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Jordmekaniske egenskaber for syv danske jorde

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Afdeling for Kulturteknik, Jyndevad
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Summary

The effects of water content upon soil mechanical properties were evaluated for soils with different texture using methods in the field as well as in the laboratory. The investigations also included comparison of methods and evaluation of the influence of soil structure upon soil mechanical properties. Seven Danish soils (5 Alfisols, 1 Inceptisol and 1 Spodosol) were investigated. The soil texture ranged from coarse sand (3% clay) to loam (15% clay).

In the field, soil strength was measured with a vane shear tester and a torsional shear box. In the laboratory the lower and upper plasticity limits were determined using a drop cone penetrometer. Soil compressibility was measured using a confined, uniaxial compression test and soil strength was measured with a drop cone penetration method and an annulus shear method. All tests were applied to samples of undisturbed soil as well as to soil samples prepared in the laboratory from air-dried, sieved soil, which were allowed to cement in a process of water saturation and subsequent drainage. The laboratory measurements were performed at six selected water potentials around field capacity.

Soil compressibility increased with increasing content of clay and was higher for remoulded than for undisturbed soil, which indicates inter-aggregate as well as intra-aggregate strength to be responsible for the resistance to severe compaction.

For soils with identical geological origin a positive, linear correlation was found between the soil cation exchange capacity and the liquid limit.

Soil cohesion estimated by the torsional shear box method was lower than vane shear strength which again was smaller than the cohesion calculated from the annulus shear measurements in soil at approximately the field water content. The shear annulus as well as the drop cone detected a higher strength in undisturbed soil than in sieved, cemented soil at identical water potential and for most soils also at comparative water contents. The drop cone method was found to be the most sensitive method to detect the decrease in strength with increasing water content.

The sandy soils were found to have lower cohesion but higher internal friction than the loamy soils. With decreasing water content, the strength increase in the sandy soils could be ascribed to an increase in soil internal friction, while the loamy soils primarily increased their cohesion.

The choice of measuring method for soil strength should be based on considerations of the purpose of the investigations,—i.e. tillage or root growth studies. Further, investigations on soil strength ought to take into account the soil macrostructure as measurements in remoulded or cemented soil do not describe the field condition.

Key words: soil strength, soil compressibility, strength and soil water content, strength and soil texture, methods for soil strength determination.

Resumé

Jordens mekaniske egenskaber blev undersøgt for syv danske jorde med forskellig geologisk oprindelse og teksturel sammensætning. I felten blev der i pløjelaget bestemt forskydningsstyrke med to metoder ved et vandindhold omkring markkapacitet. I laboratoriet bestemtes jordens modstand mod sammenpresning samt dens forskydningsstyrke. Disse målinger blev foretaget på jordprøver afdrænet til seks forskellige vandindhold omkring markkapacitet, og målingerne gennemførtes på jord i naturlig lejring såvel som sigtet jord pakket til en bestemt volumenvægt.

Jordens sammenpakkelighed ved høje tryk øgedes med stigende lerindhold i jorden og var større i forbehandlet jord end i jord i naturlig lejring med samme volumenvægt. Dette viser, at jordens sekundærstruktur har en indflydelse på dens modstand mod pakning.

De fundne værdier for jordens kohæsion var afhængig af anvendt målemetode, hvilket kan tilskrives metodernes forskellige vekselvirkning med jorden. Ved jordmekaniske undersøgelser med henblik på rodvækstbetingelser bør anvendes en metode, der måler jordstyrken i de naturlige brudflader.

Forskydningsstyrken i sandede jorde fandtes at kunne tilskrives høje værdier for indre friktion, mens kohæsionen i disse jorde var lav. Med faldende vandindhold blev der i alle jorde fundet en øget forskydningsstyrke, som for de lerholdige jorde skyldtes en øget kohæsion, mens de sandede jorde primært øgede deres indre friktion.

Nøgleord: forskydningsstyrke, sammenpakkelighed, jordstyrke og vandindhold, jordstyrke og tekstur, målemetoder til jordstyrkebestemmelse.

Introduction

Production of food in agriculture implies cultivation of the soil. The interaction between the tillage implement and the soil has been observed by man for thousands of years, but the knowledge of the soil mechanical conditions in physical terms is still rather poor. With the increasing amount and power of machinery used in the traffic and cultivation of soil it is of increasing importance to improve our knowledge of the soil mechanical properties. This is to avoid detrimental effects of soil compaction as well as to reduce the amount of tillage to be carried out when growing the crops. Especially, the change in soil behaviour with changing water content is of interest in relation to soil tillage, many tillage operations being possible only in a rather narrow range of water content.

Many investigations in soil mechanical conditions have been based upon measurements on soil in a remoulded state. For agricultural purposes, however, it is important to detect the influence of soil macrostructure.

The present investigation was planned to take into account the elements mentioned above. In seven soils of differing texture and origin several soil mechanical properties were measured in remoulded as well as in undisturbed soil samples and at a range of water content around field capacity. Field methods were used as well.

Size distribution of particles in a dispersed as well as in an aggregated state and the pore size distribution of the soils in investigation are described elsewhere (Schjønning, 1992).

Materials and methods

Soils

A total of 7 soils was included in the investigation, Figure 1. The geological origin of the soils is glacial deposits except soil No. 1, which is developed on marine sediments. Soil type according to the USDA Soil Taxonomy System and topsoil texture are given in Table 1.

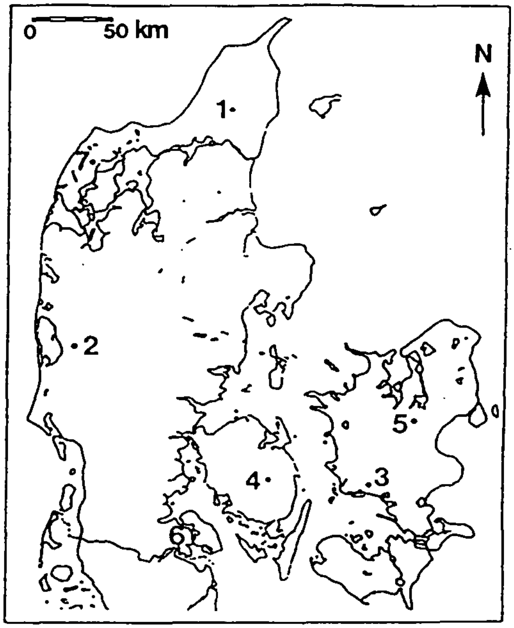


Figure 1. Location of soils in investigation.

At each location a representative field of the area was chosen, which was grown with a winter wheat crop. Sampling and field measurements took place in the spring, when the soil had a water content at about field capacity. The soil had been ploughed and subsequently harrowed in the autumn and then sown with a traditional drill. In an area of the field comprising about 0.5 ha (~ 50 m×100 m) 6 plots were randomly selected and used for field measurements and as sampling sites.

Sampling

In the middle of the plough layer (8-12 cm depth) 18 cores of undisturbed soil (diameter = 61.0 mm, height = 34.2 mm, volume = 100.0 cm^3) were sampled at each plot making up a total of 108 samples at each location. An amount of about 90 kg of remoulded soil was also collected for each soil.

In the soil layer beneath the cultivated top soil (mostly at a depth of 30-40 cm and always below the mould) 6 cores of undisturbed soil were sampled at each plot making up a total of 36 samples from this soil layer. Additionally, an amount of about 90 kg remoulded soil was collected.

Table 1. Soil type (Soil Taxonomy System) and texture for investigated soils.

Location	Field	Soil type	Depth	Texture (% w/w)				
No. Name			cm	Org. matter	Clay	Silt	Fine sand	Coarse sand
		μm:			< 2	2-20	20-200	200-2000
1 Tylstrup	D 3 west	Cumulic Haplumbrept	0-20	2.6	3.6	2.9	82.2	8.7
			30-40	1.7	3.6	2.9	87.7	4.1
2 Borris	7 & 9	Orthic Haplohumod	0-20	2.2	5.2	5.8	55.1	31.7
			30-40	1.0	5.2	5.8	55.7	32.3
3 Tystofte	E 8	Not classified*	0-20	2.0	10.5	12.0	52.3	23.2
			30-40	1.4	10.5	11.0	52.7	24.4
4 Årslev	Ø 2	Typic Agrudalf	0-20	2.2	10.6	11.9	49.2	26.1
			30-40	1.2	13.6	10.4	50.3	24.5
5 Roskilde	A 2 east	Typic Agrudalf	0-20	2.6	11.0	13.5	49.3	23.6
			30-40	1.9	10.6	12.9	49.9	24.7
6 Rønhave	A 5	Typic Agrudalf	0-20	2.6	12.1	15.4	53.3	16.6
			30-40	1.4	15.2	13.3	53.2	16.9
7 Silstrup	F 4	Not classified	0-20	3.2	14.8	13.2	45.5	23.3
			30-40	2.2	15.7	13.3	46.9	21.9

* same origin as 5

Field measurements

In each of the selected field plots the top soil was carefully removed to a depth of about 8 cm. The in situ shear strength was measured by a commercial, hand-held vane shear tester (Serota & Jangle, 1972), with two vanes, one 33 mm diameter, 50 mm high, and the other 19 mm diameter, 25 mm high. The measurement range of this instrument is 0 to 28 kPa with the larger vane and 0 to 124 kPa with the smaller. 8 replicate measurements were made for each plot.

Shear strength at 6 normal loads ranging from 4.2 kPa to 19.8 kPa was determined with a 100 mm diameter torsional shear box as described by Payne & Fountaine (1952). This test was carried out in 3 of the selected 6 plots only, but at all normal loads in each of these 3 plots.

Laboratory measurements

All undisturbed soil cores were placed on top of a sandbox and slowly saturated with water from beneath.

36 samples from each of the two soil layers were taken to a confined uniaxial compression test with strain-controlled stress application (rate of piston elevation: 1 mm/min.), in principle as described by Koolen (1974). Prior to this test the 6×6 samples were drained to the potentials –30, –50, –75, –100, –160 and –300 hPa respectively, securing 1 sample from each field plot

at each of the potentials. The displacement (compaction) was automatically recorded by a computer and followed to a maximum stress of 800 kPa or until the test was stopped when water expelled from the sample.

72 samples from the 8-12 cm layer were drained to the potentials already mentioned for the compression test; i.e. 12 samples (6 plots × 2 replicates) at each potential. Penetration of a 30°, 0.08 kg cone was determined for all 72 samples with a standard drop cone penetrometer (Campbell & Hunter 1986). Penetration was measured at 3 points for each sample. After this nearly non-destructive measurement, shear strength was determined in the same samples at 6 normal loads (30, 60, 90, 120, 150 and 180 kPa) measuring shear for each potential, using a shear annulus mounted in a mechanical press (Schjønning 1986). In the selection of the two replicate samples at each potential and normal load it was secured that all 6 sampling plots in the field were evenly represented.

The remoulded soil from the 8-12 cm layer was air-dried and ground to pass through a 2 mm sieve. 100 cm^3 metal rings (diameter = 61 mm, height = 34.2 mm) were filled with soil in a standardized manner, the ring placed on top of a small vibrator when being filled. A metal shielding ring placed on top of the sample ring allowed for a homogeneous filling of the sample ring to the very top and was used also to control a weight (0.5 kg) placed on top of the soil material the last 15 seconds of vibration. It was not attempted to achieve a predetermined volume weight and neither was it attempted to reach identical volume weights for different soil types—only within the same soil type. But all samples received the same energy input when being filled.

The soil samples were then carefully placed on top of a sandbox and slowly saturated with water from beneath (a saturation process of about 1 week). When stabilized by drainage to a tension of about 10 cm water column the samples were taken to the equipment used to bring the soil to 6 different pre-determined water potentials: –30, –50, –100 hPa (drainage apparatus: sandbox with hanging water column) and –160, –300, –700 hPa (drainage apparatus: ceramic plates with suction). It was secured that the samples were given the same time period for drainage (~ 2 weeks) in order to avoid different conditions for "age hardening" at different water potentials.

A total of 72 samples were prepared for each soil type leaving 12 samples for each water potential. 3 replicate samples from each water potential were used in the uniaxial, confined compression test described earlier. Drop-cone penetrometer readings were taken for the 9 remaining samples at each potential. Later on these cores were used in the shear annulus method for strength determination. 3 replicate samples were analyzed at each of 3 normal loads: 30, 60 and 90 kPa.

For soil types with water stable aggregates, the wet aggregate stability was determined by a method of Hartge (1971), expressing stability of macro -aggregates 2-8 mm in diameter.

For both soil layers air-dried soil sieved through a 2 mm aperture sieve was used for determination of texture (a combination of a flotation and a sieve method), particle density (a pycnometer method) and exchangeable K^+, Na^+, Mg^{++}, Ca^{++} and H^+. Further, pH in a 0.01 M $CaCl_2$-solution and the organic carbon content were determined.

For all soil types and both soil layers, about 5 kg of air-dried, 2 mm sieved soil was ground to pass a 500 μm sieve and wetted with distilled water yielding 16 subsamples having water contents from air dry to saturated. After a 48 hour period of equilibration in an airtight container including several times of mixing, the drop cone penetration was determined and used for estimating the upper and lower plastic limits (Hansbo, 1957; NN, 1975; Campbell, 1975, 1976).

Results and discussion

Drop cone liquid limit, drop cone plastic limit and the plasticity index for the 7 soils in investigation are listed in Table 2. The plastic limit was determined from drop cone penetrations using the regression method suggested by Lehfeldt & Kullmann (1982). This means reading the intersect of two hand-drawn regression lines in a log (penetration) vs. water content plot, as shown in Figure 2 for the Årslev-soil. The intersect is taken as the smallest penetration, which, according to Campbell (1976), represents a water content related to the plastic limit for the specific soil. Alternatively, the plastic limit was read as the water content at 2 mm penetration (Schofield & Wroth, 1968; Towner, 1973) (column labelled "2" in Table 2). The water content

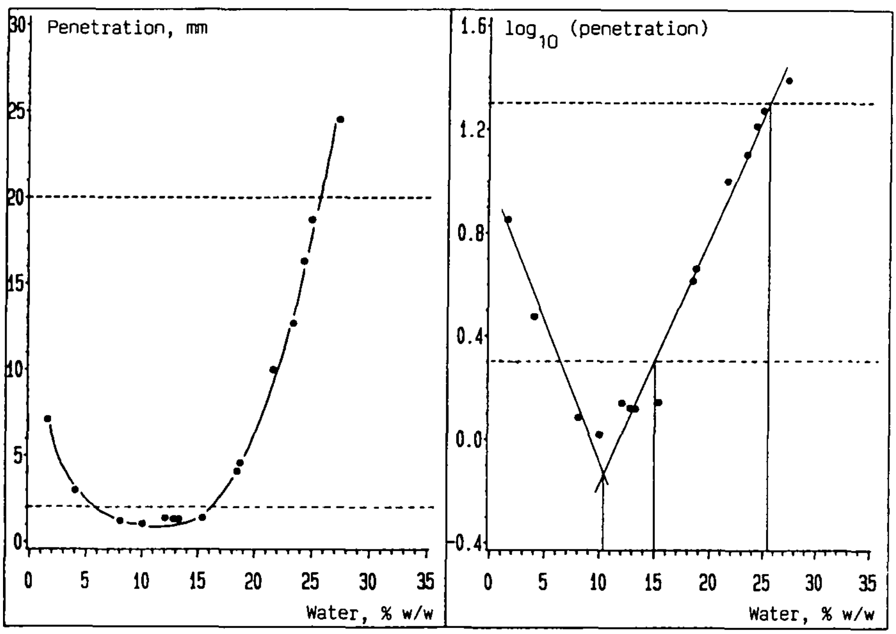


Figure 2. Example of reading the drop cone penetration/water content curve. Minimum as well as 2 mm and 20 mm penetration is read from the log presentation (right). Årslev soil, plough layer.

at 20 mm penetration was taken as the liquid limit (Campbell, 1975).

As stated by Campbell (1976) the drop cone penetration plastic limit is numerically less than, but correlates closely with, the Casagrande plastic limit (Casagrande, 1932). This relationship could not be examined for the present soils, the low content of clay in most soils making the thread-rolling procedure in the classical method impossible.

Table 2. Plastic and liquid limit determined by the drop cone method and the plasticity index for 7 Danish soils.

Location	Depth	%, w/w				
	cm	Plastic limit		Liquid limit	Plasticity index	
		1)	2)		1)	2)
Tylstrup	0-20	11.9	(10.5)	30.9	19.0	(20.4)
	30-40	12.5	(14.9)	32.7	20.2	(17.8)
Borris	0-20	12.1	(13.4)	27.6	15.5	(14.2)
	30-40	9.8	(13.2)	27.2	17.4	(14.0)
Tystofte	0-20	10.2	14.3	22.4	12.2	8.1
	30-40	9.2	13.6	21.1	11.9	7.5
Årslev	0-20	10.3	15.0	25.5	15.2	10.5
	30-40	9.9	15.3	23.2	13.3	7.9
Roskilde	0-20	10.0	14.9	24.8	14.8	9.9
	30-40	11.7	15.8	22.8	11.1	7.0
Rønhave	0-20	11.6	17.6	29.4	17.8	11.8
	30-40	10.0	15.6	25.6	15.6	10.0
Silstrup	0-20	14.1	19.0	33.0	18.9	14.0
	30-40	14.8	20.0	29.8	15.0	9.8

1) reading plastic limit at the smallest penetration (Campbell, 1976)
2) reading plastic limit at 2 mm penetration (Towner, 1973)

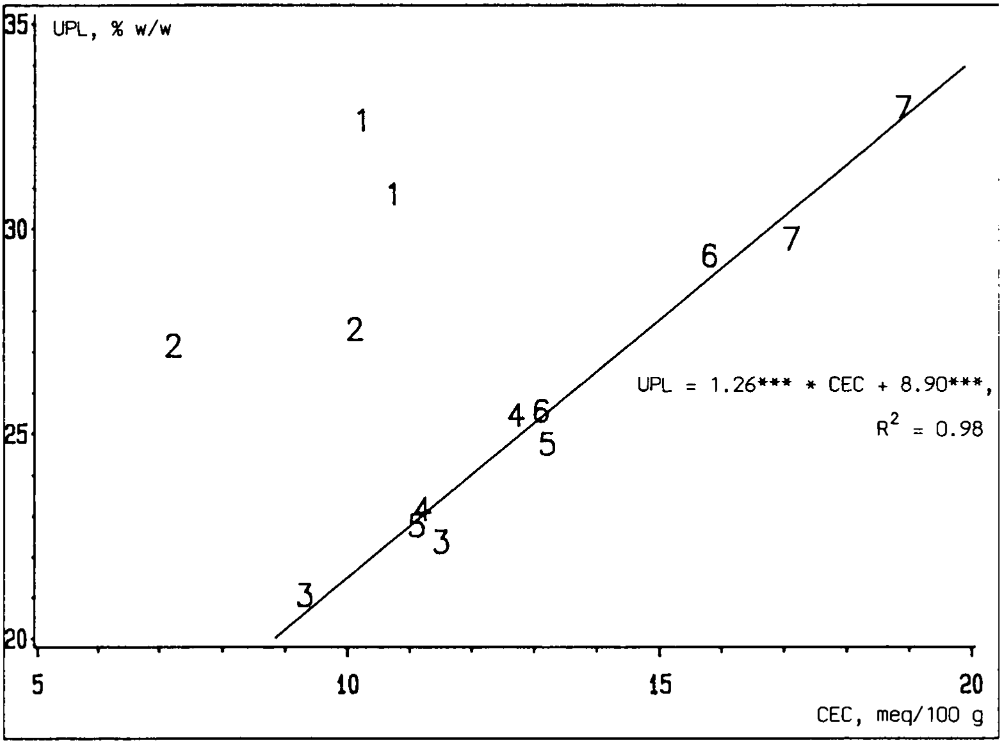
Plasticity in the normal sense of the word will not occur in sandy soils with a clay content below about 10%. However, as argued by Campbell (1976), the presence of a minimum on the moisture content/cone penetration curve suggests that a change in the physical state of the soil occurs at this point. In the present investigation, the estimated values for the liquid and plastic limit will be related to the soil behaviour at those water contents in the mechanical tests performed.

The soil chemical parameters given in Table 3 also influence the soil structure and hence the soil mechanical conditions. Notice the increasing cation exchange capacity with increasing content of clay (cf. Table 1), the CEC being an expression of the soil potential for aggregation.

The liquid limit (upper plasticity limit) as determined by the drop cone penetrometer (Table 2) clearly correlates to the amount of electrically active colloids in the soil as represented by the cation exchange capacity, CEC, Figure 3. Notice, that for the soils of similar origin (moraine deposits from the Weichsel ice period), a close correlation exists between CEC and liquid limit.

Table 3. pH in 0.01 M $CaCl_2$, exchangeable Na^+, K^+, Ca^{++}, Mg^{++} and "H^+", cation exchange capacity and base saturation for 7 Danish soils.

Location	Depth cm	pH($CaCl_2$)	Exchangeable "bases", m. eqv/100 g					Exchangeable "acidic" cations. m. eqv/100 g	Cation exchange capacity m. eqv/100 g	Base saturation
			Na^+	K^+	Ca^{++}	Mg^{++}	sum	"H^+"	CEC	%
Tylstrup	0-20	5.3	0.02	0.26	3.29	0.49	4.1	6.6	10.7	38.3
	30-40	5.3	0.02	0.14	2.18	0.18	2.5	7.7	10.2	24.5
Borris	0-20	6.1	0.04	0.25	5.19	0.46	5.9	4.2	10.1	58.4
	30-40	6.0	0.03	0.16	3.19	0.27	3.7	3.5	7.2	51.4
Tystofte	0-20	5.6	0.04	0.20	6.54	0.30	7.1	4.4	11.5	61.7
	30-40	5.7	0.06	0.12	5.69	0.24	6.1	3.2	9.3	65.6
Årslev	0-20	6.0	0.06	0.39	7.49	0.44	8.4	4.3	12.7	66.1
	30-40	5.9	0.04	0.32	6.84	0.39	7.6	3.6	11.2	67.9
Roskilde	0-20	6.2	0.06	0.27	8.73	0.12	9.2	4.0	13.2	69.7
	30-40	6.2	0.06	0.15	6.54	0.08	6.8	4.3	11.1	61.3
Rønhave	0-20	6.6	0.07	0.30	12.38	0.29	13.0	2.8	15.8	82.3
	30-40	6.5	0.10	0.19	10.08	0.26	10.6	2.5	13.1	80.9
Silstrup	0-20	6.6	0.15	0.22	14.27	0.67	15.3	3.6	18.9	81.0
	30-40	6.2	0.16	0.14	12.48	0.60	13.4	3.7	17.1	78.4



Figur 3. The upper plasticity limit (UPL) as determined by the drop cone penetrometer related to the cation exchange capacity (CEC). Numbers refer to locations (Table 1). 8-12 cm layer as well as 30-40 cm layer are included. Locations 1 and 2 were not included in the regression shown.

The torsional shear box field method estimates the cohesion as well as the friction component of shear strength. From Appendix 1 and Table 4 a trend of increasing cohesion with increasing content of clay is revealed. An exception is the Borris soil in which a relative high value of cohesion has been estimated. Also with the shear vane higher strengths are found in the loamy soils compared to sandy soils, Table 4. The shear vane overestimate the cohesion, which is in accordance with O'Sullivan & Ball (1982). They found this effect to be more pronounced in a loam soil than in a more cohesive sandy clay loam. For the soils in this investigation, however, no distinct difference in this relation has been detected, the vane estimating the strength to a value about a factor 2 the shear box cohesion for all soils. The normal load at which the shear box strength equals the vane strength is increasing with the soil content of clay, Table 4. This, on the other hand, could be an indication of an even poorer vane estimation of the cohesion in the heavier soils.

Table 4. Vane shear strength, cohesion and friction components of torsional shear box strength (estimated by the Coulomb model of strength-normal load relation) and the calculated normal load (P_{vane}) at which the torsional shear strength equals the vane strength. Dry bulk density and water content are also given. 7 Danish soils, plough layer.

Location	Vane strength	Torsional box		P_{vane}	Dry bulk density	Water content
				cohesion	friction	
	kPa	kPa	(tan ϕ)	kPa	g cm^{-3}	% v/v
Tylstrup	21.0 (79) *	9.7 (73) *	0.91	12.4	1.41	15.2
Borris	23.2 (87)	15.3 (115)	0.70	11.3	1.53	21.6
Tystofte	24.3 (92)	10.7 (81)	0.89	15.3	1.54	21.3
Årslev	19.9 (75)	11.2 (85)	0.83	10.5	1.54	25.5
Roskilde	26.3 (99)	12.3 (93)	0.90	15.6	1.60	27.8
Rønhave	29.3 (110)	16.5 (125)	0.67	19.1	1.49	26.1
Silstrup	41.8 (157)	16.8 (127)	1.04	24.0	1.52	26.0

* Figures in brackets indicate the estimated parameter as related to the average value for the 7 soils (per cent).

Void ratio was chosen as the soil parameter describing the compaction state in the uniaxial, confined compression test. Plotting the void ratio vs. the logarithm of normal load a linear relation will exist at high pressures, describing the virgin compression curve, Figure 4. Larson et al. (1980) used bulk density as the soil parameter in compression tests. However, void ratio was preferred in this investigation because it is an additive parameter and was found to give a linear relation to the logarithm of pressure.

It should be noted, that the strain-controlled stress application procedure used in this study is different from what is often used in soil compression studies, e.g. Larson et al. (1980) and McBride (1989), who used a stepwise stress application, allowing the soil to (nearly) equilibrate at each level of stress.

For the plough layer soil, at all locations, soil compaction at a normal load of 100 kPa is lowest in dry soil (high pF values, Appendix 2). Multivariate analysis revealed, that the initial density of the samples had a significant influence upon the soil compaction, which is in accordance with findings of McBride (1989). This phenomenon explains the rather fluctuating curves when using raw data with each point in the plots representing only 6 replicate samples. When this effect was taken out of the data (linear regression of initial density and soil compressibility, Appendix 2—solid lines) a better impression of the influence of water potential upon soil compressibility is obtained. However, still no distinct water potential could be estimated, at which the soils change their compressibility abruptly.

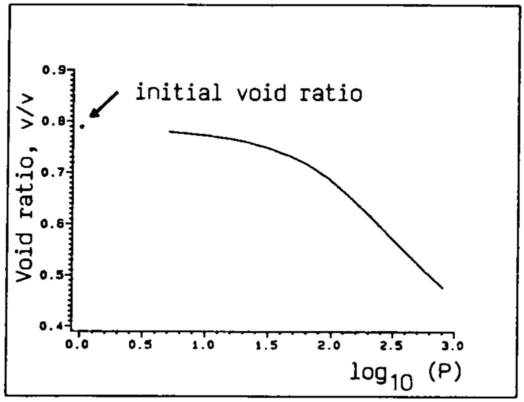


Figure 4. Example of the void ratio/log (normal load) relation from the unaxial confined compression test (Rønhave, –300 hPa potential, replicate 1). The linear part of the curve was used to calculate the compression index, C.

The slope of the virgin compression curve (compression index C, Figure 4) was estimated from linear regression for each soil sample tested. Also for this parameter, which is believed to be a measure of the strength of the soil microstructure, a significant effect of the initial sample density was found. The C-index from all samples tested including undisturbed soil samples from both soil layers as well as the specimen produced in the laboratory from air-dried, sieved soil were input to a linear regression model in order to eliminate the effects of the initial density. Data produced by combination of an average C-index and the residuals from the above-mentioned regression are given in Appendix 3 and Table 5. There is no significant difference in the magnitude of the C-index at different water potentials within the same soil, Appendix 3, which is in accordance with Larson et al. (1980). For the soil samples in undisturbed condition in the 0-20 cm layer the sandy soils (Tylstrup and Borris) have a somewhat smaller level of the C-index than the loamy soils, whose C-values in the range of 0.13-0.16 could neither be related to the soil content of clay (Table 1) nor to the CEC values (Table 3, Figure 3). However, for the soil samples, which have been produced from sieved soil in the laboratory a somewhat different pattern arose (Appendix 3, Table 5). The virgin compression index C increased with an increasing clay content, which is in accordance with Larson et al. (1980), who too used soil in a remoulded state. Despite the fact that the "artificial" soil samples were allowed to "age-harden" for a period of 3 weeks (Materials and Methods-section) the compression index was higher (more susceptible to compaction) than in the samples with an undisturbed macrostructure. Noteworthy is also the fact that the B-horizon-samples for all soil types exhibit a higher C-index than the plough-layer soil (Appendix 3, Table 5). Apparently, the higher content of humus in the latter samples strengthen the soil structure, inducing a smaller susceptibility to severe compaction.

Table 5. The virgin compression index C adjusted for effects of the initial bulk density. See text for details.

Location		Sample type		
		undisturbed		remoulded
	Soil layer, cm:	0-20	30-40	0-20
Tylstrup		0.063	0.079	0.102
Borris		0.090	0.126	0.139
Tystofte		0.139	0.175	0.171
Årslev		0.153	0.174	0.182
Roskilde		0.133	0.176	0.185
Rønhave		0.162	0.175	0.216
Silstrup		0.133	0.202	0.236

The peak strength from the annulus shear strength/strain-relation, Figure 5a, was used for calculation of the cohesion and friction component of soil strength, using the Coulumb equation

$$\tau = C + \tan \phi \cdot P \tag{1}$$

where τ is shear strength, kPa, C is apparent cohesion, kPa, P is the normal stress, kPa, and ϕ is the angle of internal friction. In some cases, especially at the highest water potentials, no peak strength was detected, Figure 5b, and the residual strength (the plateau level at higher strain values) was used in calculations.

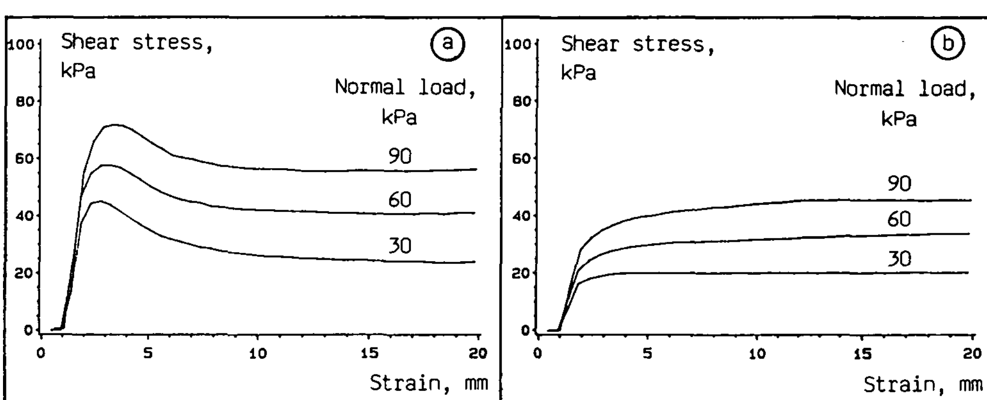


Figure 5. Examples of recorded stress/strain relations from the annulus shear method. a: Borris soil, remoulded, –300 hPa potential, b: Silstrup soil, remoulded, –30 hPa potential.

For the undisturbed soil samples, the average shear strength from all levels of normal load (30, 60, 90, 120, 150 and 180 kPa) is plotted vs. the water potential in Appendix 4. At all locations, the soil strength is increasing with decreasing water content (high pF-values). However, no distinct water potential can be detected, at which the soil strength changes abruptly. The average strength is higher for the structured loamy soils compared to the sandy soils, Appendix 4.

When differentiating the soil strength into cohesion and friction it is revealed, that the increase in strength in drier soil for all locations except the fine sandy soil at Tylstrup can be ascribed to an increased cohesion (Appendix 5, solid lines). In the Tylstrup soil, on the contrary, the strength increase is due to an increased internal friction. The peculiar results in the Silstrup-soil (location 7) are probably caused by a great many stones occurring in this soil.

Zhang & Hartge (1990) found a local maximum of soil cohesion at a pF-value of about 1.6-1.8 for mixtures of fine sand and organic matter investigated in the same range of water potential as in this investigation. When sandy soils of morainic origin are found with their natural structure, however, their cohesion seems to increase with increasing pF-value, Appendix 5.

The strength estimates from the annulus shear method are tabulated in Appendix 12 together with the average soil density and water content measured at each of the investigated water potentials.

The sinkage of the shear annulus was registered when the normal load had been applied but the shearing had not yet started (static sinkage, Appendix 6) and again when the shearing had stopped (dynamic sinkage, Appendix 7). The results are marked by the soil-borne variation, the grid points in Appendices 6 and 7 being the mean of only 2 replicate samples. Nevertheless, from Appendix 6 it is clear, that for all soil types, the static sinkage, expressing the soil compressibility, is highest at high water potential (small pF-values) and high normal load, as expected. From Appendix 6 no clear difference among soil types can be detected.

The combined action of shear and normal stress reduce sinkage at small levels of normal stress and especially in dry soil, Appendix 7 (sinkage < 0). The effect is most pronounced in the soils exhibiting aggregation (cf. Schjønning, 1992). At higher levels of normal stress, the dynamic sinkage (effective compaction) exceeds the static one, the quotient between the two (dynamic/static) being highest at 90-120 kPa normal stress for all soils when averaged for water content (calculations not shown in the Appendices).

The annulus shear strength of remoulded soil in metal rings is shown in Appendix 8. These strength values are averages for the applied normal loads of 30, 60 and 90 kPa. Thus, Appendix 8 cannot be compared directly to the analogous Figure for undisturbed samples (Appendix 4), which represent 6 levels of normal load. For all soils an increasing strength has been measured with decreasing potential, Appendix 8. The sandy soils (Tylstrup and Borris) have unchanged strengths at water potentials below about –100 hPa (pF > 2). As for the undisturbed cores the increase in strength includes an increase in cohesion for all locations except Tylstrup, Appendix 9. However, in the case of remoulded soil in cores, the increased strength at some of the locations has to be attributed to an increased angle of internal friction (Appendix 9). In the undisturbed soil this was solely the case for Tylstrup (Appendix 5). The cohesion in remoulded, drained soil is less than in undisturbed soil (Appendices 5 and 9) except for the fine sandy soil at Tylstrup. The same holds for the friction except for Tylstrup at high water content. Clearly, the age hardening of the remoulded soil through the 3 weeks of rewetting and drainage in the laboratory did not reach the level of strength in undisturbed cores from the field. Differences in the bulk density also might influence the observed strengths in remoulded and undisturbed samples.

Table 6. Cohesion estimated in the field by the torsional shear box and in the laboratory by the shear annulus. 7 Danish soils, plough layer. The field water content and dry bulk density are given in Table 4.

Location	Cohesion, kPa	
	Torsional shear box (field)	Shear annulus (lab., -100 hPa water pot.)
Tylstrup	9.7	25.1
Borris	15.3	44.5
Tystofte	10.7	34.9
Årslev	11.2	56.8
Roskilde	12.3	62.3
Rønhave	16.5	58.2
Silstrup	16.8	77.3

Table 6 compares the soil cohesion estimated in the field by the torsional shear box to the cohesion from the shear annulus-method. The samples drained to –100 hPa water potential were chosen for this comparison because it is the water potential most often found at field capacity for the soils in investigation. The shear annulus method estimate cohesive strengths about a factor 3-5 higher than the shear box method, Table 6. The discrepancy probably partly is due to differences in water content despite the assumption about field capacity mentioned above. Anyhow, smaller values from the box method were expected, because this method will measure the strength at the weakest plane in the soil, while the shear annulus causes the soil to shear at a plane, which is defined more by the instrument than by planes of weakness in the soil.

Results from drop cone penetrations in undisturbed soil cores as well as in remoulded soil drained to specific potentials are shown in the Appendices 10 and 11. This estimate of soil strength is given as the reciprocal of the squared penetration according to the findings of Hansbo (1957) and Towner (1973) that the shear strength of soils is related to drop cone penetration by

$$\tau = K \cdot Q \cdot \frac{1}{h^2} \tag{2}$$

where K is a texture-dependent factor of proportionality, m s^{-2}, Q is the weight of the cone (0.08 kg) and h is the penetration depth, m.

Due to the unknown value of K for each soil type, the locations should not be compared in Appendices 10 and 11. From the plots it can be seen, that the drop cone strength calculated according to equation (2) is very sensitive to change in water content. However, as found by Campbell & Hunter (1986) it is questionable, whether the penetration depth (h) should be squared in the reciprocal relation to soil strength.

Accepting the Hansbo-relation, however, most of the loamy soils with a clay content of more than 10% (cf. Table 1) display a rather steep increase in strength of undisturbed soil at a water potential of about –75 to –100 hPa (~ pF 1.9-2.0), Appendix 10. This is not the case for the remoulded soil. The pore size distribution for the remoulded soil is, however, very different from the natural soil, which is reflected in the water contents at comparable potentials, Appendix 11. For all soils, except Silstrup, the difference in strength estimated in undisturbed compared to remoulded soil has nearly disappeared when plotted vs. the water content. The discrepancy for the Silstrup soil perhaps can be explained by a high content of stones larger than 2 mm, implicating a different texture in the remoulded soil, which was sieved through a 2 mm sieve.

Appendix 11 reveals that the drop cone plastic limit is a poor estimate of a water content at which the soil changes its strength abruptly, even when strength estimated from a drop cone test is used. For all of the loamy soils, the Campbell-suggested plastic limit is far below the water content at which the soil strength increases to high values, going from a wet to a drier condition. The Schofield & Wroth/Towner-derived use of the 2 mm penetration plastic limit is somewhat better (especially for the Tystofte soil, Appendix 11) but still without any clear relation to the soil strength for most of the locations.

Table 7. Water stable aggregates in a five minute sieving procedure, per cent w/w.

Location	Stable aggregates in fraction			
	6-8 mm	4-8 mm	2-8 mm	1-8** mm
Tylstrup*	–	–	–	–
Borris*	–	–	–	–
Tystofte	40.6	41.0	39.5	48.9
Årslev	46.9	50.0	47.9	58.2
Roskilde	38.6	46.9	44.9	54.4
Rønhave	60.2	57.6	59.8	70.1
Silstrup	65.0	65.0	68.6	78.2

* no water-stable aggregates
** aggregates in the 2-8 mm fraction not disrupted to diameters less than 1 mm

The stability of individual aggregates, i.e. the intra-aggregate soil strength, is increasing with increasing soil content of clay or cation exchange capacity, Table 7. This holds true even for the large aggregates 6-8 mm diameter in which other binding forces are expected to be predominant (Tisdall & Oades, 1982).

Conclusions

For soils with identical geological origin a positive, linear correlation was found between the soil cation exchange capacity and the liquid limit.

A comparison of two field methods for soil strength determination showed, that the shear vane overestimates the cohesion as determined by a torsional shear box. The laboratory shear annulus method, on the other hand, estimates higher values for soil cohesion than the field shear box method. The lack of agreement between these methods can be ascribed to the way in which they interact with the soil.

The torsional shear box method is suitable to an in situ determination of the soil strength in its weakest planes, i.e. especially in root growth studies. A problem with the torsional shear box is the risk of disturbing / weakening the planes, which will "break" in shear, when the box is brought in its measuring position. The rather small values of cohesion, which were found in this investigation, perhaps partly are due to that problem.

The laboratory shear annulus method is attractive, when the scope of the investigation is soil strength in relation to soil tillage. The present study has shown, that the method is suitable to estimate soil type differences and the influence of soil water content.

The uniaxial, confined compression method can be used to estimate the virgin compression index, i.e. compressibility at high loads, and the compaction caused by stresses similar to inflation pressure in agricultural vehicle tires, as well. The results in this paper indicate, that soil macrostructure has a significant influence upon the virgin compression index.

Provided that the Hansbo-relation of strength and drop cone penetration is valid, the drop cone method has been found to be a sensitive method of estimating soil strength. However, the texture-dependent proportionality factor relating strength and the reciprocal of the squared penetration prevent a quantification of the measurement to absolute figures and due to this also prevent a comparison of soil types.

Plastic limits estimated by drop cone measurements in newly remoulded soil have been found to have no clear correlation to water contents at which the different mechanical parameters change abruptly. The water content read at 2 mm penetration (100 times the strength at 20 mm penetration ~ liquid limit, according to Schofield & Wroth, 1968) from the water content /drop cone penetration curve was found to give limits, which were closer to the relevant water contents than the "smallest penetration"-limit.

Soil compressibility increases with increasing content of clay and is higher for remoulded than for undisturbed soil, which indicates inter-aggregate bonds as well as intra-aggregate strength to be responsible for the resistance to severe compaction.

A non-aggregated sandy soil was found to have a constant cohesion at different water contents, while the total strength increased with decreasing water content due to an increasing internal friction. The other soils in investigation, on the contrary, had increasing strengths, which could primarily be ascribed to an increasing cohesion when the soil became drier.

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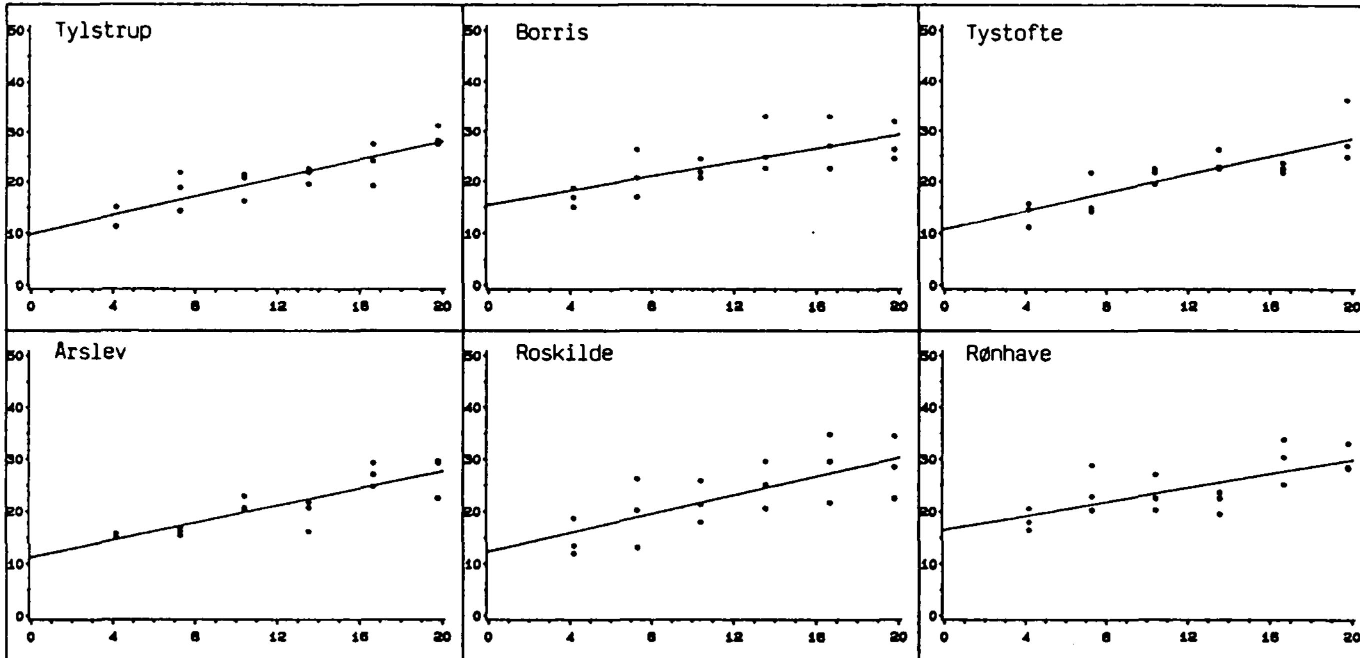
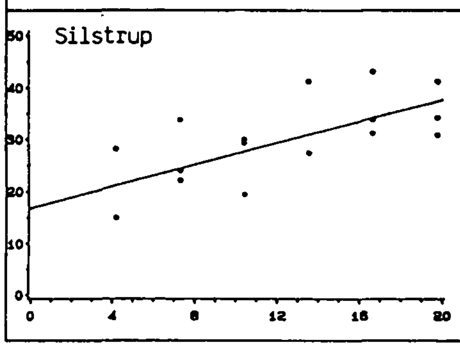
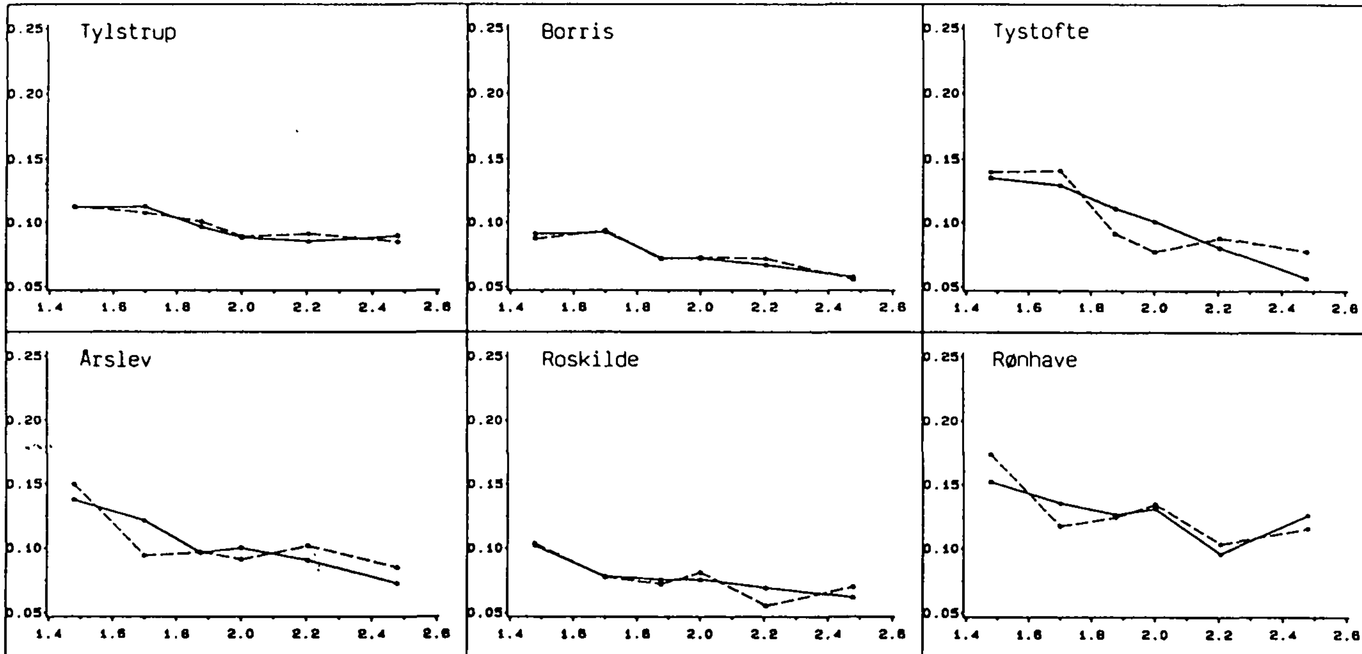
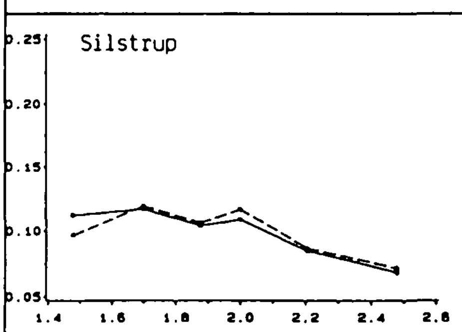




Appendix 1. Shear stress at 6 levels of normal load performing the field torsional shear box method. The field water content and dry bulk density are given in Table 4.

Abscissa: normal stress, kPa
Ordinate: maximum shear stress, kPa

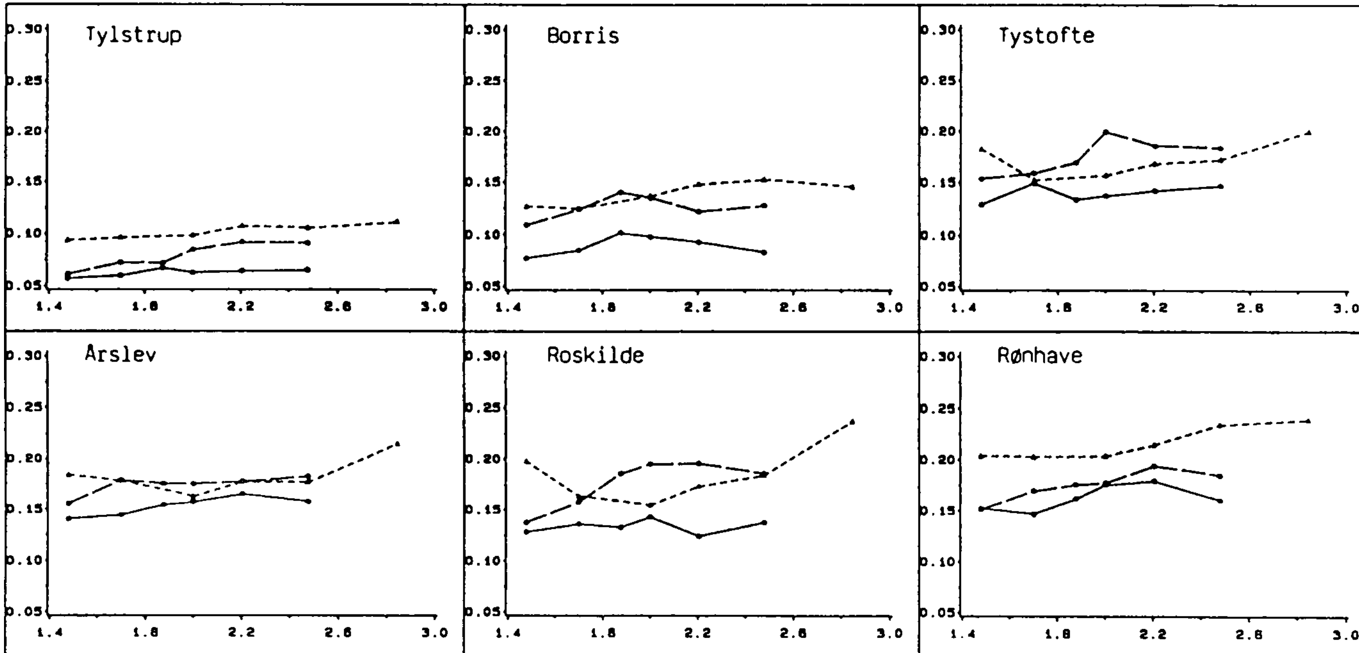


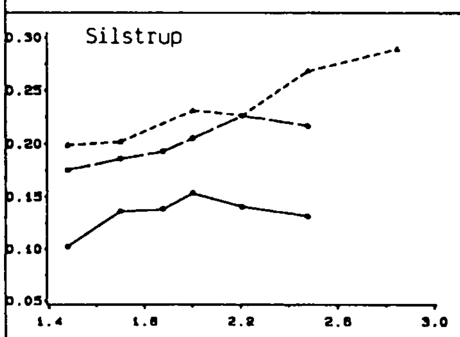


Appendix 2. Reduction in void ratio when loaded with 100 kPa normal load. Uniaxial, confined compression test, undisturbed soil, plough layer.

- - - - measured data
——— data calibrated to identical initial bulk density for each soil type

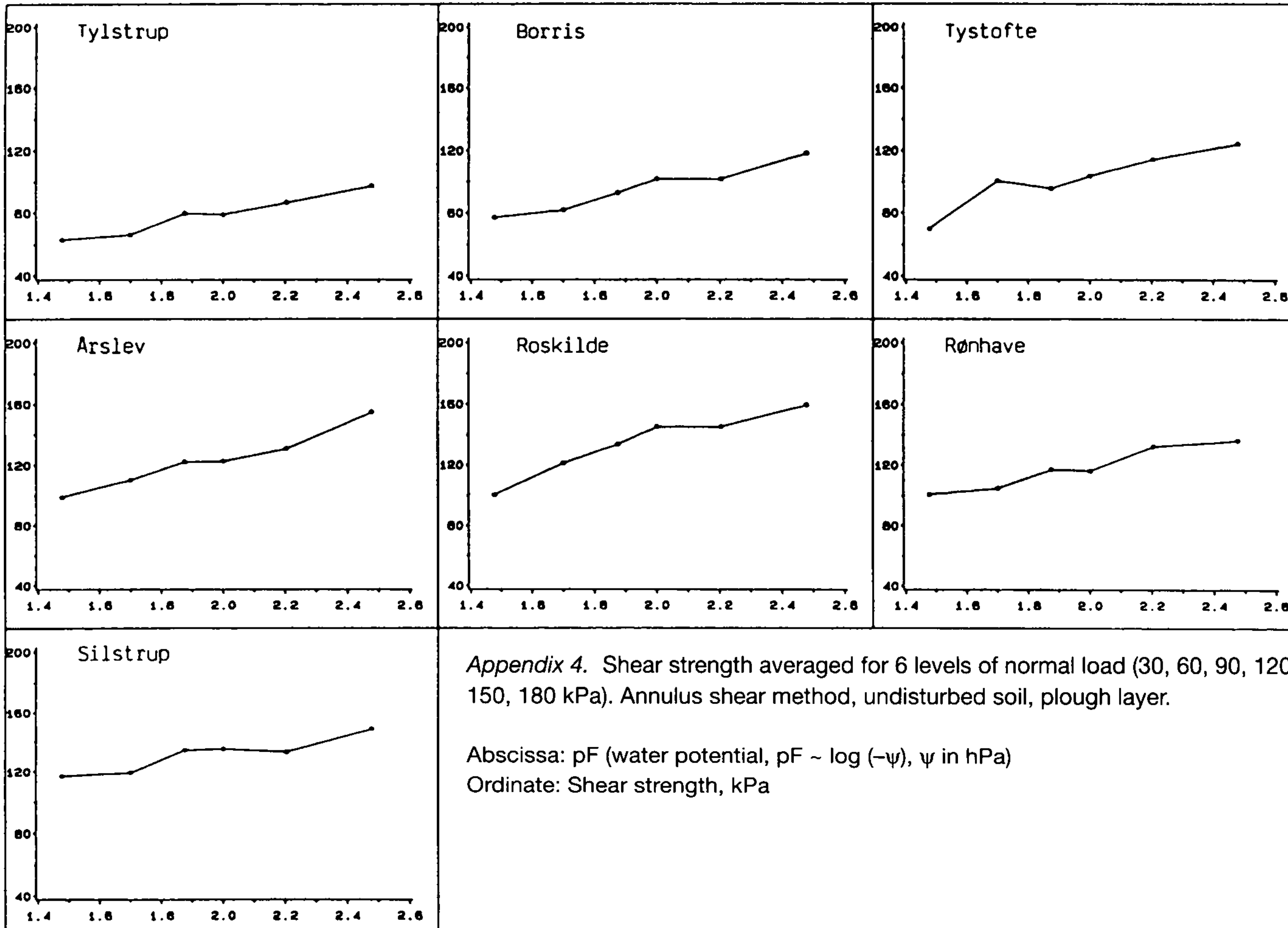
Abscissa: pF (water potential, pF ~ log (−ψ), ψ in hPa)
Ordinate: Δ void ratio, v/v





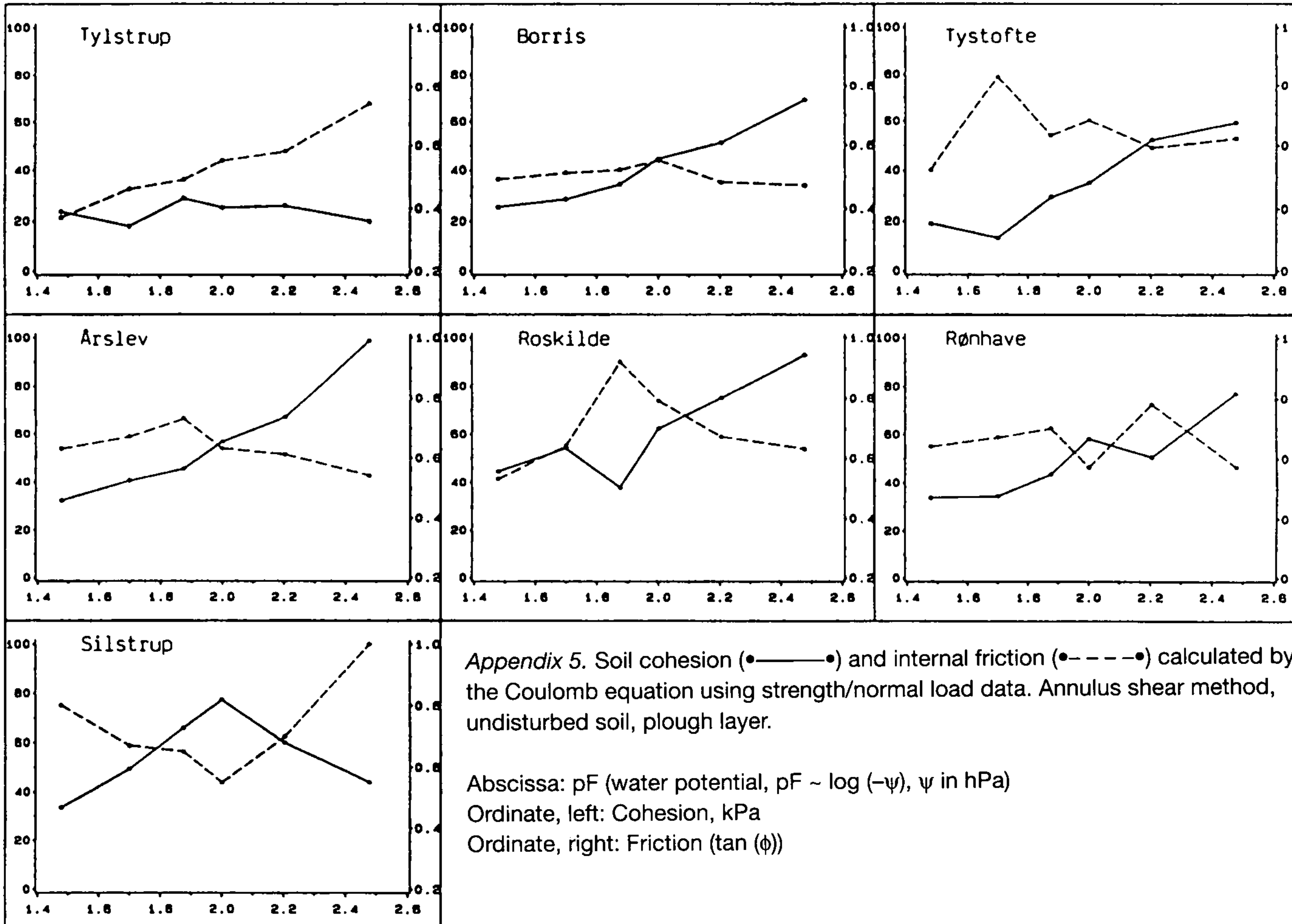
Appendix 3. Compression index C (numerical value of the slope of the virgin compression curve: vold ratio/log (pressure)). Calibrated to identical initial bulk density for each soil type. Uniaxial, confined compression test.

•——• plough layer, undisturbed soil
•– –• B-horizon, undisturbed soil
▲---▲ plough layer, remoulded soil
Abscissa: pF (water potential, pF ~ log $(-\psi)$, ψ in hPa)
Ordinate: Compression index C, v/v



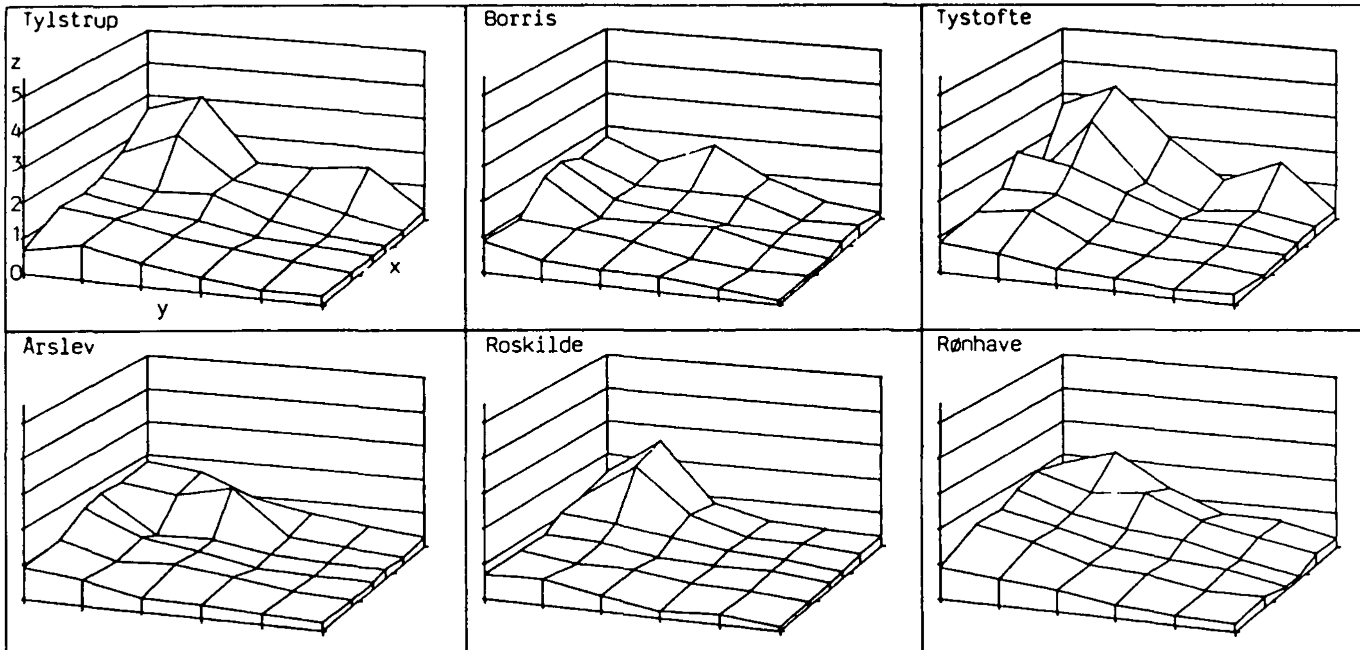
Appendix 4. Shear strength averaged for 6 levels of normal load (30, 60, 90, 120, 150, 180 kPa). Annulus shear method, undisturbed soil, plough layer.

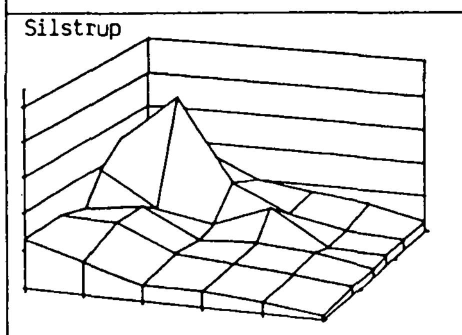
Abscissa: pF (water potential, pF ~ log (−ψ), ψ in hPa)
Ordinate: Shear strength, kPa



Appendix 5. Soil cohesion (•———•) and internal friction (•– – – –•) calculated by the Coulomb equation using strength/normal load data. Annulus shear method, undisturbed soil, plough layer.

Abscissa: pF (water potential, pF ~ log (–ψ), ψ in hPa)
Ordinate, left: Cohesion, kPa
Ordinate, right: Friction (tan (ϕ))



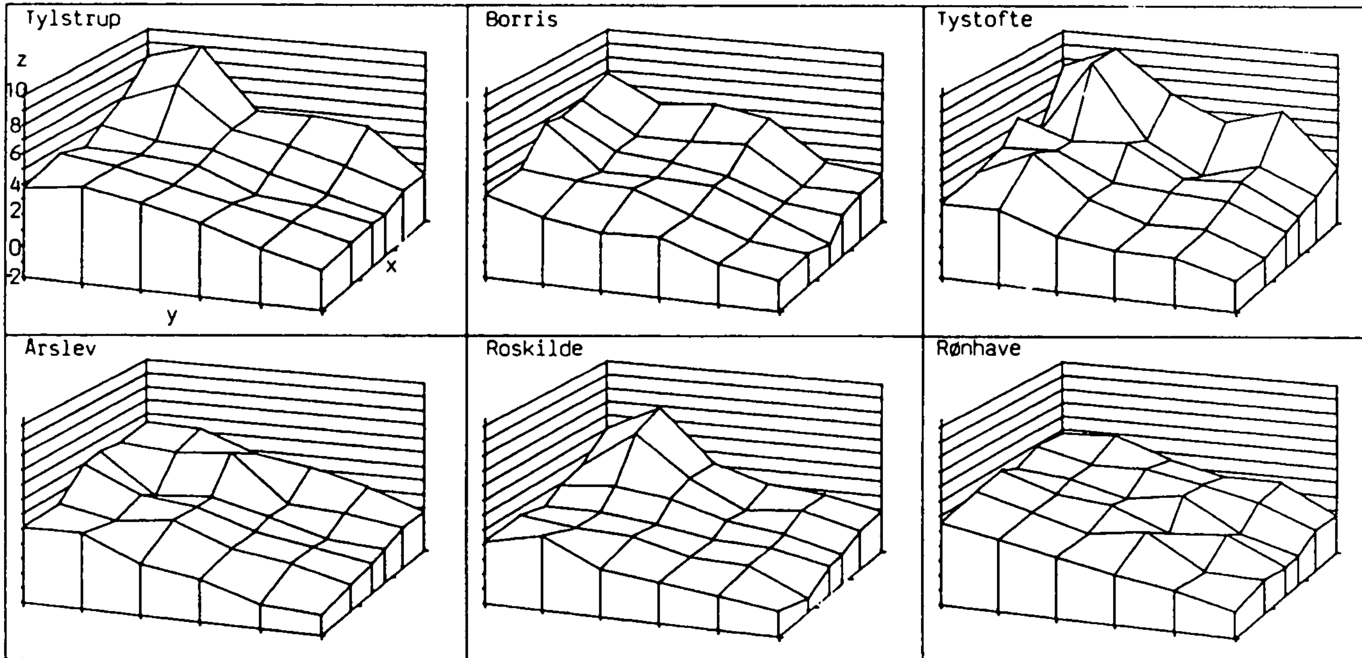


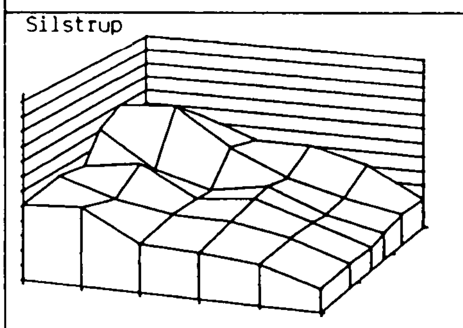
Appendix 6. Static sinkage (compaction) at 6 water potentials and 6 levels of normal load. Annulus shear method, undisturbed soil, plough layer.

x-axis: Water potentials, pF 1.5, 1.7, 1.9, 2.0, 2.2, 2.5, with lowest pF values "deepest" in the picture.

Y-axis: Normal load, 30, 60, 90, 120, 150, 180 kPa, with lowest values to the right on the axis.

z-axis: Sinkage of shear annulus, mm.



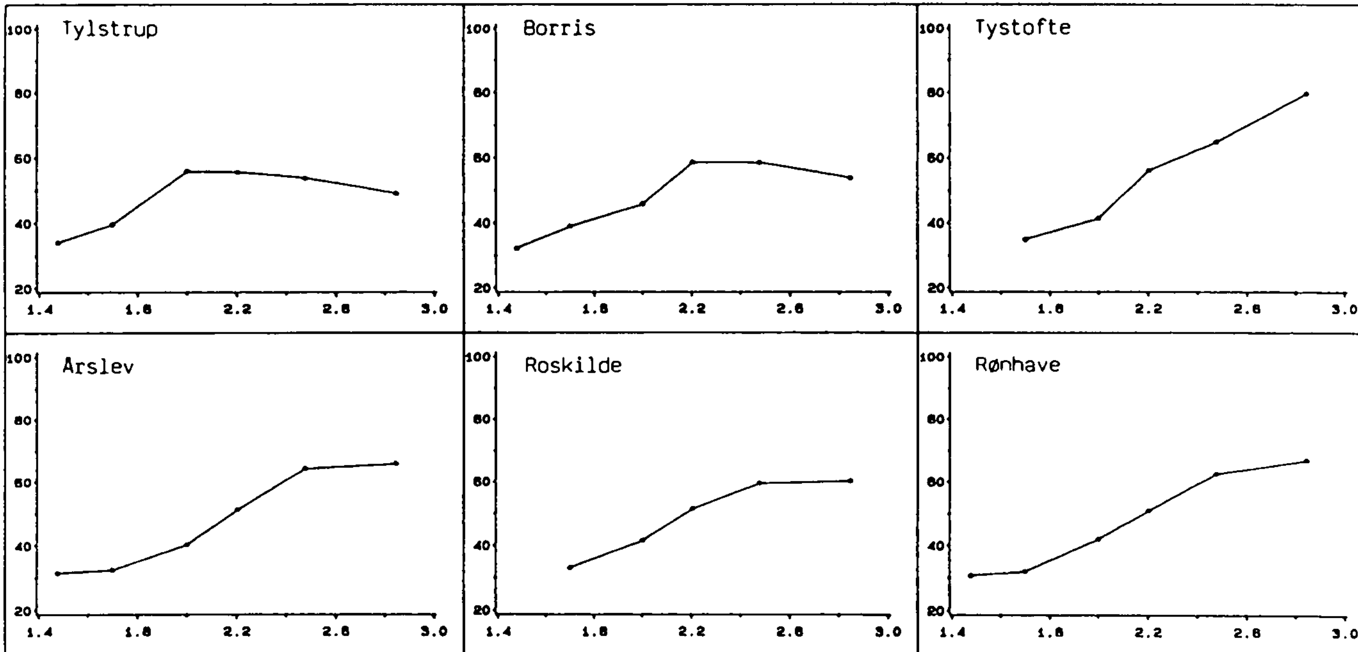


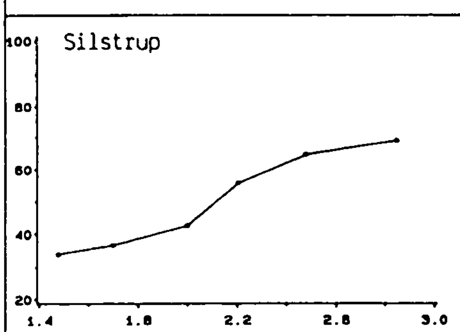
Appendix 7. Dynamic sinkage (compaction with a normal as well as a shearing stress) at 6 water potentials and 6 levels of normal load. Annulus shear method, undisturbed soil, plough layer.

x-axis: Water potentials, pF 1.5, 1.7, 1.9, 2.0, 2.2, 2.5, with lowest pF-values "deepest" in the picture.

y-axis: Normal load, 30, 60, 90, 120, 150, 180 kPa, with lowest values to the right on the axis.

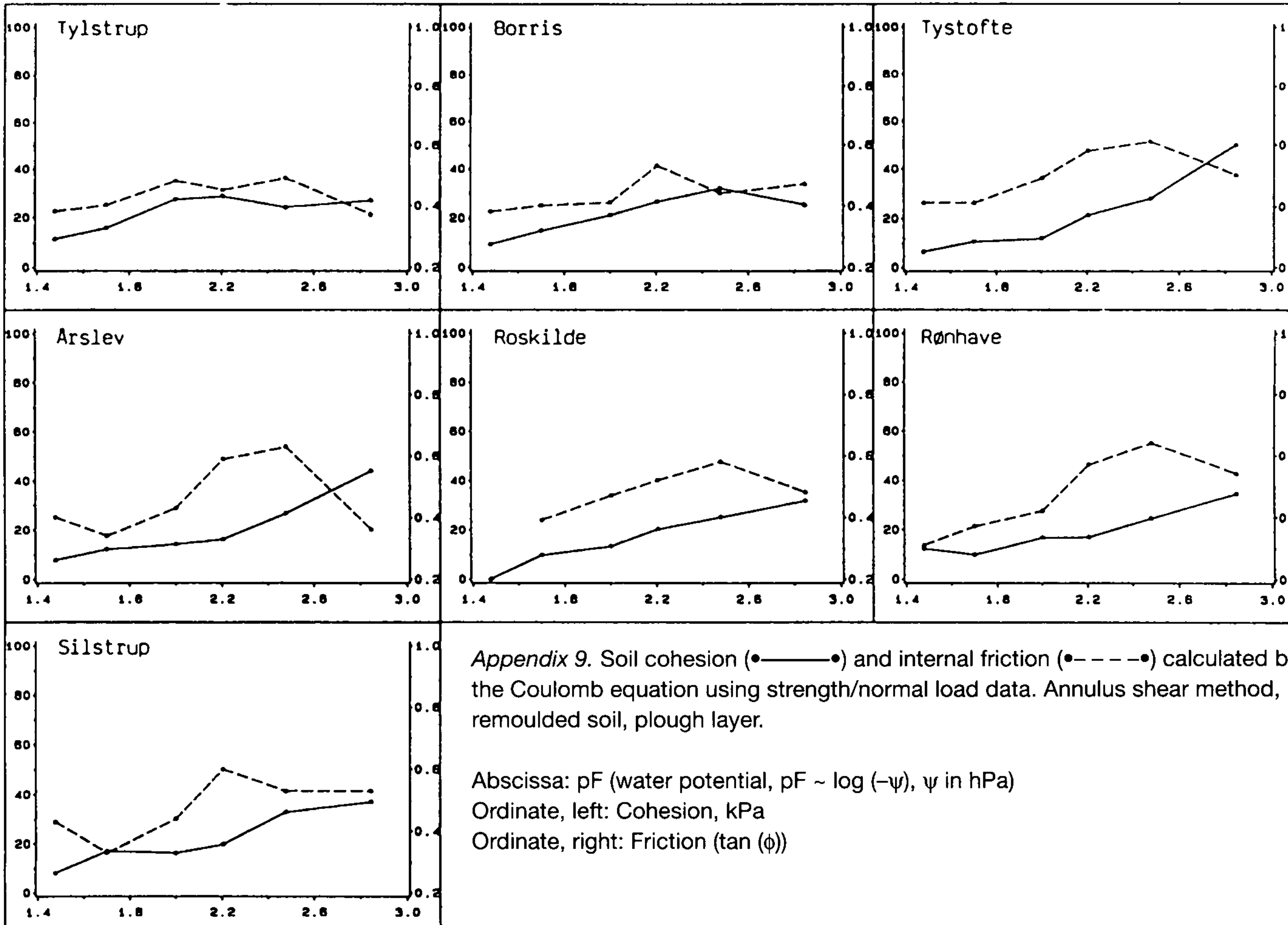
z-axis: Sinkage of shear annulus, mm.





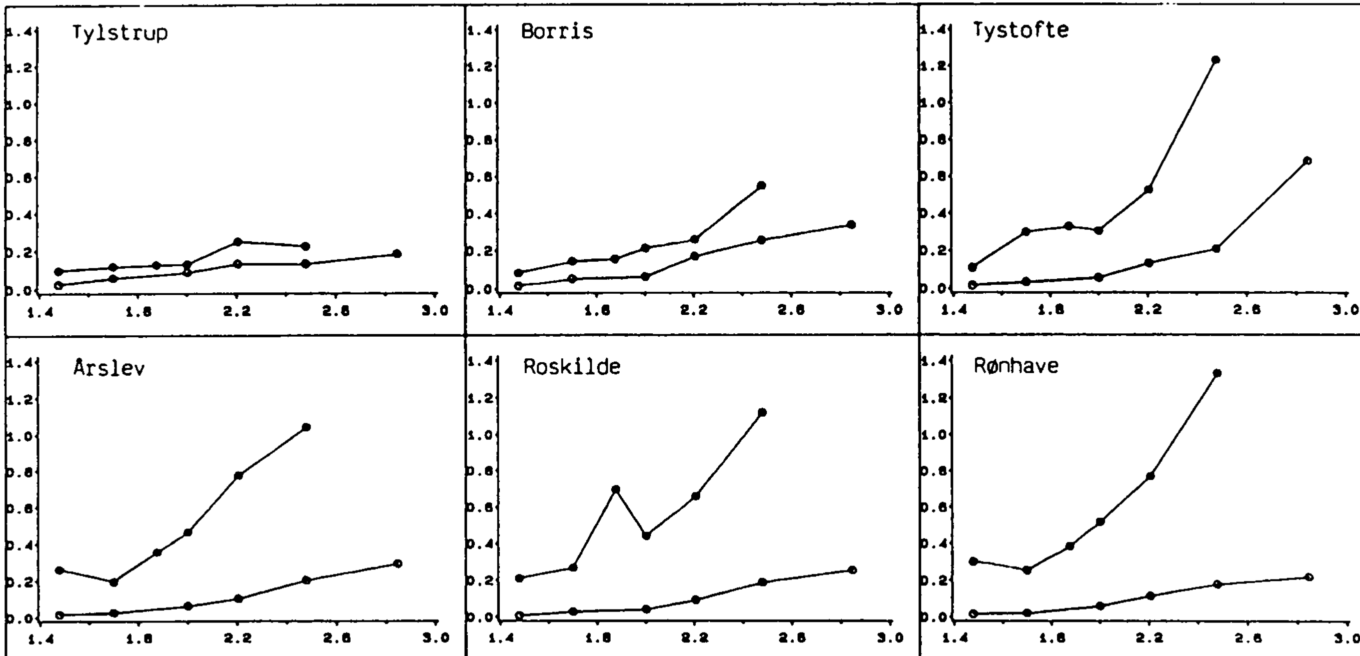
Appendix 8. Shear strength averaged for 3 levels of normal load (30, 60, 90 kPa). Annulus shear method, remoulded soil, plough layer.

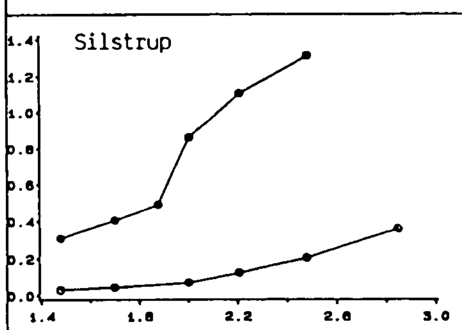
Abscissa: pF (eater potential, pF ~ log (−ψ), ψ in hPa)
Ordinate: Shear strength, kPa



Appendix 9. Soil cohesion (•———•) and internal friction (•- - - -•) calculated by the Coulomb equation using strength/normal load data. Annulus shear method, remoulded soil, plough layer.

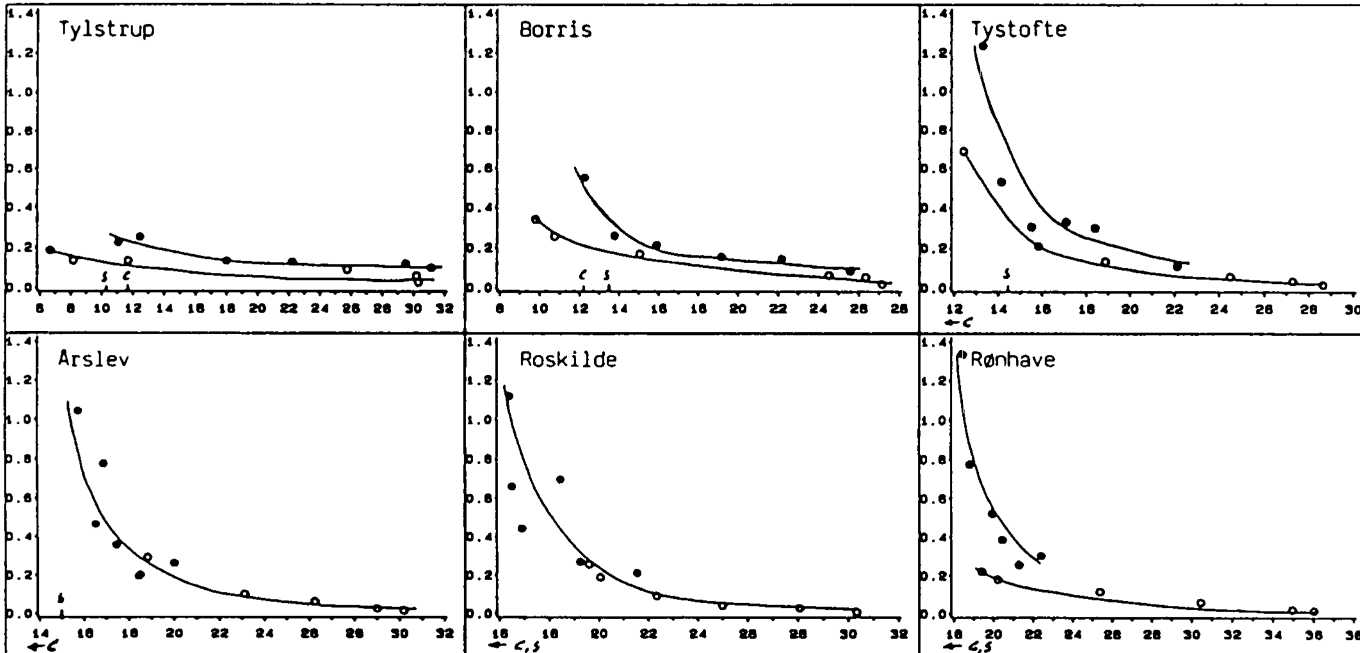
Abscissa: pF (water potential, pF ~ log (−ψ), ψ in hPa)
Ordinate, left: Cohesion, kPa
Ordinate, right: Friction (tan (ϕ))

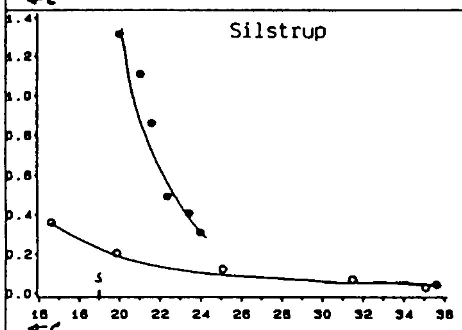




Appendix 10. The drop cone parameter, $1/h^2$, for remoulded soil (open symbols) and undisturbed soil (closed symbols).

Abscissa: pF (water potential, pF ~ log (−ψ)m ψ in hPa)
Ordinate: $1/h^2$, $m^{-2} \cdot 10^{-6}$ (h = penetration, m)





Appendix 11. The drop cone parameter, $1/h^2$, for remoulded soil (open symbols) and undisturbed soil (closed symbols) plotted vs. the gravimetric water content for different locations. Curves are fitted by hand. "C" and"S" indicate the drop cone plastic limit estimated by the Campbell and Schofield & Wroth suggested reading of the penetration/water content plot, respectively.

Abscissa: Water content, % w/w
Ordinate: $1/h^2$, $m^{-2} \cdot 10^{-6}$ (h = penetration, m)

Appendix 12. Strength estimates as differentiated to cohesion (c) and internal friction (tan τ) in undisturbed soil cores drained to different water potentials. The dry bulk density and volumetric water content are given as well. These data enable estimation of soil strength (τ) at a given water potential and normal load (P), using the Coulomb equation $\tau = C + \tan\phi \cdot P$. Confidence limits for these estimates can be calculated using the expression

$$t_{(n-2),\,1-\alpha/2} \cdot s \cdot \sqrt{1/n + \frac{(P_i - \bar{P})^2}{SAK_p}} \; .$$

With $n = 12$, $\alpha = 0.05$, $t_{10,0.975} = 2.228$, $\bar{P} = 105$ and $SAK_P = 31500$ this given

$$2.228 \cdot s \cdot \sqrt{1/12 + \frac{(P_i - 105)^2}{31500}} \cdot$$

As an example, the strength at the loamy soil at Rønhave at a potential of 100 hPa (~ pF 2) and at a normal load of 100 kPa (~ 1 bar) can be estimated to

$$(58.2 + 0.57 \cdot 100) \pm \left(2.228 \cdot 10.2 \cdot \sqrt{1/12 + \frac{(100-105)^2}{31500}}\right) \text{kPa} = 115.2 \pm 6.6 \text{ kPa}.$$

Location	Water potential hPa	Cohesion (C) kPa	Friction (tan ϕ)	Root MS_e (s) from regression Input to the calculation of confidence limits	Dry bulk density* g cm^{-3}	Water content* % v/v
Tylstrup	–30	23.6	0.37	11.0	1.38	42.8
	–50	17.9	0.46	11.8	1.37	40.3
	–75	28.8	0.49	3.0	1.39	30.8
	–100	25.1	0.55	3.4	1.38	24.7
	–160	25.9	0.58	4.8	1.39	17.2
	–300	19.8	0.74	15.8	1.38	15.2
Borris	–30	25.3	0.49	20.5	1.48	37.8
	–50	28.4	0.51	9.6	1.48	32.8
	–75	34.3	0.52	7.5	1.47	28.1
	–100	44.5	0.55	10.7	1.48	23.4
	–160	51.0	0.48	9.1	1.46	20.1
	–300	68.9	0.47	10.2	1.51	18.4

App 12, continued

Tystofte	–30	18.9	0.52	4.9	1.48	32.8
	–50	13.1	0.83	18.5	1.53	28.2
	–75	29.3	0.63	5.3	1.48	25.2
	–100	34.9	0.68	9.9	1.48	23.0
	–160	52.1	0.59	13.3	1.51	21.3
	–300	59.1	0.62	15.3	1.52	20.2
Årslev	–30	32.1	0.63	12.2	1.55	30.9
	–50	40.5	0.67	15.1	1.52	28.0
	–75	45.4	0.73	13.1	1.55	27.0
	–100	56.6	0.63	11.9	1.52	25.1
	–160	66.9	0.61	15.9	1.53	25.8
	–300	98.6	0.54	31.6	1.52	23.9
Roskilde	–30	44.4	0.53	22.3	1.55	33.2
	–50	54.1	0.64	22.1	1.54	29.5
	–75	37.7	0.92	32.5	1.56	28.6
	–100	62.3	0.79	15.7	1.58	26.6
	–160	75.1	0.67	15.4	1.57	25.8
	–300	92.9	0.63	25.2	1.56	25.5
Rønhave	–30	33.7	0.64	10.1	1.48	33.1
	–50	34.4	0.67	12.2	1.47	31.3
	–75	43.4	0.70	22.3	1.45	29.7
	–100	58.2	0.57	10.2	1.44	28.7
	–160	50.4	0.78	23.9	1.45	27.2
	–300	76.9	0.57	12.8	1.45	26.7
Silstrup	–30	33.4	0.80	26.3	1.45	34.6
	–50	49.3	0.67	34.1	1.44	33.7
	–75	66.0	0.65	10.9	1.47	32.7
	–100	77.3	0.55	20.5	1.48	31.9
	–160	59.9	0.70	19.9	1.41	29.6
	–300	43.9	1.00	24.5	1.43	28.6

* averaged for the 12 samples included in the regression for each combination of location and water potential.

Afdelinger m.v. under Statens Planteavlsforsøg

Direktionen

Direktionssekretariatet, Skovbrynet 18, 2800 Lyngby	45 93 09 99
Informationstjenesten, Skovbrynet 18, 2800 Lyngby	45 93 09 99
Afdeling for Biometri og informatik, Lottenborgvej 24, 2800 Lyngby	45 93 09 99

Landbrugscentret

Centerledelse, Fagligt Sekretariat, Forkningscenter Foulum, Postbox 23, 8830 Tjele	86 65 25 00
Afdeling for Grovfoder og Kartofler, Forskningscenter Foulum, Postboks 21, 8830 Tjele	86 65 25 00
Afdeling for Industriplanter og Frøavl, Ledreborg Allé 100, 4000 Roskilde	42 36 18 11
Afdeling for Sortsafprøvning, Teglværksvej 10, Tystofte, 4230 Skælskør	53 59 61 41
Afdeling for Kulturteknik, Flensborgvej 22, Jyndevad, 6360 Tinglev	74 64 83 16
Afdeling for Jordbiologi og -kemi, Lottenborgvej 24, 2800 Lyngby	45 93 09 99
Afdeling for Planteernæring og -fysiologi, Vejenvej 55, Askov, 6600 Vejen	75 36 02 77
Afdeling for Jordbrugsmeteorologi, Forskningscenter Foulum, Postbox 25, 8830 Tjele	86 65 25 00
Afdeling for Arealdata og Kortlægning, Enghavevej 2, 7100 Vejle	75 83 23 44
Borris Forsøgsstation, Vestergade 46, 6900 Skjern	97 36 62 33
Lundgård Forsøgsstation, Kongeåvej 90, 6600 Vejen	75 36 01 33
Rønhave Forsøgsstation, Hestehave 20, 6400 Sønderborg	74 42 38 97
Silstrup Forsøgsstation, Oddesundvej 65, 7700 Thisted	97 92 15 88
Tylstrup Forsøgsstation, Forsøgsvej 30, 9382 Tylstrup	98 26 13 99
Ødum Forsøgsstation, Amdrupvej 22, 8370 Hadsten	86 98 92 44
Laboratoriet for Biavl, Lyngby, Skovbrynet 18, 2800 Lyngby	45 93 09 99
Laboratoriet for Biavl, Roskilde, Ledreborg Allé 100, 4000 Roskilde	42 36 18 11

Havebrugscentret

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Afdeling for Grønsager, Kirstinebjergvej 6, 5792 Årslev	65 99 17 66
Afdeling for Blomsterdyrkning, Kirstinebjergvej 10, 5792 Årslev	65 99 17 66
Afdeling for Frugt og Bær, Kirsteinebjergvej 12, 5792 Årslev	65 99 17 66
Afdeling for Planteskoleplanter, Kirstinebjergvej 10, 5792 Årslev	65 99 17 66
Laboratoriet for Forædling og Formering, Kirstinebjergvej 10, 5792 Årslev	65 99 17 66
Laboratoriet for Gartneriteknik, Kirstinebjergvej 10, 5792 Årslev	65 99 17 66
Laboratoriet for Levnedsmiddelforskning, Kirstinebjergvej 12, 5792 Årslev	65 99 17 66

Planteværnscentret

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Afdeling for Plantepatologi, Lottenborgvej 2, 2800 Lyngby	45 87 25 10
Afdeling for Jordbrugszoologi, Lottenborgvej 2, 2800 Lyngby	45 87 25 10
Afdeling for Ukrudtsbekæmpelse, Flakkebjerg, 4200 Slagelse	53 58 63 00
Afdeling for Pesticidanalyser og Økotoksikologi, Flakkebjerg, 4200 Slagelse	53 58 63 00
Bioteknologigruppen, Lottenborgvej 2, 2800 Lyngby	45 87 25 10

Centrallaboratoriet

Centrallaboratoriet, Forskningscenter Foulum, Postbox 22, 8830 Tjele	86 65 25 00

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