296	0.952	0.646
170	0.311	1.11	0.921
21.2	0.335		
170	0.326		
680	0.309		
2720	0.286		
4160	0.277		
8280	0.258		
14270	0.236		3.06
24280	0.206	3.09	1.12
10220	0.215	0.255	0.183
4160	0.230	0.132	0.106
1100	0.251	0.133	0.120
255	0.274	0.176	0.131
85.0	0.288	0.0965	0.0681
21.2	0.297	0.0542	0.0344
1.72	0.308		

LI-S
Final m.c.=19.8%

Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (m^2/yr) (t_{50})	(t_{90})
340	0.701		1.92
680	0.639		1.85
1360	0.575		1.82
2720	0.507	5.42	3.91
1360	0.514	1.81	1.33
680	0.530	0.722	0.523
340	0.547	0.388	0.189
170	0.566	0.253	0.164
85.0	0.585	0.159	0.123
42.5	0.603	0.0978	0.0766
21.2	0.617		
42.5	0.614		
85.0	0.605		
170	0.592		
340	0.577		
680	0.557		
1360	0.535		
2720	0.502		2.52
5440	0.446		1.97
10880	0.385	5.33	2.77
5440	0.395	1.77	1.30
2720	0.411	0.776	0.722
1360	0.428	0.470	0.404
680	0.446	0.275	0.231
340	0.463	0.176	0.141
170	0.480	0.0902	0.0861
85.0	0.498	0.0528	0.0528
42.5	0.516	0.0410	0.0420
21.2	0.530		
42.5	0.546		
85.0	0.541		
170	0.530		
340	0.515		
680	0.499		
1360	0.473		
2720	0.445		
4160	0.425		
8280	0.381		1.56
16290	0.345		1.14
24280	0.308	3.72	2.93
16290	0.312	1.57	1.06
8280	0.327	0.681	0.445
4160	0.346	1.03	0.514
2720	0.360	0.438	0.353
1360	0.376	0.259	0.226
680	0.393	0.182	0.150
340	0.413	0.0918	0.0741
170	0.431	0.0508	0.0470
85.0	0.452	0.0366	0.0378
42.5	0.468	0.0312	0.0356
21.2	0.479	0.0254	0.0347
1.72	0.504		

Table C-1-7 Flockton mudstone FM

FM-U
Initial m.c.=3.6%
Final m.c.=7.7%

Pressure (kN/m^2)	Void ratio	c_{vs} (t_{50})	$(m^2/yr.)$ (t_{90})
3620	0.125		
5440	0.122		
10880	0.118	1.47	1.05
680	0.130	0.861	0.553
170	0.159	0.745	0.520
21.2	0.207		
170	0.180		
680	0.157		
4160	0.131		
16290	0.113		
34340	0.087	1.04	0.522
4160	0.102	0.351	0.276
340	0.131	0.232	0.175
85.0	0.162	0.203	0.169
21.2	0.194	0.155	0.102
1.47	0.206		

FM-S
Final m.c.=22.5%

Pressure (kN/m^2)	Void ratio	c_v/c_{vs} (t_{50})	$(m^2/yr.)$ (t_{90})
170	0.800		1.10
340	0.755		1.11
680	0.693		1.21
1360	0.617		1.39
2720	0.525	12.4	9.46
1360	0.529	3.41	2.47
680	0.546	1.29	0.962
340	0.569	0.593	0.429
170	0.599	0.344	0.255
85.0	0.628	0.219	0.189
42.5	0.652	0.154	0.141
21.2	0.672		
42.5	0.686		
85.0	0.685		
170	0.670		
340	0.651		
680	0.602		
1360	0.566		
2720	0.532		1.61
5440	0.437		1.46
10880	0.349	8.14	6.50
5440	0.353	4.19	3.07
2720	0.366	1.61	1.24
1360	0.387	0.760	0.640
680	0.413	0.423	0.334
340	0.444	0.223	0.184
170	0.478	0.123	0.113
85.0	0.514	0.193?	0.194?
42.5	0.532	0.0457	0.0602
21.2	0.563		
42.5	0.584		
85.0	0.578		
170	0.568		
340	0.541		
680	0.508		
1360	0.472		
2720	0.429		
4160	0.401		
8280	0.350		
16290	0.304		1.52
34340	0.212	2.02	0.949
16290	0.226	1.22	0.848
8280	0.249	0.669	0.640
4160	0.274	0.669	0.319
2720	0.291	0.311	0.262
1360	0.322	0.195	0.157
680	0.354	0.128	0.102
340	0.386	0.0769	0.0716
170	0.423	0.0552	0.0656
85.0	0.456	0.0328	0.0410
42.5	0.493	0.0245	0.0261
21.2	0.523	0.0344	0.0366
1.47	0.576		

Table C-1-8 Fuller's Earth saturated with NaCl

FE-S-Na Final m.c. =243.7%

Pressure	Void	c_v/c_{vs}	(m^2/yr)
(kN/m^2)	ratio	(t_{50})	(t_{90})
42.5	7.514		0.0138
85.0	7.005		0.0161
170	6.006		0.0147
340	5.007		0.0157
680	4.044		0.0155
1360	3.081		0.0152
2720	2.265	0.0388	0.0319
1360	2.377	0.00514	0.00495
680	2.603	0.00517	0.00486
340	2.897	0.00344	0.00319
170	3.351	0.000810	0.000987
85.0	3.912	0.000571	0.000590
42.5	4.533	0.000483	0.000502
21.2	5.108		
42.5	5.092		
85.0	4.825		
170	4.477		
340	4.042		
680	3.501		
1360	2.922		
2720	2.189		
5440	1.587		0.00788
10880	0.827	0.00908	0.00460
5440	0.986	0.00237	0.00208
2720	1.218	0.00183	0.00183
1360	1.460	0.00117	0.00117
680	1.728	0.000848	0.000829
340	2.149	0.000564	0.000577
170	2.733	0.000467	0.000511
85.0	3.414	0.000388	0.000407
42.5	4.192	0.000272	0.000260
21.2	4.951	0.000274	0.000312
1.72	6.406		

Table C-2 Results of the consolidation-swelling tests with n-decane of the undisturbed (U) and remoulded (S) samples in the modified oedometers

London Clay LCW-U
replaced with
n-decane

Initial m.c.=27.9%
Final n-decane
content =17.3%
Final m.c.=2.0%

Pressure (kN/m^2)	Void ratio
361	0.671
680	0.667
1360	0.649
2720	0.612
5440	0.558
10880	0.489
2720	0.522
680	0.578
340	0.611
170	0.635
85.0	0.654
21.2	0.673
1.72	0.686

Oxford Clay OX10-U
replaced with
n-decane

Initial m.c.=19.2%
Final n-decane
content=12.5%
Final m.c.=1.8%

Pressure (kN/m^2)	Void ratio
173	0.516
340	0.504
680	0.487
1360	0.463
2720	0.427
5440	0.394
10880	0.351
2720	0.367
680	0.395
340	0.412
170	0.427
85.0	0.439
21.2	0.453
1.47	0.462

London Clay LCW-S
air-dried and
remoulded
with n-decane

Final n-decane
content =16.1%

Pressure (kN/m^2)	Void ratio
170	1.308
340	1.241
510	1.187
1020	1.070
1870	0.952
3570	0.816
7140	0.689
1700	0.710
340	0.732
85.0	0.741
21.2	0.745
340	0.739
1700	0.724
4160	0.699
8280	0.660
16290	0.581
24280	0.535
8280	0.544
4160	0.556
1700	0.566
340	0.578
21.2	0.586
1.72	0.589

London Clay LCW-S
remoulded with water
and replaced with
n-decane

Final n-decane
content =19.7%
Final m.c.=2.4%

Pressure (kN/m^2)	Void ratio
with water	
170	1.164
340	1.086
510	1.031
1020	0.905
1870	0.778
3570	0.654
7140	0.532
3570	0.557
1700	0.609
680	0.670
340	0.715
170	0.764
85.0	0.813
42.5	0.850
21.2	0.883
1.72	0.932
replaced with n-decane	
21.2	0.792
85.0	0.767
340	0.725
680	0.693
1870	0.643
3570	0.606
7140	0.558
1700	0.585
340	0.657
85.0	0.724
21.2	0.770
1.72	0.789

Table C-2 (continued)

Remoulded with water and replaced with n-decane

Pressure (kN/m^2)	Fuller's Earth FE-S	Oxford Clay OX19-S	Lias Clay LI-S
	Final n-decane content =50.9% Final m.c.=4.9%	Final n-decane content =17.8% Final m.c.=1.2%	Final n-decane content =13.9% Final m.c.=0.4%
	Void ratio	Void ratio	Void ratio
remoulded with water			
170	2.862	1.091	0.768
340	2.713	0.982	0.710
680	2.491	0.873	0.646
1360	2.259	0.743	0.571
2720	2.003	0.625	0.497
5440	1.734	0.521	0.435
10880	1.428	0.424	0.372
5440	1.510	0.445	0.383
2720	1.609	0.477	0.396
1360	1.718	0.516	0.415
680	1.825	0.554	0.436
340	1.919	0.595	0.452
170	2.005	0.638	0.473
85.0	2.077	0.673	0.490
42.5	2.151	0.709	0.507
21.2	2.212	0.742	0.522
1.47	2.364	0.798	0.544
replaced with n-decane			
21.2	2.030	0.685	0.529
85.0	1.988	0.669	0.522
340	1.897	0.634	0.505
1360	1.784	0.596	0.479
2720	1.712	0.571	0.464
5440	1.603	0.532	0.446
10880	1.465	0.488	0.415
2720	1.547	0.514	0.427
680	1.676	0.547	0.443
170	1.809	0.590	0.468
85.0	1.861	0.609	0.480
21.2	1.954	0.642	0.493
1.47	2.042	0.664	0.499

Table C-3 Results of the swelling tests of the undisturbed samples in the swell cell .

London Clay LC-U

Initial m.c.=25.3%
Final m.c.=28.1%

Pressure (kN/m^2)	Void ratio
Distilled water	
390	0.706
Constituted water	
393	0.706
70.6	0.720
25.5	0.728
1.86	0.736
Distilled water	
412	0.706
192	0.721
132	0.731
59.8	0.750
27.0	0.760
1.86	0.777

London Clay LCW-U

Initial m.c.=26.6%
Final m.c.=30.3%

Pressure (kN/m^2)	Void ratio
Distilled water	
489	0.741
Constituted water	
472	0.741
170	0.750
72.6	0.761
24.3	0.771
1.86	0.781
Distilled water	
505	0.741
244	0.751
110	0.770
35.3	0.797
1.86	0.829

Fuller's Earth FE-U

Initial m.c.=85.5%
Final m.c.=88.1%

Pressure (kN/m^2)	Void ratio
Distilled water	
77.5	2.400
Constituted water	
76.5	2.400
44.1	2.405
21.6	2.412
1.86	2.421
Distilled water	
80.4	2.400
42.2	2.410
19.6	2.423
1.86	2.457

Oxford Clay OX10-U

Initial m.c.=19.3%
Final m.c.=23.0%

Pressure (kN/m^2)	Void ratio
Distilled water	
180	0.542
Constituted water	
182	0.542
73.1	0.551
25.7	0.561
1.86	0.575
Distilled water	
196	0.542
85.4	0.554
31.9	0.572
1.86	0.607

Oxford Clay OX19-U

Initial m.c.=20.9%
Final m.c.=26.2%

Pressure (kN/m^2)	Void ratio
Distilled water	
345	0.623
Constituted water	
347	0.623
180	0.630
72.5	0.637
23.9	0.644
1.86	0.658
Distilled water	
367	0.623
204	0.631
87.3	0.647
25.6	0.669
1.86	0.697

Table C-4 Chemical composition of the cell waters after testing in the swell cell and the modified oedometers

Sample			Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Cl (ppm)	Total cations (M)
London Clay	LC-U	SC-D	2.78	1.10	2.85	1.11	8.0	$2.66x10^{-4}$
	LC-U	SC-P	191	35.2	513	212	--	$3.07x10^{-2}$
	LC-U	OD	8.21	5.73	12.1	5.12	35.2	$1.02x10^{-3}$
	LC-S	OD	9.40	6.41	14.8	4.81	34.5	$1.14x10^{-3}$
London Clay	LCW-U	SC-D	6.05	1.98	1.74	0.37	10.9	$3.72x10^{-4}$
	LCW-U	SC-P	1190	71.6	140	56.0	--	$5.94x10^{-2}$
	LCW-U	OD	6.82	2.71	1.96	0.50	13.4	$4.35x10^{-4}$
	LCW-S	OD	7.50	2.75	2.25	0.42	15.2	$4.70x10^{-4}$
Fuller's Earth	FE-U	SC-D	--	0.23	0.83	0.17	0.6	$3.36x10^{-5}$
	FE-U	SC-P	28.0	1.22	35.7	10.7	--	$2.58x10^{-3}$
	FE-U	OD	--	0.33	0.14	0.03	0.3	$1.32x10^{-5}$
	FE-S	OD	--	0.42	0.75	0.04	0.3	$3.11x10^{-5}$
	FE-S-Na	OD	1.43	--	--	--	--	$6.22x10^{-5}$
Oxford Clay	OX10-U	SC-D	2.66	0.80	0.59	0.18	5.2	$1.58x10^{-4}$
	OX10-U	SC-P	1100	120	685	240	--	$7.79x10^{-2}$
	OX10-U	OD	2.75	0.80	0.67	0.20	4.0	$1.65x10^{-4}$
	OX10-S	OD	3.62	0.97	0.82	0.21	7.3	$2.11x10^{-4}$
Oxford Clay	OX19-U	SC-D	65.5	0.23	12.5	0.17	85.6	$3.17x10^{-3}$
	OX19-U	SC-P	2400	79.6	801	201	--	$1.35x10^{-1}$
	OX19-U	OD	1.73	0.70	0.29	0.06	2.7	$1.03x10^{-4}$
	OX19-S	OD	9.13	1.03	3.45	1.04	16.7	$5.52x10^{-4}$
Lias Clay	LI-U	OD	11.5	0.97	0.66	0.29	18.3	$5.53x10^{-4}$
	LI-S	OD	13.1	1.20	0.72	0.23	25.0	$6.28x10^{-4}$
Flockton mudstone	FM-U	OD	11.3	0.66	0.98	0.21	16.0	$5.41x10^{-4}$
	FM-S	OD	12.9	0.75	0.95	0.26	23.5	$6.15x10^{-4}$

U : Undisturbed sample.
S : Remoulded sample.
SC : Test in the swell cell.
D : With distilled water bath.
P : With reconstituted pore water bath.
OD : Test in the modified oedometer.