Soil Fragmentation and Friability

Effects of Soil Water and Soil Management

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Ph.D. Dissertation

Preface

This thesis is submitted together with the five enclosed papers in partial fulfilment of the requirements of the Ph.D. degree at The Royal Veterinary and Agricultural University, Copenhagen (KVL).

The work presented has been carried out partly at Dept. of Crop Physiology and Soil Science, Danish Institute of Agricultural Sciences (DIAS) and partly at Dept. of Land Resource Science, University of Guelph, Ontario, Canada where I stayed for six months in year 2000. Most of the work was carried out in the context of Project I.3 "Soil fertility and soil tilth as influenced by organic farming practices and soil tillage" operated under the Danish Research Centre for Organic Farming (DARCOF). The DARCOF project included the characterization of soil tilth of differently managed soils. Soil fragmentation and friability were integrated elements in this project. Financial support from DARCOF further enabled more basic studies, which hereby is gratefully acknowledged. I would also like to acknowledge the financial support of my stay in Canada provided by Knud Højgaards Fond, Studiefonden for Danmarks Jordbrugsvidenskabelige Ph.D.-forening, Søren Christian Sørensen og hustrus Mindefond, Agronomfonden, Ellen Backes Legat, Generalmajor J.F. Classens Legat, Frk. Marie Elisabeth Nielsens Legat, Landbrugets Studiefond, Fyns Stifts Patriotiske Selskabs Fællesfond and Frimodt-Heineke Fonden.

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Summary

Soil fragmentation is a primary aim in most tillage operations in order to create a soil environment favourable for crop establishment and growth. Soils vary around the world from those exhibiting a self-mulching nature to those of a hardsetting nature. These extremes have been reported for Australian and other tropical and subtropical soils. In humid temperate climates, soil tillage is generally needed in order to produce a favourable environment for crop establishment and growth. The ease of preparing a favourable arable layer depends on complex interactions between climate, soil and the tillage implement. Especially soil water affects soil strength and fragmentation properties and thereby the ease of preparing a suitable arable layer. Soil management affects soil fragmentation and friability indirectly through effects on soil structure formation and stabilization and directly through the influence of soil tillage and traffic. The overall purpose of this thesis is to contribute to the understanding of soil fragmentation and friability as affected by soil management and soil water regime. The reaction of the soil upon tillage was evaluated within the concept of soil tilth as defined by Soil Science Society of America (SSSA) "*the physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration*".

The study involved soils from two case studies, the Askov long-term experiment on animal manure and mineral fertilizers, a field experiment with non-inversion tillage and a field experiment on compaction and intensive tillage. All the soils included in the study were humid sandy loams predominantly developed on Weichselian glacial moraine deposits. The soils were classified as Oxy aquic Agriudolls/Glossic Phaeozems according to Soil Taxonomy/WRB except for the Askov soil that was classified as Ultic Hapludalfs/Dystric Luvisols according to Soil Taxonomy/WRB. For all soils the clay content ranged from about 12 to 21 g per $100g^{-1}$ and soil organic matter ranged from 1.8 to 3.9 g $100g^{-1}$. The case studies included two long-term forage cropping system soils with a grass ley in the crop rotation (DFG(1) and DFG(2)), which were compared with a neighbouring counterpart. DFG(1) was compared with a forage cropping system soil without grass ley in the crop rotation (i.e., only annual crops), labelled DFA, whereas DFG(2) was compared with a continuously cash cropped soil with very low input of organic matter (no animal manure and straw removed), labelled CCC. An unfertilized (UNF), animal manured (AM) and a mineral fertilized (NPK) soil was included from the Askov long-term experiment on animal manure and mineral fertilizers established in 1894. The tillage experiment included a non-inversion tilled soil, labelled NINV, (non-inversion subsoil loosening to 35 cm depth and seedbed preparation with rotovator) and a conventionally tilled soil, labelled CONV, (mouldboard ploughing to 22 cm and secondary tine cultivation). The experiment on soil compaction and intensive tillage involved two "extreme" tillage and traffic treatments and a reference treatment (REF). The extreme treatments were soil compaction (PAC) and intensive tillage (INT) that were performed on wet soil just after spring ploughing and prior to seedbed preparation. The field experiments on non-inversion tillage, and soil compaction and intensive tillage were both conducted at the organically managed Rugballegård Research Station.

Ease of tillage is commonly extrapolated from measurement of tensile strength in a compression test using air-dry or oven-dry aggregates. This procedure may lead to erroneous conclusion on soil behaviour of moist soil in the field. Therefore a multi-level analytical strategy was followed, i.e., soil fragmentation and friability were characterized using qualitative and quantitative *in situ*, on-field and laboratory methods.

Soil fragmentation and friability were assessed in the field *qualitatively* by visual examination and *quantitatively* by employing a simple drop-shatter fragmentation test, denoted *soil drop test*. The energy input in the soil drop test was low in comparison with the energy input in typical seedbed cultivation. However, the soil drop test was sensitive enough to display significant differences between treatments in most cases. In the laboratory soil fragmentation and friability were evaluated by measuring tensile strength and specific rupture energy on field-sampled aggregates. In general, tensile strength was determined on air-dry aggregates and in some cases on aggregates adjusted to pressure potentials in the range -100 hPa to -166 MPa (air-dry). In addition, a direct tension test was developed to measure tensile strength of moist soil without making assumptions on the mode of failure. Undisturbed field-sampled soil cores were used in the test. The method was applicable at high matric potentials (-50 and -100 hPa) but not at -300 hPa. The direct tension test results corresponded well with the predicted values determined from the indirect measurements of aggregate tensile strength.

In general, a fairly good agreement was found between the different methods in the hierarchy of methods applied. This indicates that sophisticated laboratory methods for assessing soil strength and fragmentation characteristics may well be used for evaluating soil behaviour under conditions prevailing in the field at the time of tillage. Nevertheless, it is recommended that laboratory methods are evaluated by using simple field methods at times and soil conditions appropriate for tillage.

The friability index showed in general a low sensitivity to long- and short-term differences in soil management. However, a clear effect of soil water was found, i.e. maximum friability index values at -300 to -1000 hPa pressure potential.

The effect of soil water on tensile strength and specific rupture energy of aggregates and on estimation of friability was investigated. As expected the study revealed the paramount influence of soil water. Interactions between soil water regime and treatment were found for cropping system soils (DFG(2) vs. CCC) and the fertilization treatments (UNF, NPK and AM) but not for the compaction treatments (PAC vs. REF). It was concluded that it might be hazardous to characterize soil fragmentation and friability properties of different treatments based on measurements at a single pressure potential and significant influence of pore characteristics was detected. Macroporosity was found to correlate to tensile strength and friability index. However, a clear correlation between tensile strength properties and pore geometry characteristics (e.g. tortuousity and continuity) was not shown. This may be due to large small-scale variations in these properties, i.e. the samples for tensile strength determination were taken next to the samples for pore characterization.

Marked long-term effects of cropping systems and fertilization were found. For two neighbouring soils with a high input of organic matter, poorer soil mechanical characteristics were found for a soil with grass in the rotation (DFG(1)) than for a soil solely grown with annual crops (mainly cereals). This difference in strength and friability characteristics may be related to a higher amount of biological structural binding and bonding agents in the soil with grass included in the rotation. Two soils with high inputs of organic matter (DFG(2) and AM) displayed more desirable aggregate strength and soil fragmentation characteristics than their counterparts (CCC and UNF, respectively) receiving low inputs of organic matter. Evidence suggests that cementation of dispersed clay was a determining factor for the stronger increase in aggregate tensile strength with increased dryness (decreased pressure potential) found for the CCC and UNF soils receiving low inputs of organic matter compared with DFG(2) and AM.

An early-stage effect of non-inversion tillage treatment (NINV) resulted in a poorer soil tilth in the topsoil layer (i.e., higher soil strength and lower ease of fragmentation and friability index) than for a conventionally mouldboard ploughed soil (CONV). Surprisingly, the effect of tillage on topsoil tilth was clearer by the end of the growing season in September than in May. This indicates that natural soil processes occurring during the growing season were not able eliminate the differences between the primary tillage treatments.

Soil compaction (PAC) resulted in strongly increased aggregate tensile strength at all the investigated water regimes (i.e., pressure potentials: -100 hPa to -166 MPa) in comparison with a reference treatment (REF). Surprisingly, soil compaction did not significantly affect the specific rupture energy of the aggregates. This was related to a clear difference in the stress-strain relationship for the soils. Aggregates from the compacted soil failed at higher stress but at lower strain than aggregates from the reference soil (i.e., higher Young modulus, (Y/ε)). This was characteristic for all size-classes and at all pressure potentials.

The results obtained in this study indicate that the prediction of soil fragmentation from tensile strength properties of soil elements may be very complex. We need more basic understanding of the fragmentation of "unconfined" soil at the different size-scales (aggregates to bulk soil) and the correlation between the different scales in order to be able to predict soil fragmentation in tillage (mainly superficial tillage) from a priori information. More specifically, the role of soil biology and soil water and pore characteristics needs to be studied in further detail.

The development of new methods and the application of well-know methods to quantify soil fragmentation and friability of soil at conditions similar to soil conditions at tillage (including water content) has been a primary aim in this thesis. However, there is still a strong need to develop new methods and modify existing methods to quantify soil fragmentation and friability under controlled conditions.

This study shows that soil compaction and intensive tillage significantly influence soil fragmentation and friability. Increasingly heavier machinery and - to some extent - more intensive seedbed preparation (PTO-driven implements) are being used in Danish agriculture. A thorough evaluation of this development on soil fragmentation and friability is needed. Furthermore, the accumulated knowledge of soil fragmentation and tensile failure in soil ought to be implemented in the design of new tillage implements.

Sammendrag (Summary in Danish)

Fragmentering og smuldringsegenskaber i jord: effekter af vandindhold og dyrkningssystem

Smuldring af jord er et af hovedformålene med jordbearbejdning. Jorde varierer fra at danne en passende struktur alene ved naturlige processer (opfugtning/udtørring, frost/tø) benævnt "self-mulching" i den engelsksprogede litteratur til at være meget svære at bearbejde til en passende struktur, benævnt "hardsetting" i den engelsk sprogede litteratur. Disse ekstrem-jorde findes i Australien og andre områder med tropisk/subtropisk klima. I fugtige tempererede områder er jordbearbejdning generelt set nødvendig for skabe at en passende jordstruktur for planteetablering og -vækst.

Denne afhandling omhandler, hvor let en jord er at bearbejde, hvilket har stor betydning for jordens dyrkningsværdi. På dansk anvendes udtrykkene "en bekvem jord" og "en let-smuldrende jord", som betegnelser for, hvor let jorden er at bearbejde. I det følgende anvendes begrebet "jordens smuldreevne" til at karakterisere denne egenskab. Udtrykket indbefatter både "soil fragmentation" og "soil friability" (friability = sprødhed på dansk) aspektet anvendt i den engelsksprogede tekst. Jordens smuldreevne afhænger af et komplekst samspil mellem klima, jord og jordbearbejdningsredskab. Særligt, spiller jordens vandindhold en væsentlig rolle. Våd jord er svær at smuldre (flyder ud, deformeres fremfor at smuldre), mens fragmentering af tør jord kan kræve stor energitilførsel. Dyrkningen påvirker jordens smuldreevne direkte i form af jordbearbejdning og trafik samt indirekte gennem effekter på opbygning og stabilisering af jordstrukturen. I afhandlingen beskrives metoder til at karakterisere og måle jordens smuldreevne. Det overordnede formål med afhandlingen er at bidrage til øget forståelse af jordens smuldreevne med særlig fokus på betydningen af dyrkning (sædskifte, gødskning, jordbearbejdning og pakning) og vandindhold. Jordens opførsel ved jordbearbejdning blev vurderet indenfor rammerne af det engelsksprogede koncept "soil tilth", som defineret af Soil Science Society of America (SSSA) "*the physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration*".

Jorde med vidt forskellig forhistorie blev anvendt i undersøgelserne. Der indgik jorde fra to case-studier, det langvarige gødningsforsøg på Askov Forsøgsstation, et jordbearbejdningsforsøg med ikke-vendende jordbearbejdning og et markforsøg med "ekstrem" behandling af jorden i form af pakning eller intensiv jordbearbejdning af våd jord. Jordtypen varierede fra sandblandet lerjord (JB 5, JB 6) til lerjord (JB 7). I jordene varierede lerindholdet fra 12 til 21 g $100g^{-1}$ og indholdet af organisk stof fra 1.8 til 3.9 g $100g^{-1}$. Alle jordene var udviklet på moræneaflejringer fra Weichsel-istiden. Med undtagelse af Askov jordene kunne alle klassificeres som Oxyaquic Agriudolls/Glossic Phaeozems ifølge henholdsvis Soil Taxonomy og WRB klassifikationssystemerne. Askov-jordene

klassificeredes som Ultic Hapludalfs/Dystric Luvisols (Soil Taxonomy/WRB). I case-studierne indgik to jorde fra et langvarigt økologisk drevet kvægbrug (DFG(1) og DFG(2)). Disse jorde er drevet i et grovfodersædskifte med græs inkluderet, og de blev årligt tilført husdyrgødning. DFG(1)blev sammenlignet med en nabo-jord fra et konventionelt drevet kvægbrug (DFA). DFA havde en lang dyrkningshistorie med dyrkning af enårige afgrøder (korn og sukkerroer) og årlig tilførsel af husdyrgødning. DFG(2) sammenlignedes med en nabo-jord fra et konventionelt planteavlsbrug (CCC). CCC var dyrket stort set ensidigt med kornavl i de seneste 20 år uden tilførsel af husdyrgødning og bortførsel af halmen (dvs. meget lav tilførsel af organisk stof). Fra det langvarige gødningsforsøg i Askov indgik behandlingerne: ugødet (UNF), husdyrgødet (AM) (=1½ AM i henhold til Askov-forsøgsplanen), og handelsgødet (NPK) (=1½ NPK). Markforsøgene med ikke-vendende jordbearbejdning og "ekstrem" behandling blev udført på den økologisk drevne Rugballegård Forsøgsstation. I jordbearbejdningsforsøget blev ikke-vendende jordbearbejdning (NINV) sammenlignet med konventionel jordbearbejdning (CONV). Den ikke-vendende jordbearbejdning inkluderede ikke-vendende løsning til 35 cm's dybde og overfladisk såbedstilberedning med tandfræser. Konventionel jordbearbejdning omfattede pløjning til 20 cm's dybde og såbedstilberedning med en traditionel såbedsharve. I "ekstrem" forsøget indgik behandlingerne: pakning (PAC), intensiv jordbearbejdning (INT) med rotorharve og en normal behandlet reference (REF). Pakning og intensiv jordbearbejdning blev udført på våd jord lige efter en tidlig forårspløjning.

Almindeligvis estimeres jordens smuldreevne ud fra indirekte målinger af trækstyrken på lufttørre eller endog ovntørre aggregater. Denne fremgangsmåde kan lede til fejlagtige slutninger omkring hvorledes uforstyrret fugtig jord opfører sig i marken. En hierarkisk analysestrategi blev derfor anvendt i dette studium. Jordens smuldreevne blev karakteriseret i marken ved brug af en kvalitativ beskrivende metode og kvantificeret ved brug af felt- og laboratoriemetoder.

Jordens smuldreevne karakteriseredes *kvalitativt* i marken ved brug af spadeprøven (Munkholm, 2000) og *kvantitativt* i marken ved brug af en simpel kasteprøve, benævnt *soil drop test* i teksten. Energitilførslen ved kasteprøven var lav i forhold til energitilførslen i en typisk såbedstilberedning. Alligevel var kasteprøven tilstrækkelig følsom til at kunne påvise sikre forskelle mellem behandlingerne i de fleste tilfælde. Fra jordene blev der udtaget jord til analyse i laboratoriet. Trækstyrke (eng.: tensile strength) (kPa) og specifik brydningsenergi (eng.: specific rupture energy) (J kg^{-1}) blev målt på enkelt-aggregater i en kompressionstest. Der blev generelt anvendt lufttørre aggregater og i nogle tilfælde opfugtede aggregater (-100 hPa til -3500 hPa) , En laboratoriemetode blev udviklet til måling af trækstyrke i en direkte test på uforstyrrede ringprøver ved høje vandindhold. Ved den direkte test sikres, at brydningen sker ved trækstyrkebrud (eng: tensile failure), hvor man ved indirekte test er nødt til at antage dette. Metoden var anvendelig ved høje trykpotentialer (-50 og -100 hPa) men ikke ved -300 hPa. Resultaterne fra den direkte trækstyrke metode var i god overensstemmelse med forventede værdier beregnet udfra trækstyrke målt på aggregater i en indirekte test.

Generelt set fandtes god overensstemmelse mellem metoderne i den hierarkiske struktur af metoder. Dette indikerer at laboratoriemetoder kan anvendes til karakterisering af jordens smuldreevne. Ikke desto mindre anbefales, at laboratorieresultaterne holdes op imod resultater og observationer fra simple feltmetoder udført på tider af året og under forhold, hvor jordbearbejdning vil være aktuel.

Der blev kun i få tilfælde påvist sikre forskelle mellem behandlinger eller jorde ved brug af det såkaldte smuldreevne indeks (eng.: friability index). En klar effekt af vandindhold blev dog påvist. Størst "friability index" blev fundet ved trykpotentialer mellem -300 to -1000 hPa.

Der blev fundet en klar forskel mellem jorde med forskellig dyrkningshistorie. Resultater fra de langvarige gødningsforsøg på Askov Forsøgsstation og fra case-studierne viste, at langvarig årlig tilførsel af husdyrgødning giver en bedre smuldreevne. I tør og fugtig tilstand havde den husdyrgødede jord svagere aggregater og viste større smuldreevne end ugødet eller kunstgødet jord. I våd tilstand udviste den husdyrgødede jorde størst aggregatstyrke og stabilitet, hvilket blev forklaret med et højere indhold af biologiske bindingselementer som følge af et højere indhold af organisk stof og en større biologisk aktivitet. Større styrke for den ugødede eller kunstgødede jord i tør tilstand forklaredes med cementering af ler dispergeret i våd tilstand. Den ugødede og kunstgødede jord havde lavere strukturstabilitet i våd tilstand end de respektive husdyrgødede jorde.

For to nabojorde med tilførsel af husdyrgødning fandtes størst styrke af lufttørre aggregater og lavest fragmentering i marken for jorden med græs i sædskiftet og meget høj biologisk aktivitet – herunder regnormeaktivitet. Forskellen blev forklaret med et højere indhold af biologisk bindingselementer i jorden med højest biologisk aktivitet. Andre undersøgelser vist, at særligt en høj regnormeaktivitet kan resultere i stærke tørre aggregater.

Effekter af jordbearbejdning og trafik blev fundet i flere forsøg. Ikke-vendende jordbearbejdning (NINV) resulterede i dårligere smuldreevne i 7-14 cm jordlaget end i en traditionelt pløjet jord (CONV). Forskelle fandtes både for kasteprøve og trækstyrke på lufttørre aggregater. Forskellen mellem behandlingerne blev ikke udvisket af naturlige strukturforbedrende processer i jorden (opfugtning/udtørring m.v.) i løbet af vækstsæsonen. Færdsel på og intensiv bearbejdning af våd jord gav i et andet forsøg en markant forringet smuldreevne. Der måltes stærkere aggregater i såvel våd/fugtig som tør jord og lavere fragmentering i marken i fugtig tilstand. Overraskende viste det sig, at fragmenteringsenergien var ens for aggregater fra pakket i forhold til upakket jord. Det skyldtes en klar forskel i belastnings- forskydningsforløbet (Young modulus, (Y/ε)) for henholdsvis pakket og upakket jord. Aggregater fra førstnævnte jord krævede større styrke at bryde, men blev brudt ved mindre forskydning end aggregater fra upakket jord. Ved jordbearbejdning tilføres væsentlig større energimængder, end det der skulle til for at bryde aggregaterne i tør såvel som fugtig tilstand. Energitilførslen ved kasteprøven var ligeledes langt større end aggregaternes fragmenteringsenergi. Resultaterne tyder på, at man skal være varsom med at forudsige fragmentation af jorden i marken alene ud fra aggregaters fragmenteringsenergi.

Resultaterne i denne afhandling viser, at jordens smuldreevne afhænger af mange faktorer. De indikerer også, at det ikke er simpelt at forudsige fragmentering af uforstyrret jord i marken udfra fragmentationsenergien målt på aggregater. For at kunne forudsige jordens fragmentering i marken ud fra jordegenskaber målt forud for jordbearbejdningen, er der behov for en større viden om jordens brydnings- og smuldreegenskaber på forskellige niveauer (aggregatstørrelse til uforstyrret jord i marken) og om sammenhængen mellem de forskellige niveauer. Mere specifikt er der behov for større viden om indflydelsen af jordbiologi, vandindhold og porestruktur på jordens smuldreevne. Den sekundære jordbearbejdning er blevet intensiveret over en årrække (PTO-drevne redskaber) og trafikbelastningen ligeså. Betydningen af denne udvikling for jordens smuldreevne bør vurderes, og den opnåede viden om jordens smuldreegenskaber bør tages i anvendelse ved design af nye jordbearbejdningssystemer og –redskaber.

List of supporting papers

I. Munkholm, L.J., Schjønning, P. & Petersen, C.T., 2001. Soil mechanical behaviour of sandy loams in a temperate climate: case studies on long-term effects of fertilization and crop rotation. Soil Use and Management 17, 269-277.

II. Munkholm, L.J., Schjønning, P., Debosz, K., Jensen, H.E. & Christensen, B.T., 2002. Aggregate strength and soil mechanical behaviour of a sandy loam under long-term fertilization treatments. European Journal of Soil Science 53, 129-137.

III. Munkholm, L.J., Schjønning, P. & Rasmussen, K.J., 2001. Non-inversion tillage effects on soil mechanical properties of a humid sandy loam. Soil & Tillage Research 62, 1-14.

IV. Munkholm, L.J. & Kay, B.D., 2002. Effect of water regime on aggregate tensile strength, rupture energy and friability. Soil Science Society of America Journal 66, 702-709.

V. Munkholm, L.J., Schjønning, P. & Kay, B.D., 2002. Tensile strength of soil cores in relation to aggregate strength, soil fragmentation and pore characteristics. Soil & Tillage Research 64, 125-135.

In the following the papers will be referred to by their Roman numeral.

List of studied objects

Study objects	Papers	Main focus
Case study 1		
Forage cropping with grass ley (DFG(1))	I	Cropping & Fertilization
Forage cropping without grass ley (DFA)		
Case study 2		
Forage cropping with grass ley (DFG(2))	I, IV	Cropping, Fertilization, Soil water & Methods
Monocultural cereal cropping (CCC)		
Askov long-term experiment on animal manure and mineral fertilizers		
Unfertilized (UNF)	II	Fertilization & Soil water
Animal manure (AM)		
Mineral fertilizers (NPK)		
Field experiment with non-inversion tillage		
Non-inversion tillage (NINV)	III	Tillage
Conventional tillage with ploughing (CONV)		
Field experiment with soil compaction and intensive cultivation		
Compaction (PAC)	IV, V	Methods & Compaction
Intensive rotary harrowing (INT)		
Reference (REF)		

List of abbreviations

AM	animal manured Askov soil (1½ AM)
CCC	continuously cash cropped soil with low organic matter input (case study 2)
CONV	conventional tillage (including mouldboard ploughing)
DFA	dairy farm cropping system soil with annual crops (case study 1)
DFG(1)	dairy farm cropping system soil with grass ley in rotation (case study 1)
DFG(2)	dairy farm cropping system soil with grass ley in rotation (case study 2)
E_{sp}	specific rupture energy ($J\ kg^{-1}$)
INT	intensive secondary tillage on wet soil
k	friability index
NINV	non-inversion primary tillage treatment
NPK	mineral fertilized Askov soil (1½ NPK)
PAC	compacted soil
REF	reference treated soil (reference to PAC and INT)
SOM	soil organic matter
UNF	unfertilized Askov soil
Y	Tensile strength (kPa)

1. Introduction

Soil fragmentation is a primary aim in tillage in order to create a soil environment favourable for crop growth. The ease of preparing a suitable arable layer (i.e., seedbed and cultivated upper zone of the rootbed) is a fundamental soil fertility/productivity characteristic. Soils vary around the world from those exhibiting a self-mulching behaviour (Grant & Blackmore, 1991) to those of a hardsetting nature (i.e. compact, hard and structureless surface soils (Chan, 1989)). Self-mulching soils fragment through natural soil processes to yield a desirable seedbed whereas hardsetting soils are very difficult to manage. These extremes have been reported for Australian and other tropical and subtropical soils. In humid temperate climates, soil tillage is generally needed to produce a favourable environment for crop establishment and growth. The ease of preparing a favourable arable layer in a specific situation depends on complex interactions between climate, soil and the tillage implement. Especially soil water affects soil strength and fragmentation properties and thereby the ease of preparing a suitable arable layer. Generally it is difficult to fragment soil in wet condition (plastic deformation and soil compaction) as well as in dry conditions (hard soil that needs high energy input to fragment). Tillage may produce a cloddy structure in both too wet and too dry condition. Therefore, it is important to know the optimum water content for tillage and the range in water contents giving the best possible result of tillage. Dexter (2000) defined the optimal water content for tillage as the "the water content at which tillage produces the greatest proportion of small aggregates", i.e. the greatest soil fragmentation. Although Dexter proposed a method for quantifying the optimal water content using water retention characteristics, much more work is needed in this area. Few have studied the effect of soil water on aggregate strength and soil friability.

Soil management affects soil fragmentation and friability indirectly through effects on soil structure formation and stabilization and directly due to the influence of soil tillage and traffic. During the last century, monocultural cropping systems and systems using exclusively mineral fertilizers have been introduced in many parts of the world and also in Denmark. The mechanical impact on soil structure as related to tillage and traffic has also changed dramatically during the last century with heavy weight tractors replacing horses as the primary pulling force. Today about 15% of the tractors sold in Denmark weigh more than 7 Mg (Jens J. Høy, personal communication). Tillage intensity has increased during the last century in Denmark from shallow and low intensive horse-driven tillage to deeper and much more intensive cultivation. Surprisingly, only few studies have addressed the long-term term effects of the above-mentioned marked changes in soil management on soil fragmentation and friability characteristics.

1.1 Soil tilth

In this work the ease of preparing a favourable arable layer for plant growth was evaluated within the concept of soil tilth. Karlen et al. (1990) stated that a soil with a good soil tilth "*usually is loose, friable and well granulated*". In an early definition Yoder (1937) equated soil tilth with soil fertility: "*soil tilth is a blanket term describing all the conditions that determine the degree of fitness of a soil as an environment for the growth and development of a crop plant"*, while more recent approaches highlight physical properties that give information on the state and dynamics of the soil "*the physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration"* (SSSA, 1996). With the aim of developing a quantitative understanding of the concept of soil tilth Karlen et al. (1990) proposed a more comprehensive definition focusing on the structural state of the soil and physical properties derived from this: *"the physical condition of a soil described by its bulk density, porosity, structure, roughness, and aggregate characteristic as related to water, nutrient, heat and air transport; stimulation of microbial and microfauna populations and processes; and impedance to seedling emergence and root penetration"*. Likewise, Hadas (1997) in his definition of soil tilth focused on the structural state of the soil as affected by tillage without explicitly including the ease of tillage aspect: "*tillage affected, quantifiable soil structural-state-dependent attributes governing and controlling a soil environment, favourable to crop production"*. Karlen et al. (1990) introduced a term called tilth-forming processes in order to emphasize that a proper soil tilth is not an inherent static property of the soils but the result of soil tilth-forming processes *"the combined action of physical, chemical, and biological processes that bond primary soil particles into simple and complex aggregates and aggregate associations that create specific structural or tilth conditions"*.

The above-mentioned authors disagree about the explicit inclusion of the ease of tillage aspect in the definition of soil tilth. This thesis has been carried out within the conceptual framework of soil tilth as defined by SSSA under the perception that soil tilth comprises the state of soil structure, the behaviour of the soil, and the stability of soil structure.

1.2 Soil fragmentation and friability

In most cases soil fragmentation by tillage is needed in order to obtain a favourable arable layer. By the term soil fragmentation is understood the process of breakdown and crumbling of soil aggregates. It may be quantified by measures such as the increase in surface area or decrease in mean weight diameter (MWD), i.e. the quantitative breakdown of soil under applied stress.

As highlighted by Karlen et al. (1990), high friability is one of the most important characteristics of a soil having a desirable tilth. The term soil friability has been discussed, defined and redefined by soil scientist for decades (e.g. Christensen, 1930; Bodman, 1949; Utomo & Dexter, 1981). In general it has been used to describe the outcome of soil fragmentation/crumbling as stated in the definition Utomo & Dexter (1981): *"Soil friability: the tendency of a mass of unconfined soil to break down and crumble under applied stress into a particular size range of smaller fragments"*. Thus, a friable soil is characterized by an *ease* of fragmentation of undesirably large aggregates/clods and a *difficulty* in fragmentation of minor aggregates into undesirable small elements. Excessively small aggregates enhance soil erodibility and may impede seedling emergence due to surface crusting. This means that a friable soil that is ideal seen from a soil fertility/productivity point of view may also be desirable seen from an environmental point of view, i.e. low energy input in tillage and low erodibility.

1.3 Soil management

Soil management may affect soil fragmentation and friability properties of the soil in a very complex manner. Different elements of soil management (e.g. crop rotation, fertilization, liming, tillage and traffic) may affect these properties in different and sometimes conflicting manners.

In general, factors that enhance clay dispersion (e.g. intensive tillage and traffic on wet soil or sodicity) have been found to result in increased tensile strength of dry aggregates and therefore reduced ease of preparing a desirable arable layer (Kay & Dexter, 1992; Barzegar et al. 1995; Watts & Dexter, 1997a). Soil compaction may not only induce clay dispersion, but also increase the number of contact points between the soil elements. These factors may explain the negative effect of soil compaction on aggregate tensile strength and friability found by Chan (1989), Guérif (1990) and Watts & Dexter (1998).

Conflicting results have been found regarding the influence of soil organic matter (SOM) on soil fragmentation and friability. A high organic matter content may indicate a high biological activity in the soil. In some cases tensile strength of dry aggregates has increased with input of organic matter (e.g., Rogowski & Kirkham, 1976; Hadas et al., 1994) or high earthworm activity (McKenzie & Dexter, 1987; Schrader & Zhang, 1997). Others have found a decrease in tensile strength of dry aggregates and friability with increasing SOM content (Zhang, 1994; Watts & Dexter, 1997a, 1998). The divergence in the response to SOM content is probably related to the differentiated effect of SOM on soil structure formation and stabilization.

2. Objectives

The purpose of this work is to contribute to the understanding of soil fragmentation and friability with special emphasis on the effects of soil management and soil water content. A number of specific objectives have been defined within the areas: 1. Experimental strategy and methodology, 2. Soil water and pore characteristics, 3. Soil management.

Experimental strategy and methodology:

Ease of preparing the arable layer is commonly extrapolated from measurement of tensile strength in a compression test using air-dry or oven-dry aggregates. The procedure of using very dry aggregates may lead to erroneous conclusions on ease of tillage. First of all because tillage usually is carried out at much higher water contents and also because bulk soil *in situ* may react differently from that predicted from measurements of tensile strength on single aggregates. The following objectives were identified:

- to evaluate the agreement between soil friability derived from classical tensile strength measurements and fragmentation in the field assessed by qualitative and quantitative methods.

- to develop a method for measuring tensile strength in a direct tension test on soil cores adjusted to water contents similar to those in the field at tillage.

Soil water content and pore characteristics:

The soil water content and the pore characteristics influence soil strength and fragmentation properties. Surprisingly, the effect of soil water on soil fragmentation and friability has been addressed in only a few studies in the past. In this study the objective was:

- to quantify the effect of soil water on aggregate tensile strength and soil friability in the range of pressure potentials from -100 hPa to air-dry and to relate aggregate strength properties to pore characteristics.

Soil management:

Crop rotations, residue management and fertilization control the input of organic matter and the duration of the cropping period and these factors highly influence the soil structure forming and stabilizing processes. Tillage and traffic directly and instantly affects soil structure and also affects the soil structure forming and stabilizing processes. The following objectives were defined:

- to elucidate long-term effects (>20 years) of fertilization and cropping systems on soil fragmentation and friability and to relate these properties to biotic and abiotic soil structural forming and stabilizing processes.

- to investigate the short-term effects of tillage and traffic on soil fragmentation and friability

3. Soil structure – aggregation, stabilization, fragmentation

3.1 Soil structure and soil aggregation

Soil is a heterogeneous medium, composed of primary particles, aggregates, pores, organic matter and soil biota of sizes in the order of magnitude from 10^{-6} to 10^{0} m. Ladd et al. (1996) defined soil structure simply as "the size, shape and arrangement of particles in soil". Dexter (1988a) presented a broader definition of soil structure: "the spatial heterogeneity of the different components or properties of soil". Hadas (1997) has elaborated on the definition of Dexter (1988a) and presented a definition that explicitly includes the soil matrix, the pore space and the soil properties: “the spatial heterogeneity of the arrangements of the soil solid constituents, the enclosed pore spaces and the derived soil properties”.

In a well-structured soil the structure can be described as ordered in a hierarchy, where small building blocks cluster into small soil aggregates that again cluster into bigger aggregates (Brewer, 1964; Tisdall & Oades, 1982; Hadas, 1987; Dexter, 1988a; Oades & Waters, 1991). According to this theory aggregates of a low order are denser and stronger than aggregates of a higher order, because each order exclude pore spaces between the particles of the next order (Dexter, 1988a). The understanding of a hierarchical ordering has led to the use of fractal theory to describe soil structure (e.g. Rieu & Sposito, 1991; Perfect & Kay, 1991). Oades & Waters (1991) found a well-developed aggregate hierarchy for clayey soils (Alfisols and Mollisols) dominated by 2:1 layer clay minerals (illite and smectite) but not for an Oxisol where kaolinte and oxides were the dominant clay minerals. For sandy loamy Danish soils, a degree of structural scaling is typically found when performing a visual description of the soil (i.e., on mm and cm scale) (Munkholm, 2000). However, the applicability of the aggregate hierarchy concept is still to be evaluated for Danish soils.

Soil aggregation includes a number of complex processes, where mineral composition, organic matter, polycations, soil fauna, plants and microbes play a role. In aggregation some of the most important processes are 1. flocculation of clay, 2. cementation of particles by e.g. cementation of dispersed clay or Fe- and Al-oxyhydroxides, 3. gluing effect of bonding agents, e.g. excreta such as polysaccharides from plants, soil fauna and microbes, and 4. cross-linking and enmeshment by fungal hyphae and plant roots (Tisdall & Oades, 1982; Goldberg, 1989; Degens, 1997; Beare et al, 1997; Ladd et al., 1996).
Sekera & Brunner (1943) and Tisdall & Oades (1982) described a hierarchical model of soil aggregation. At <2 μm level, Tisdall & Oades hypothesised that aggregation occurs due to flocculation of clay particles (e.g. by exchange of Na for a polycation like Ca, Mg, Al or Fe) and/or of condensation of humic polymers by "cation-bridging" by e.g. Ca. For silt sized soil units (2-20 μm) and microaggregates (20-250 μm) they hypothesise that aggregation in addition is due to a gluing effect by polysaccharides. Clay-cation-humic polymer complexes are supposed to be glued to plant roots, fungal hyphae and bacteria by "bonding agents" such as polysaccharides. In the formation of macroaggregates (>250 μm), roots and fungal hyphae are supposed to play a part. A number of papers have given some evidence of the validity of

the conceptual model of aggregation (e.g. Muneer & Oades, 1989a,b; Dorioz et al., 1993; Degens, 1997).

3.2 The ideal arable soil layer

The crops require ample aeration for the plant roots and for decomposition of organic matter, and at the same time an adequate soil/root contact to secure uptake of water and nutrients. Karlen et al. (1990) stated that a soil with a good soil tilth "*usually is loose, friable and well granulated*". Similar perceptions of an optimal arable layer for plant growth have been proposed in the German-speaking world where the term "Bodengare" has been used to describe a soil with an optimal environment for crop growth. Sekera and Brunner (1943) considered a crumb structure as the desired soil structure in relation to plant growth. However, Görbing (1947, p. 112) defined "Bodengare" in a broader sense, i.e. the term cannot simply be replaced by "crumb structure". By a "Gare" soil Görbing understands a biologically active soil that is the fundament for developing crumb structure in the upper 20 cm of the soil profile. "*Gar ist ein Boden, dessen Krümelstruktur durch das Leben selbst gebildet wird, von den Wurzlen aller den Boden besiedelnden Pflanzen bis zu den Mikroorganismen, im harmonischen Kräftespiel mit allen physikalischen, chemischen und kolloidchemischen Vorgänge im Boden*" (Görbing, 1947, p. 177).

The above described qualitative perceptions of a "crumb structure" as the optimal environment for plant growth are supported by empirical data. Braunack & Dexter (1989) concluded in a review that the optimal seedbed (i.e. the soil layer that has been tilled to a condition to promote seed germination and the emergence of seedlings) is produced by 0.5-8 mm aggregates. Based on literature results Berntsen & Berre (1993) concluded that an optimal seedbed for cereals is characterized by about 50% of the aggregates by weight in the 0.5-6 mm fraction and an even and firm layer below the seedbed prepared top-layer. A large fraction of small aggregates (<0.5-1 mm) is not desirable because of increased risk of wind and water erosion. Furthermore a large fraction of aggregates larger than 8 mm is not desirable because of a reduction in the soil/root contact area and a higher impedance to root penetration. The before-mentioned optimal size distribution of aggregates was proposed for the seedbed. Much less experimental work has been done to characterize the optimal soil structure below the seedbed. However, Misra et al. (1986) showed for roots of cotton, sunflower and pea the axial root growth force needed to penetrate the aggregates increased with increasing aggregate size up to about 12 mm in aggregate diameter. This finding supports the perception that a crumb structure is desirable throughout the arable layer. However, plant roots are flexible and therefore able to use cracks and pores to penetrate strong soil layers. This implies that the abundance, continuity and spatial distribution of cracks and pores are of importance for root growth in compact soil.

To obtain an optimal aggregate size distribution, the large aggregates should fragment easily whereas the small aggregates should resist mechanical breakdown. Therefore, the scaling of the strength of the aggregates as well as the base level of strength for the large aggregates determines the fragmentation behaviour. In most cases tillage is needed to obtain a desirable arable layer. However, self-mulching soils that fragment upon drying and re-wetting into water stable optimal sized aggregates are reported for some heavy clay soils with high shrinking and swelling potential (mainly Vertisols) (Grant & Blackmore, 1991). For lighter soils an ideal self-mulching behaviour is unlikely – especially in humid climates with fewer and less pronounced drying/wetting cycles than in tropical or subtropical climates.

3.3 Soil fracture

A brief introduction to the mechanical behaviour of unsaturated soil is presented below. Special emphasis is put on tensile failure in chapter 2.3.2. For further details on the general behaviour of unsaturated soil, please consult textbooks and papers by e.g. Spoor & Goodwin (1979), Hettiarachi & O'Callaghan (1980), Koolen & Kuipers (1983), Hettiarachi, (1988, 1990), Petersen (1993).

A stressed, unsaturated soil may display mechanical behaviour ranging from brittle failure to ductile flow (Hatibu & Hettiarachi, 1993). Some have defined brittle failure as soil failure under expansion (i.e., super critical state space according to critical state soil mechanics) (e.g. Hettiarachi, 1990; Petersen, 1993) as opposed to soil failure under compaction (i.e., sub critical state space in critical state soil mechanics). This definition of brittle failure encompasses soil fracture in shear and tensile failure mode. In theory, shear failure results in loosening of the entire soil volume, whereas tensile failure results in soil cracking or break-up along a few fracture planes (see further description below) (Hettiarachi & O'Callaghan, 1980). However, in practice, shear failure often results in fracture along well-defined slip planes (i.e., break-up into large blocks) with disturbance of the fracture surface upon failure (Hettiarachi & O'Callaghan, 1980, Koolen & Kuipers, 1983). Hatibu & Hettiarachi (1993) defined brittle failure as "… the culmination of the progressive development of microcracks leading ultimately to slip separation along a small number of discontinuities within the soil matrix. Brittle fracture is, therefore, the sudden loss of strength". This definition corresponds to Koolen & Kuipers (1983, p. 61) description of "brittle/tensile failure" and they further described brittle failure as resulting in no disturbance of the micro-structure of the fracture surfaces as opposed to shear failure. The above mentioned authors have defined brittle failure in a broad (shear and tensile failure) or more narrow sense (exclusively tensile failure). In this thesis the broad definition of brittle failure will be used which means that brittle and tensile failures are not synonymous.

The paper by Hatibu & Hettiarachi (1993) gives a very clear and interesting presentation on the transition from ductile flow to brittle failure. They assessed brittle failure either from a visual evaluation of the state of cylindrical samples after testing or the stress-strain relationship for the tested sample. In the visual evaluation, samples showing expansion upon breaking were classified as brittle whereas samples predominantly showing plastic deformation until failure or flow were classified as ductile. The method of using the stress-strain relationships to characterize brittle/ductile behaviour, denoted "strength envelop method", is illustrated in Figure 1. Large differences between the peak and residual deviatory stress indicate brittle failure and small differences ductile flow.

Whether a stressed soil mass will fail in a ductile (with compaction) or brittle manner (overall loosening) depends on the initial soil condition (water content, bulk density, confining stress, texture, cementation and cracks) and the spatial variability of water content, bulk density etc. in the soil mass. Generally, brittle failure prevails at a combination of low confining stress and water content as displayed in the simple model presented by Hatibu & Hettiarachi (1993) (Figure 2).

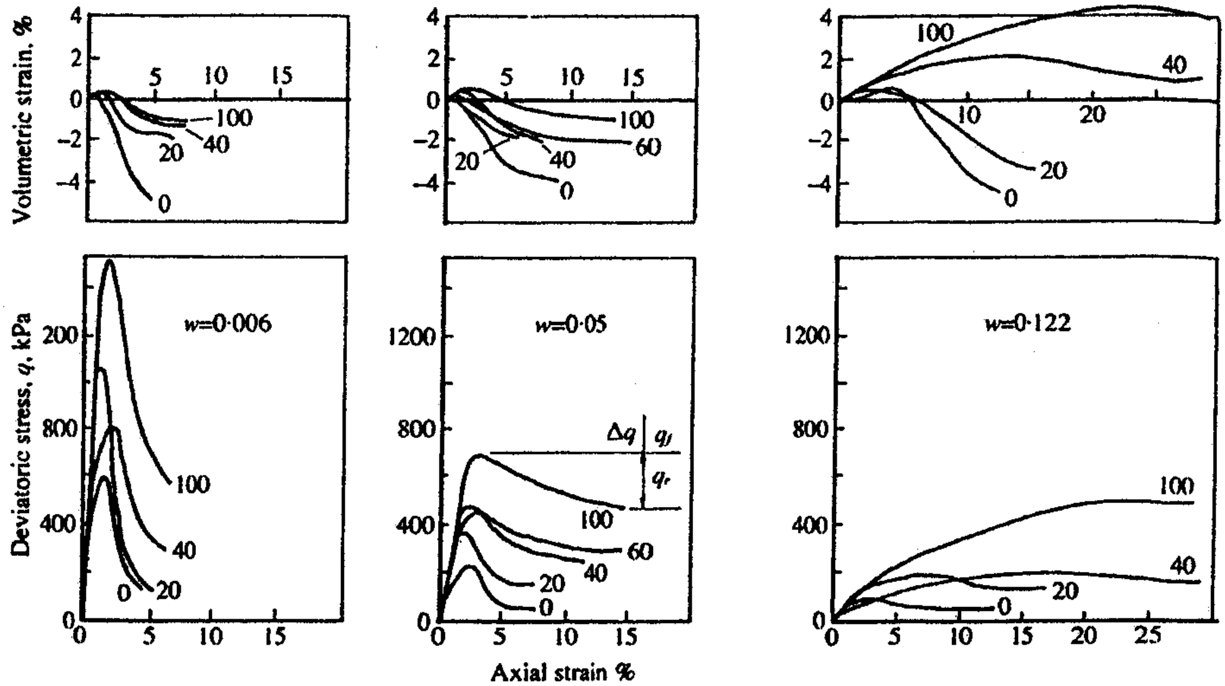

Figure 1. Typical triaxial compression test results obtained from cemented samples of Rothamsted Loam at three moisture levels. The figures shown against each curve represent the confining stress (in kPa) and w is the water content. The upper set of graphs shows volume changes (compaction: positive values, dilation: negative values) and lower set the corresponding deviatoric stress-strain characteristics. Typical peak and residual deviatoric stresses are shown on one curve by the symbols q_f and q_r, respectively. The deviatoric stress is calculated as σ_1-σ_3, i.e., the difference between the major and minor (confining) principle stresses. (From Hatibu & Hettiarachi, 1993).

In comparison with shear failure, tensile failure is characterized by a large difference between the mean normal stresses (i.e., high deviatoric stress), which most easily is achieved for unconfined dry soil in a compression test (Hettiarachi & O'Callaghan, 1980).

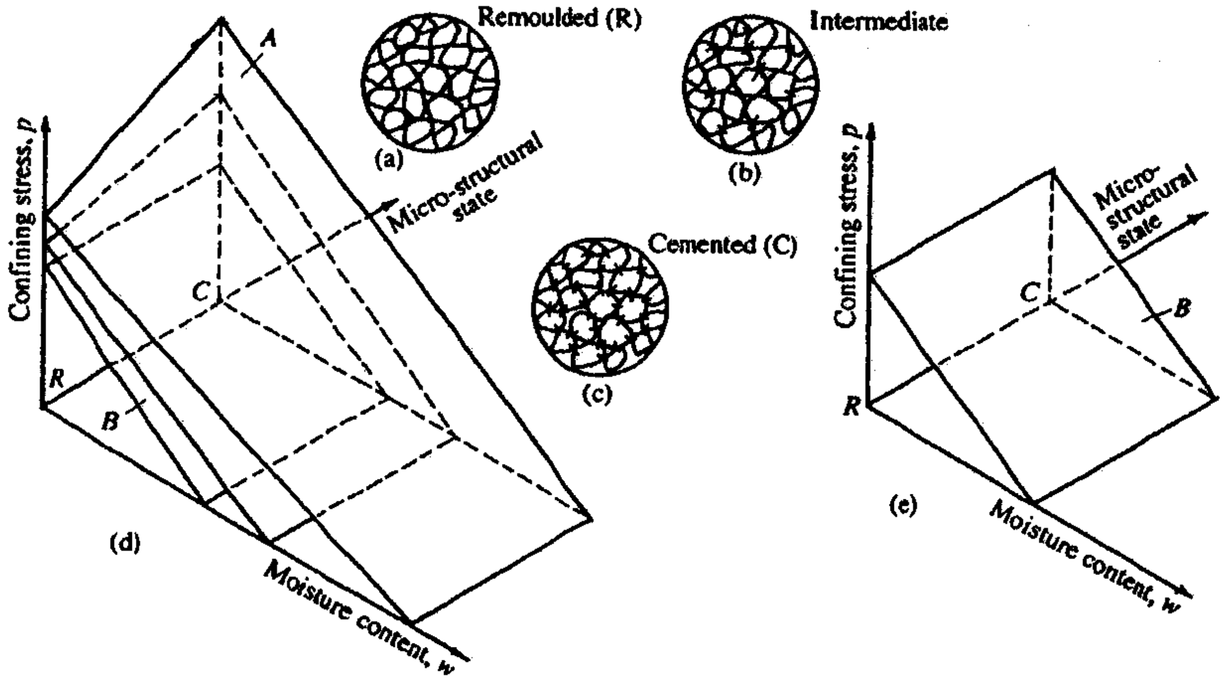

Figure 2. Development of a "transition surface" which demarcates the conditions conducive to either brittle or ductile failure. Schematic representation of microstructural state axis: (a) Fully remoulded state, ("R"), (b) Partly remoulded state and (c) Fully cemented state ("C"). (d) Influence of clay content on transition surface configuration: A, High clay content; B, Low clay content. (e) Transition surface for a sandy soil. (From Hatibu & Hetttiarachi, 1993)

At increasing clay content a higher confining stress and/or water content is needed to induce ductile failure. The role of microstructure (cracks) is also hypothesized in Figure 2 (i.e., cemented soil with cracks is more likely to fail in brittle mode than a remoulded soil.

3.3.1 Soil failure in tillage

Tillage may result in soil behaviour in either a brittle or ductile manner depending on the initial soil conditions and the type, design and adjustment of the selected tillage implement. Soil loosening is a primary objective in nearly all tillage operations (i.e., brittle failure is desirable). Soil is very weak in tension (Hettiarchi, 1988) and Dexter (1988a) stated that tensile failure is more efficient than shear in producing additional surface area at a given energy input. Therefore, tensile failure *may* be a desirable form of failure in soil loosening. Snyder & Miller (1989) noted that tensile failure *is* a dominant process in the phenomenon of soil break-up or crumbling produced by tillage implements. No doubt this is true, but the extent of tensile failure in tillage operations depends on the actual soil condition etc. Koolen & Kuipers (1983) argued that a combination of shear and tensile failure was characteristic for soil behaviour in mouldboard ploughing. Hettiarachi & O'Callaghan (1980) indicated the use of wide cutting blades to loosen soil may result in soil loosening in shear failure mode at low or moderate confining stress, and compaction at high confining stress. Superficial harrowing (i.e., low confining stress) with narrow rigid tines may induce tensile or shear failure (Hettiarachi & O'Callaghan, 1980).

3.3.2 Tensile failure

According to the tensile fracture theory developed by Griffith (1920), tensile failure occurs due to the propagation of cracks in the stressed sample. An applied stress is concentrated at crack tips and the crack propagates if the stress exceeds the strength in the crack tip, which may lead to catastrophic failure of the sample. The stress concentration increases with increased length and narrowness of the cracks tips. It also depends on the orientation of the cracks to the applied stress, and the form and interaction of the cracks (e.g. Hallett et al., 1995a). Stress concentration is expected to increase with increased pore continuity and to decrease with increased pore tortuousity. Therefore tensile strength of a soil fragment is supposed to be strongly related to soil crack characteristics. Experimental results have supported this hypothesis. Hallett et al. (1995b) found that dry natural soil blocks fragmented mainly along pre-existing crack surfaces. Guérif (1990) found a strong negative correlation between macroporosity and tensile strength of dry soil. For a moist soil, according to Snyder & Miller (1989), stress concentration will take place in the air-filled cracks and pores. Water-filled pores will show no stress concentration because the load on the cracks and pores is uniformly borne by the pore water (Snyder & Miller, 1989). Normally, the tensile strength of soil units shows a profound size effect, i.e. a decrease in strength with increased size, which may be related to the distribution and size of cracks in the soil units (i.e., increased crack length with sample size is expected). The tensile failure theory implies that tensile failure is strongly related to the hierarchical ordering of soil structure, which may be modelled using fractal theory (e.g. Perfect & Kay, 1995). The scaling effect of tensile strength with sample size is described in further detail in section 4.3.

4. Methodologies for evaluation of soil fragmentation and friability

Soil fragmentation may be characterized by descriptive field methods as well as by quantitative field and laboratory methods. Only a few researchers have related laboratory results on soil fragmentation to observed soil behaviour in the field, see e.g. Macks et al. (1996) who found a good agreement between visual evaluation of soil structure and tensile strength and friability indices determined on air-dry aggregates in the laboratory. As a qualitative judgement of soil fragmentation cannot stand alone in science, the observations must be quantified using reproducible scientific tests. However, it may also be hazardous to base an evaluation of soil fragmentation and friability properties solely on the results obtained from laboratory tests performed at predefined conditions. These may give very little information on soil behaviour in the field at tillage at distinctly different soil conditions. Therefore, a multi-level analytical strategy was followed in this study, which included field studies with *in situ* and on-site qualitative and quantitative methods as well as laboratory studies under controlled soil conditions.

4.1 Field methods

In the field soil fragmentation and friability were visually described and evaluated qualitatively using a developed drop shatter test denoted *soil drop test*. The results obtained by the soil drop test were supplemented by soil strength determinations in the field using a cone penetrometer (Olsen, 1988), a vane shear method (Serota & Jangle, 1972) and a torsional shear test (Payne & Fountain, 1952).

4.1.1 Visual soil description

Soil fragmentation and friability can be examined qualitatively in the field by simply studying how an unconfined sample of bulk soil fragments when dropped from a specific height as specified in the *spade-diagnosis* by Görbing (1947) and Preuschen (1983). Examination of friability is integrated in the standard procedure of soil profile description, relating it to soil consistency and grade of soil structure (FAO, 1990; Soil Survey Staff, 1993). It is also an integral part of the *spade-analysis* method described by Munkholm (2000). Soil aggregation is evaluated by describing the type and size of the dominant soil structural units. The grade of soil structure is examined from the soil fragmentation resulting from dropping an undisturbed soil sample. The strength of soil units is roughly evaluated in moist (-100 to -15000 hPa) and if possible in dry (below -15000 hPa) state by crushing in the hand (unconfined, uni-axial compression between thumb and finger).

4.1.2 Soil fragmentation

Görbing (1947) recommended to end the *spade-diagnosis* by dropping the studied soil block (0-30 cm) on the soil surface and describe how it fragmented. Ideally, the soil should crumble into optimally sized soil units. To quantify the observed fragmentation, the drop-shatter test described by Marshall & Quirk (1950) and modified by Hadas & Wolf (1984a) was adapted in this study.

In principle, a soil sample is supplied with a specific energy input by dropping it from a specific height and subsequently determining the aggregate size distribution.

4.1.2.1 Method development

In this study the objective was to acquire quantitative information on the fragmentation of bulk soil under field conditions. The test was performed in the field at a water content similar to the water content at secondary tillage (seedbed preparation). Intact soil clods were used by Marshall & Quirk (1950) and Hadas & Wolf (1984a). However in this study undisturbed cubic soil samples (7.0 x 8.0 x 11.5 cm) were collected from the 7-15 cm soil layer. The samples were either dropped from a height of 75 cm into a metal box or transferred directly to a nest of sieves. A fairly low height was chosen in order to minimize the influence of air resistance, which would affect small aggregates more than large aggregates (Hadas & Wolf, 1984a). Aggregate size distribution was determined for both dropped and non-dropped samples (see Schjønning et al., 2002a for further details). The ease of soil fragmentation was expressed graphically as aggregate size distribution (**Papers I, V**) or as calculated values in the form of the geometric mean diameter (GMD) or the mean weight diameter (MWD) (**Papers I, II, V**) or as surface area (**Paper III**). Significant differences in soil fragmentation between soil management or tillage treatments were obtained in most cases (**Paper I, III** and **V**) when using the soil drop test.

The energy input in the soil drop test corresponds approximately to 8.9 J kg^{-1} dry soil (**Paper V**). This level is low in comparison with estimated energy input in different tillage operations. Patterson et al. (1980) estimated that a secondary tine cultivation on clay loam required an energy input of 24 MJ ha^{-1} at the implement connection. When assuming a dry bulk density of 1.4 g cm^{-3} and a tillage depth of 5 cm this corresponds approximately to an energy input of 34 J kg^{-1} dry soil. However, tensile failure is a very “energy-efficient” mode of failure compared to compaction and shear. As discussed in Chapter 3.3 brittle failure in secondary tillage may be related to shear as well as tensile failure.

4.2 Laboratory methods

In the laboratory tensile strength of undisturbed soil cores and aggregates was determined at a range of pressure potentials. The results were compared to the above-mentioned field measurements and to the laboratory measurements of annulus shear strength according to the method of Schjønning (1986). Finally, the results were correlated to soil pore characteristics (**Papers I** and **V**).

4.2.1 Bulk soil tensile strength

Methods of measuring tensile strength in a compression test on single aggregates (e.g. Dexter & Kroesbergen, 1985; Dexter & Watts, 2000) or on soil cores (e.g. the Brazilian method, (Kirkham et al., 1959)) are well known. However, it is difficult to measure tensile strength in a compression test at soil water contents similar to those in the field at tillage. Plastic deformation will occur in wet soil and the mode of failure shifts from pure tensile to shearing and compression. Methods for measuring soil tensile strength in a direct tension test have been introduced by a number of authors (Gill, 1959; Farrell et al., 1967; Nearing et al., 1988; Junge et al., 2000). However, they all measured tensile strength on remoulded soil packed into cylinders or moulds.

4.2.1.1 Method development

The primary objective was to develop a method for measuring tensile strength in a direct tension test on undisturbed, field-sampled soil cores at water contents around field capacity. For that purpose, undisturbed soil cores (height 5.00 cm, diameter 4.45 cm) were sampled in two-piece steel cylinders, adjusted to predefined pressure potentials on sandboxes or ceramic plates and subjected to a direct tension test (Figure 3) (consult **Paper V** for further details). Problems with the soil cores sliding in the rings were encountered in the trials. The problem was overcome reasonably well at -50 and -100 hPa pressure potential by gluing the soil to the metal ring with silicone glue, but not at -300 hPa. The approach of Farrell et al. (1967) may be applicable for measurements on soil cores drier than -100 hPa. They used the epoxy resin, Araldite, to seal the ends of the soil cores to end plates.

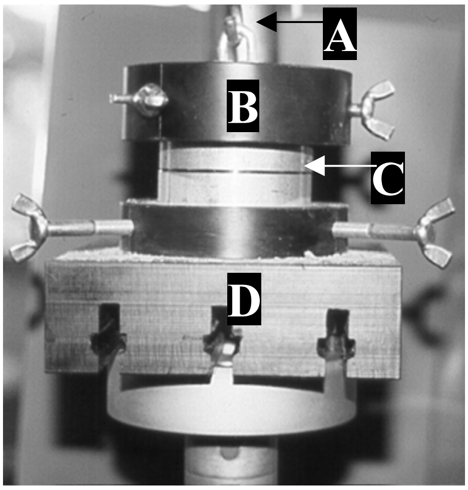

Figure 3. The experimental setup of the direct tension test on soil cores. (A) adjustable steel bar connected to the pressure transducer, (B) plastic cap attached to the upper half of the two-piece cylinder, (C) two-piece cylinder enclosing the undisturbed soil core, (D) rigid frame to which the lower half of the two-piece cylinder is fastened. (**Paper V**).

As the soil cores were kept inside the cylinders during the tension test, some soil-metal friction could not be avoided, i.e. the cores did not always break at the interface between the two cylinders. The results suggested a stronger influence of soil-metal friction for the compacted PAC soil than for the reference treated REF soil at -100 hPa (**Paper V**). However, the statistical tests did not reveal a significant influence of soil-metal friction on the tensile strength results.

The range of tensile strengths measured in this study (2-3.2 kPa) agreed with results reported by Nearing et al. (1988) who measured tensile strength on repacked soil cores (3.88 cm diameter) at comparable water contents. Farrell et al. (1967) measured tensile strength between 10-15 kPa on repacked soil cores (3.8 cm in diameter) at water contents between -100 and -500 hPa. Even though they used soil of similar textural composition as the soil used in **Paper V**, it is difficult to compare the results because they used dense soil (i.e. bulk density: 1.7 g cm^{-3}).

The direct tensile strength results agreed well with the aggregate tensile strength results, reported in **Paper IV** (Figure 4). In both cases the PAC soil had the largest tensile strength and, as expected, the tensile strength of the soil cores was markedly lower than the tensile strength of the soil aggregates measured at the same pressure potential (-100 hPa). Notice that the predicted tensile strength of soil aggregates with a diameter similar to that of the soil cores (4.45 cm) was close to the tensile strength measured on soil cores. This indicates a good correlation between the indirect (compression) and direct tension test. Plastic deformation was supposed to play a significant role in the indirect tension test (compression) when using moist aggregates, which would result in erroneously low estimates of tensile strength. However, the good correlation found between the indirect and direct test does not support this hypothesis.

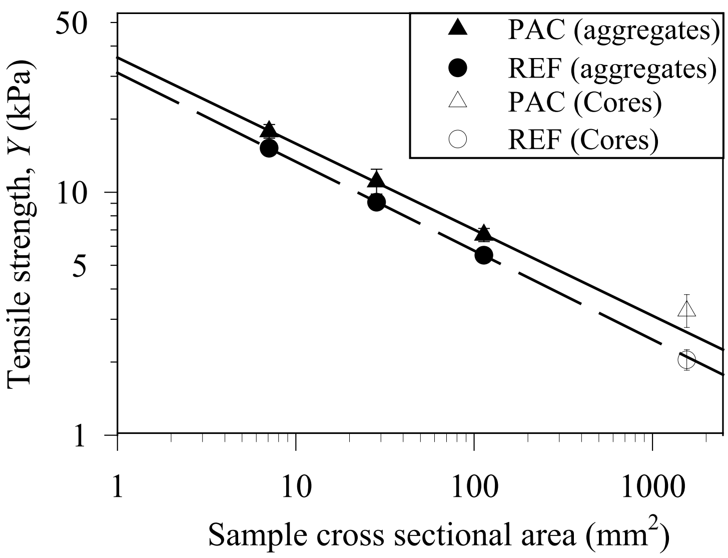

Figure 4. The relationship between tensile strength, *Y* (kPa) and sample cross sectional area, *A* (m^2) in a log-log scale. Lines indicate linear regression for log aggregate tensile strength vs. log aggregate cross sectional area (i.e., direct tension test results not included). All measurements were performed at –100 hPa pressure potential. (──) PAC, (-----) REF. Bars indicate +/- 1 standard error of the mean. PAC: compacted, REF: reference. (**Paper V**).

4.2.2 Tensile strength and rupture energy of aggregates

Tensile strength may be determined from the force needed to crack an individual aggregate between two flat parallel plates (Rogowski (1964), Rogowski & Kirkham (1976), Braunack et al. (1979), and Dexter & Kroesbergen (1985)):

$$Y=c * F/d^2 \qquad (1)$$

Y= tensile strength; *F*= polar force of failure; *d*= diameter of spherical particle.

The *c* factor in Eq. 1 is a constant that depends on the relationship between compressive and tensile stress in the centre of the studied aggregate. Assuming spherical aggregates, this relationship may be modelled as dependent on two parameters: the Poisson ratio (displacement in x direction/displacement in the y direction) and the angle, θ, between the fracture plane and the marked compression axis (y-axis in Figure 5) (Hadas & Lennard, 1988)

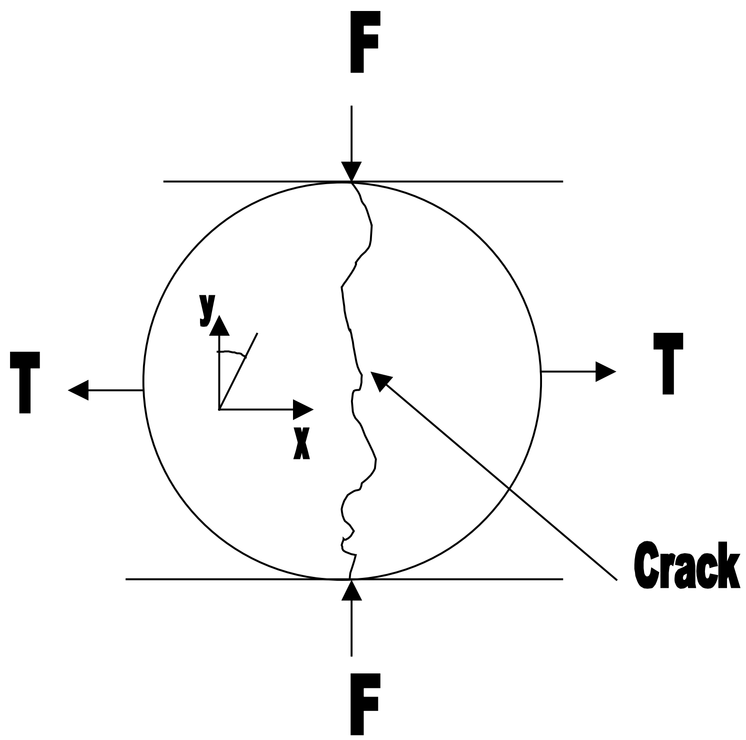

Figure 5. Illustration of tensile failure in an aggregate loaded diametrically. *T* denotes tensile force, *F* is the applied force, θ is an example of an angle between the fracture plane and the y-axis.

Aggregate shape, water content, aggregate density and spread of strengths affect the *c* value as pointed out by Perfect & Kay (1994a). Most authors have used *c*=0.576, which was proposed by Rogowski (1964) and Dexter (1975). This value is based on the assumption of spherical form, perfect elastic behaviour (Poisson ratio = 0.5) and the angle, θ<5°. Other values have been proposed based on studies of remoulded soil (e.g. Hadas & Lennard, 1988), test pieces of rocks (e.g. Hiramatsu & Oka, 1966) or replicates of natural field aggregates in Plaster of Paris (Dexter, 1988b). The most commonly used value (c=0.576) was applied in this thesis in order to easily compare with results in the literature and because exact values are not important for most studies as stated by Dexter & Watts (2000). A single value of c was used even though the investigated treatments displayed significantly different aggregate density and measurements were carried out at a wide range of pressure potentials (-100 hPa to -166 MPa).

Determination of Y according to Equation 1 is based on the assumption of spherical aggregates, tensile failure, and similar stress/strain relationship (*Young's modulus*) in compression (indirect) tests as well as tensile tests (Snyder & Miller, 1985). A number of studies have shown that natural field sampled aggregates are not perfectly spherical (Braunack et al.,1979; Dexter, 1985; Hadas, 1990). The assumption of perfectly tensile failure (i.e. purely elastic deformation until failure) may be fulfilled for dry soil (Rogowski et al., 1968) but not for wetter soil (Farrell et al., 1967). However, Utomo & Dexter (1981) reported that tensile failure was the mode of failure for aggregates even wetter than the plastic limit when crushing individual aggregates between two parallel plates (i.e. unconfined compression test). The assumption of similar stress/strain relationship in compression as in tension may also be violated. Farrell et al. (1967) found a difference in the stress/strain relationship between indirect and direct tensile strength measurements on soil cores. In order to overcome the problems of fulfilling the assumptions, Perfect & Kay (1994b) suggested calculating specific rupture energy instead of tensile strength, Y avoiding assumptions having to be taken regarding the exact mode of loading by which the soil fails. This principle has been applied in **Paper IV**. The rupture energy, E, was derived by calculating the area under the stress-strain curve:

$$E \approx \sum_i F(w_i)\Delta s_i \qquad (2)$$

where $F(w_i)$ is the mean force at the ith subinterval and Δs_i is the displacement length of the ith subinterval. The specific rupture energy was estimated on the gravimetric basis, E_{sp}:

$$E_{sp} = E / m \qquad (3)$$

For the **Paper IV** study, tensile strength and specific rupture energy were determined on approximately 3150 aggregates. The aggregates were sampled in the Case study 2 soil and in two treatments (PAC and REF) from the soil compaction field trial (page xiii). Four aggregate size-classes were used (1-2, 2-4, 4-8 and 8-16 mm) adjusted to five pressure potentials (air-dry (~-166 MPa), -3500 hPa, -1000 hPa, -300 hPa and -100 hPa). The strain rate was 2 mm min^{-1} and the compressive force was measured 30 times s^{-1} by a load cell (0-100 N, +/- 0.03 N) or a load cell

(0-500 N, +/- 0.15 N) (i.e., the latter used for the largest aggregates). For the other papers, aggregates of the above-mentioned four size classes were generally used and the tensile strength test carried out at the same strain rate, sampling frequency and using the same load cells.

4.3 Soil friability

Soil friability has been quantified using very different approaches. In an early study Christensen (1930) measured strength on soil cores (remoulded soil) in an unconfined uni-axial compression test. He proposed the ratio between unit deformation (relative axial strain) and the work of deformation to the yield point as a friability index. Snyder et al. (1995) determined soil fragmentation at different pressure potentials in a specially designed fragmentation test. They suggested geometric mean diameter (GMD), surface energy (i.e. the ratio between fragmentation energy and the new surface area produced) and relative rebound (i.e. the ratio between peak load just prior to fracture and the load immediately after the first fracture event) as friability indices. The GMD and the surface energy data displayed very similar trends and were highly correlated. GMD was suggested as a preferable index as it is much simpler to measure. However, in the literature the most extensively used friability index is the index proposed by Utomo & Dexter (1981), which is based on measurement of tensile strength, Y, of aggregates in a crushing test.

4.3.1 Friability indices based on aggregate tensile strength measurements

Methods for quantifying friability based on aggregate tensile strength measurements have been reviewed by Watts & Dexter (1998) and Dexter & Watts (2000). In the "classical" procedure described by Utomo & Dexter (1981) the friability index, denoted, k_1, was determined as the scaling of aggregate tensile strength, Y, with aggregate volume, V.

$$Y = c_1 V^{-k_1} \qquad (4)$$

where c_1 is a fitting parameter. When log-transforming Equation (4)

$$\log Y = \log c_1 - k_1 \log V \qquad (5)$$

When assuming spherical aggregates the aggregate volume depends on the radius of the aggregates.

Therefore Equation (5) may also be expressed on the basis of aggregate cross sectional area, A:

$$\log Y = \log c_2 - \frac{3}{2} k_1 \log A \qquad (6)$$

or aggregate diameter, d:

$$\log Y = \log c_3 - 3k_1 \log d \qquad (7)$$

where c_2 and c_3 are fitting parameters.

The larger the strength of the small aggregates in relation to the large aggregates, the higher the friability index. The scaling effect of aggregate tensile strength may be explained by increased possibility and probability of long cracks with size according to the Griffith theory (Rogowski, 1964, Dexter, 1975). Others have applied Weibull statistical theory (Freudenthal, 1968; Braunack et al., 1979) or a Weibull-fractal cube theory (Perfect & Kay, 1995) to describe the relationship between aggregate tensile strength and size. When applying Weibull statistical theory, k_1 is an estimate of the average spread of strength for the differently sized aggregates used.

For a specific size of aggregates, *i*, the cumulative frequency distribution of Y can be expressed as:

$$P(y \leq Y) = (y / \alpha)^{1/k_2} \tag{8}$$

where $P(y<Y)$ is the probability of failure (cumulative relative frequency for Y), α is a constant and k_2 is a constant indicating the spread of strength. The k_2 parameter has also been used as an index of soil friability by e.g. Perfect & Kay (1994b) and Watts & Dexter (1998). The friability indices k_1 and k_2 would be identical according to the Weibull statistical theory when assuming invariant spread of strength. However, scale invariant spread of strength has not been found by e.g. Braunack et al. (1979), Hadas (1987), and Perfect & Kay (1994a). Watts & Dexter (1998) have also suggested using simply the standard deviation from aggregate tensile strength measurements on a single size of aggregates (13.2-19.0 mm used) as a new index of soil friability.

$$k_3 = \sigma_Y / \overline{Y} \tag{9}$$

Perfect & Kay (1994b) suggested using specific rupture energy rather than tensile strength to determine the friability index in order to avoid making assumptions on the exact mode of failure. For air-dry aggregates they found a linear correlation between the friability index calculated on the basis of tensile strength and specific rupture energy (R^2=0.54). The friability index when using specific rupture energy as input variable was 1.45 times higher than when tensile strength was used as input variable.

4.3.2 Applied friability indices

In this study indices of friability based on soil fragmentation (GMD, surface area) were determined from the soil drop test. Friability indices were also estimated from the measurement of tensile strength or specific rupture energy on differently sized aggregates according to Equation 5. Whether the friability index should be estimated from the relationship between tensile strength and either sample volume, cross sectional area, or diameter (Equations 5-7) is not a crucial point. However, it may be preferable to relate tensile strength/rupture energy to the sample cross sectional area (Equation 6) as the aggregates generally fail in a plane. In addition it would make it possible to show tensile strength/rupture energy data determined on aggregates and soil cores in the same diagram as illustrated in Figure 4. The estimation of the friability index may then be based on data obtained from measurement of tensile strength on aggregates as well as cores.

The procedure of estimating soil friability indices from tensile strength measurements on a single aggregate size fraction (Equations 8 and 9) was not followed. It was believed to be too hazardous to characterize soil friability based on the tensile strength characteristics of a single size fraction. It is likely that the different aggregate forming processes scales with aggregate size as indicated in the study by Hadas & Wolf (1984b).

5. Soil water effects

It is well known that soil strength typically increases upon drying, at least up to a certain point where the continuity of the water film is broken. In this thesis two studies were carried out on the influence of soil water on the soil fragmentation process (**Papers II** and **IV**). The most detailed study reported in **Paper IV** involved two sites on a sandy loam soil. At the first site a diversely cropped and animal manured soil (DFG) (*=DFG(2)*) was compared with a neighbouring soil (CCC) that for twenty years had been grown with annual cash crops and had received low inputs of organic matter. At the other site a field experiment was carried out and compacted soil (PAC) was compared with reference treated soil (REF). The **Paper II** study included three treatments from the Long-term experiment on Animal Manure and Mineral Fertilizers at Askov Research Station initiated in 1894 on a sandy loam: unfertilized (UNF) animal manured (AM) and mineral fertilized (NPK).

5.1 Aggregate tensile strength and rupture energy

In both studies the tensile strength of the aggregates increased with decreasing pressure potential. In **Paper IV** the relationship was modelled by a power function of the type (Figure 6 a, c):

$$Y = q(-\Psi)^n \qquad (10)$$

where q and n are regression coefficients and Ψ is the pressure potential (hPa).

The coefficient, q, is an extrapolated estimate of the tensile strength of the soil aggregates at pressure potential equal to -1 hPa, i.e. close to saturation. A strong correlation between tensile strength and pressure potential was found for both the cropping system (R^2: 0.92-0.94) and the traffic treatments soils (R^2: 0.67-0.81) (Tables 5 and 6 in **Paper IV**). The relationship between specific rupture energy, E_{sp}, and pressure potential could also be fitted by a power function for the cropping system soils (R^2: 0.70-0.87) (Figure 6b), but not for the traffic treatments (Figure 6d).

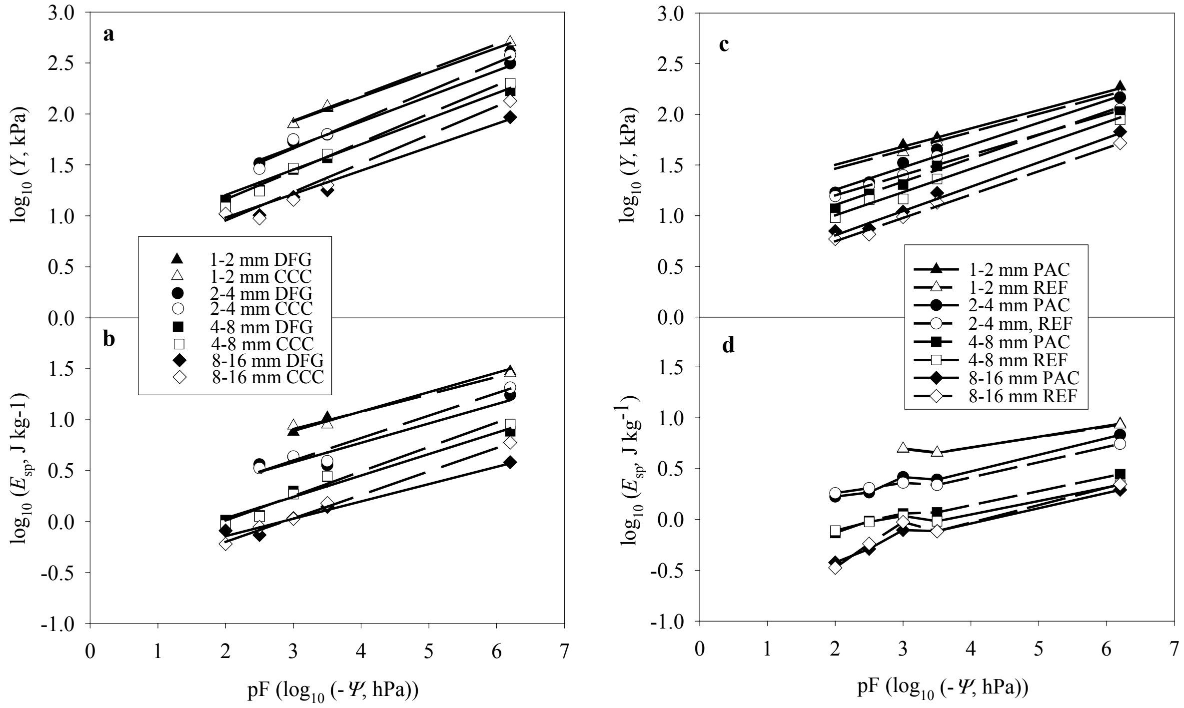

Figure 6. (a) Aggregate tensile strength, Y, and (b) specific rupture energy, E_{sp}, as a function of pressure potential for the cropping system soils. Lines are linear regression lines, (----) CCC, (——) DFG. (c) Aggregate tensile strength, Y, and (d) specific rupture energy, E_{sp}, as a function of pressure potential for the traffic treatments. Lines for log (Y) vs. pF are linear regression lines. (----) REF, (——) PAC. CCC: continuous cash cropped, DFG: dairy farming cropping system soil with grass ley (=DFG(2) in text). PAC: compacted, REF: reference. DFG=DFG(2) in thesis. (**Paper IV**).

An increase in aggregate strength upon drying agrees with other studies (Lipiec & Tarkiewiicz, 1986; Guérif, 1988; Chan, 1989; Causarano, 1993). The increase in strength with decreasing water content can be ascribed to an increase in the cohesive forces of capillary-bound water by decreased pore water pressure as described by the effective stress theory (Bishop, 1961; Snyder & Miller, 1989) and to increased effectiveness of cementing materials (Caron et al., 1992). Especially cementation of dispersed clay will definitely contribute to an increase in aggregate strength with decreased water content (Caron et al., 1992).

The diversely cropped and animal manured DFG (=*DFG(2)*) soil displayed a lower increase in aggregate tensile strength with decreasing pressure potential than the cash cropped CCC soil with low input of organic matter although significant differences were only found for the 4-8 and 8-16 mm aggregates. Likewise, the animal manured soil (AM) with the highest organic matter content tended to have higher strength in wet condition (i.e. pressure potentials around -100 hPa) and lower strength in moist and dry soil in comparison with the unfertilized soil (UNF), while the mineral fertilized soil (NPK) displayed an intermediary position (**Paper II**). The different response to soil water content for the AM and UNF soils was clearly revealed for the 8-16 mm aggregates (Figure 7). The relation of aggregate fragmentation properties to aggregate forming and stabilizing factors is discussed in Chapter 5.

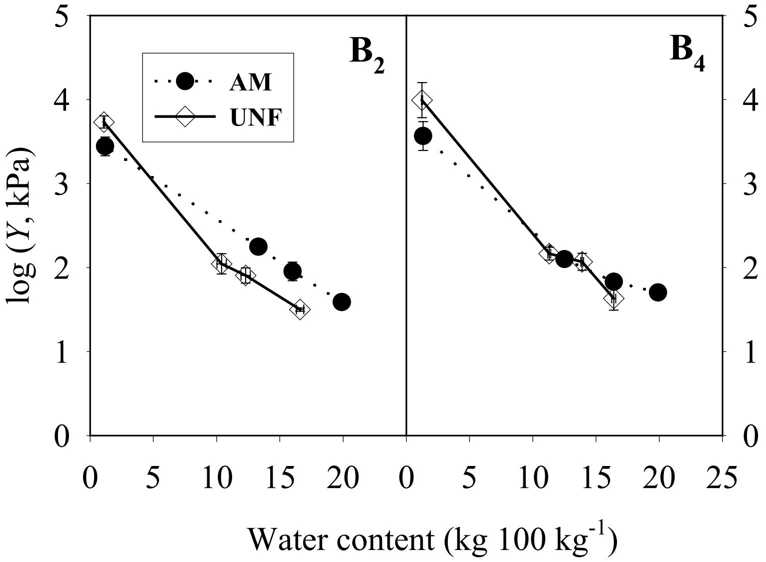

Figure 7. Log tensile strength of 8-16 mm aggregates related to gravimetric water content determined on core samples and bulk soil (only for air-dry soil). Error bars indicated +/- 1 standard error (n=36). AM: animal manured, UNF: unfertilized. (**Paper II**).

The traffic treatments in the **Paper IV** study displayed a consistent trend in tensile strength. In general the compacted soil had stronger aggregates at all pressure potentials except at -300 hPa. A strong influence of wheel traffic on tensile strength is in accordance with a number of other studies (e.g. Arvidsson & Håkansson, 1996; Watts et al., 1996; Watts & Dexter, 1998).

The aggregate tensile strength, Y, and specific rupture energy, E_{sp}, data showed very similar trends for the cropping system soils (Table 3 in **Paper IV**). This was, however, not the case for the traffic treatments where clear differences between treatments were found in Y but not in E_{sp} (see Table 4 in **Paper IV**). Aggregates from the compacted soil failed at higher stress but at lower strain than aggregates from the reference soil (i.e., higher Young modulus, (Y/ε)). This was characteristic for all size-classes and at all pressure potentials (Figure 8). ε was defined as the relative strain at rupture (i.e., strain at rupture (mm) divided by the estimated aggregate diameter in mm). Rogowski et al. (1968) also found that Y/ε was strongly positively correlated to bulk density in a study where they tested the stress-strain relationship for 2-8 mm aggregates from a wide range of soils. A strong increase in Y/ε with decreasing pressure potential (i.e. weaker bonding forces and more plastic deformation at pressure potentials), agrees with findings by Panayiotopoulos (1996).

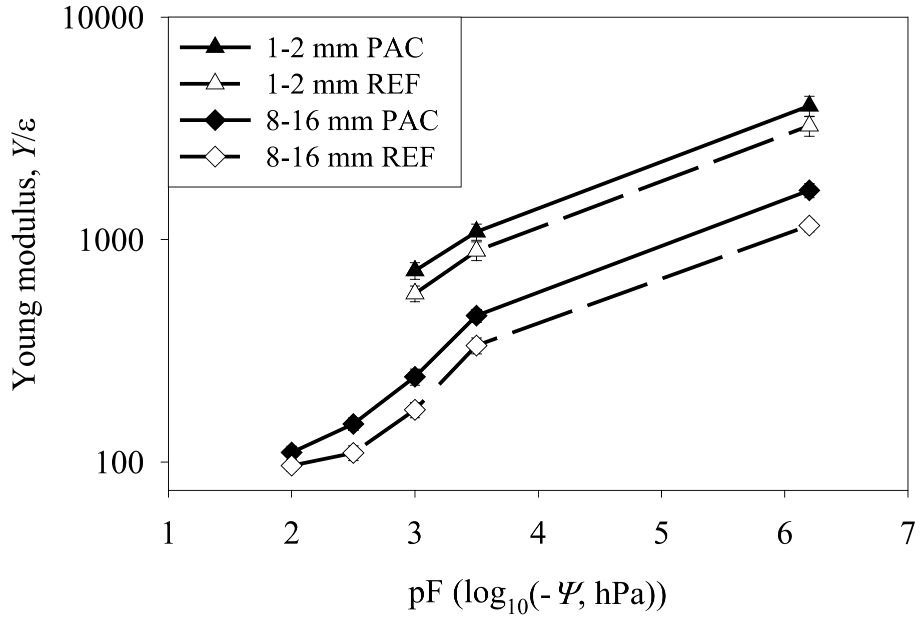

Figure 8. The relationship between stress and strain (Young's modulus), Y/ε, as a function of pressure potential for the traffic treatments. Bars indicate +/- 1 standard error. PAC: compacted, REF: reference. (**Paper IV**).

5.2 Soil friability

In both **Papers II** and **IV** the maximum value of the friability index based on tensile strength measurements was found between -300 and -1000 hPa pressure potential (Figure 9). This finding agrees quite well with other findings (Utomo & Dexter, 1981; Shanmuganathan & Oades, 1982; Causarano, 1993). Utomo & Dexter found a maximum friability index for two sandy loam soils at around -1000 hPa pressure potential, which was close to the plastic limit. Shanmuganathan & Oades (1982) also found a maximum friability at water content around the plastic limit for a remoulded sandy loam soil. Causarano (1993) found a higher friability of moist soil (-100 hPa) than of dry soil (-1.5 MPa) and air-dry soil (-82.5 MPa) for both a sandy loam and a clay soil. Optimal friability in the range between -300 and -1000 hPa determined from tensile strength measurements correspond with soil fragmentation results by Snyder et al. (1995). They found maximum soil fragmentation at -400 to -700 hPa for a silty clay loam.

The friability indices based on measurement of Y (k_Y) and E_{sp}(k_E) were rather poorly correlated (R^2 = 0.41**) (Figure 10). In most cases k_E was larger than k_Y , which is in accordance with Perfect & Kay (1994b). However, they found that k_E increased linearly with k_Y. In contrast to this study they determined the friability index from the spread of strength on aggregates from a specific size fraction.

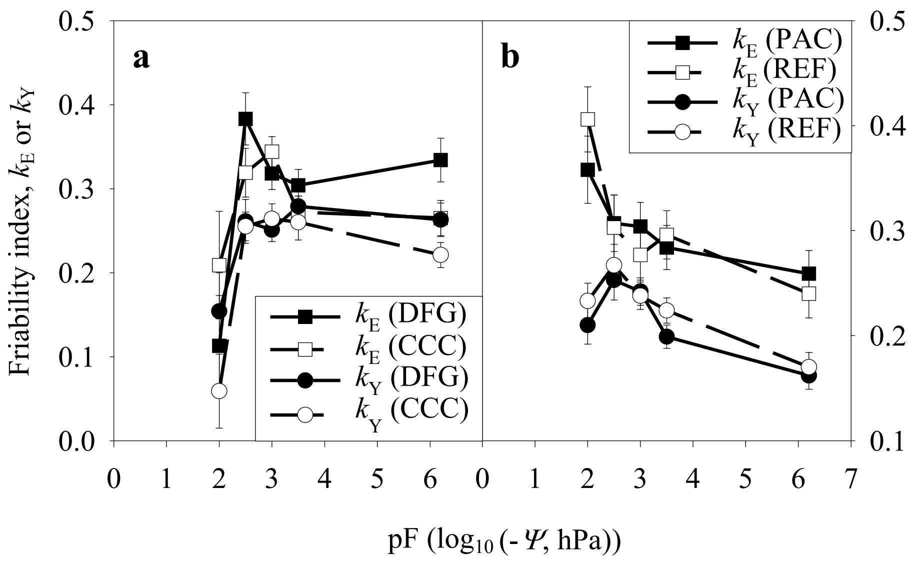

Figure 9. Friability indices, k_Y, and k_E, as a function of pressure potential for the cropping system soils (DFG and CCC) and traffic treatments (PAC and REF). Bars indicate +/-1 standard error (n=9 for the cropping system soils and n=3 for traffic treatments). DFG=DFG(2) in thesis. (**Paper IV**).

Evidence suggests that a range of soils exhibits maximum friability between approximately -300 and -1000 hPa, which may be interpreted as an optimal range of pressure potential for tillage. However, it must be emphasized that most of the studied soils were sandy loams. Other soil types may exhibit optimal friability at different water potentials.

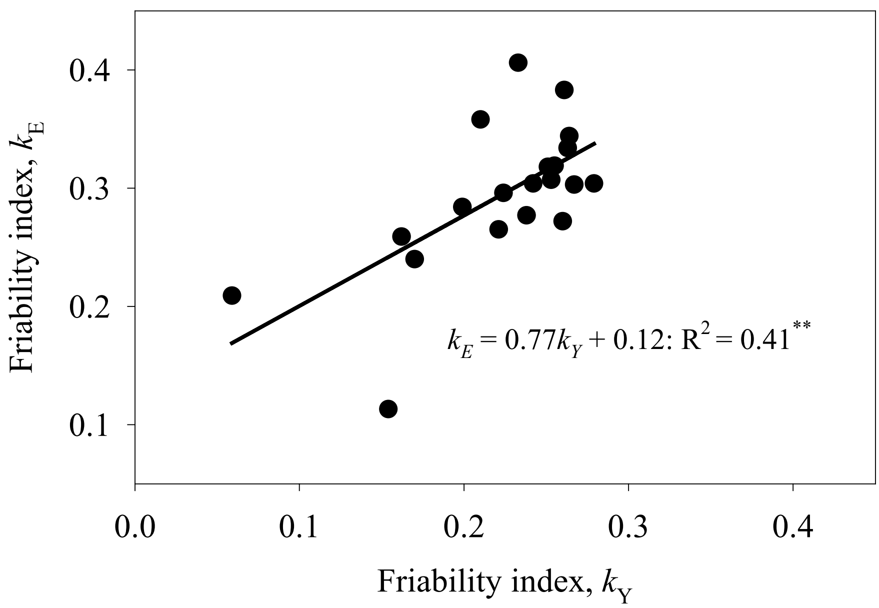

Figure 10. The relationship between the friability indices, k_Y and k_E (all data included). (**Paper IV**).

6. Cropping system and fertilization effects

Long-term effects of cropping system were reported in **Papers I** and **IV** discussed above. The study included two sandy loam soils (labelled DFG(1) and DFG(2)) that for at least half a century had been managed as part of a organic dairy farm production system including application of farmyard manure to the soils. The DFG(1) soil was compared with a neighbouring soil that had been managed as part of a conventional dairy farm production system without grass leys in the crop rotation (DFA) and this pair was labelled *case study 1*. The DFG(2) soil was compared with a neighbouring soil that for more than 20 years had been grown with annual cash crops and received very low input of organic matter (CCC). This pair was labelled *case study 2* in **Paper I** and it was also included in **Paper IV**. The multi-level analytical strategy outlined in chapter 3 was followed.

Long-term effects of fertilization were reported in **Paper II**. The study included three treatments from the Long-term experiment on Animal Manure and Mineral Fertilizers at Askov Research Station initiated in 1894 on a sandy loam: unfertilized (UNF) animal manured (AM) and mineral fertilized (NPK) (Christensen et al., 1994).

6.1 Cropping systems

Surprisingly, the grassed and manure added DFG(1) soil showed poorer soil tilth than its arable, manure added DFA counterpart. The visual evaluation revealed no clear differences between the case study 1 soils concerning soil structural properties – except for a markedly higher earthworm activity in the DFG(1) soil. The results from the soil drop test showed that the DFG(1) soil fragmentation was significantly poorer than the DFA soil, i.e. geometrical mean diameter (GMD) of 23.1 and 17.3 mm for the DFG(1) and the DFA soil, respectively, for dropped samples. Torsional shear box results from the field showed a higher strength for the DFG(1) soil than the DFA soil. A larger tensile strength of large aggregates (4-8 and 8-16 mm) was found for the DFG(1) soil. Lastly, a significantly lower friability was estimated for the DFG(1) soil than for the DFA counterpart (friability index, k, of 0.20 and 0.28, respectively).

For the case study 2 soils, the series of measurements unambiguously revealed significant long-term effects of soil management. The continuously cash cropped and mineral fertilized CCC soil had a poor soil tilth compared with the animal manured DFG(2) soil with a diversified crop rotation. Furthermore, the differences between the soils were consistent from spring to autumn. The DFG(2) soil had a crumblier structure than the cloddy and rather massive CCC soil (Figure 11a,b). Even in the top 6 cm layer of the soil, the CCC soil had a partly subangular blocky structure. The CCC soil was very firm when moist whereas the DFG(2) soil was less hard. The visual observations are consistent with findings by Reganold (1988) who reported a cloddier structure for a conventionally managed soil always grown with annual crops and never receiving green manure than for an organically managed soil with a diversified crop rotation and receiving green manure. The CCC soil displayed a lower ease of fragmentation when applying the soil drop test, i.e. the CCC and DFG(2) had a GMD of 27.4 and 16.1 mm, respectively, for dropped samples in the spring (Figure 12). The soil drop test performed in the autumn confirmed the general trend found in the spring. Furthermore, the CCC soil had higher shear strength when employing different shear strength methods in the field at field capacity and in the laboratory at -300 hPa. The tensile strength of moist and dry soil was consistent with shear strength measurements, i.e. the CCC soil had a significantly higher tensile strength of 8-16 mm aggregates (Figure 6, Chapter 5).

6.2 Fertilization

More than 100 years of contrasting fertilization had significantly influenced soil chemical and physical properties essential for plant growth. The treatment with no fertilization during a century led to a dense soil low in soil organic matter (SOM), microbial biomass and exchangeable K and Mg. The simple soil drop test did not reveal significant differences between the treatments, although the NPK soil tended to fragment to smaller aggregates than the UNF and the AM soils in the B_2 field. As shown in Figure 7 (Chapter 5) tensile strength decreased with increasing water content. Roughly, the unfertilized soil tended to show the lowest strength in wet soil (i.e. pressure potentials around -100 hPa) and the highest strength in moist and dry soil. The unfertilized soil displayed the lowest soil cohesion when determined by a torsional shear box at field capacity but the highest cohesion when the soil was sheared by a grousered annulus at -300 hPa pressure potential.

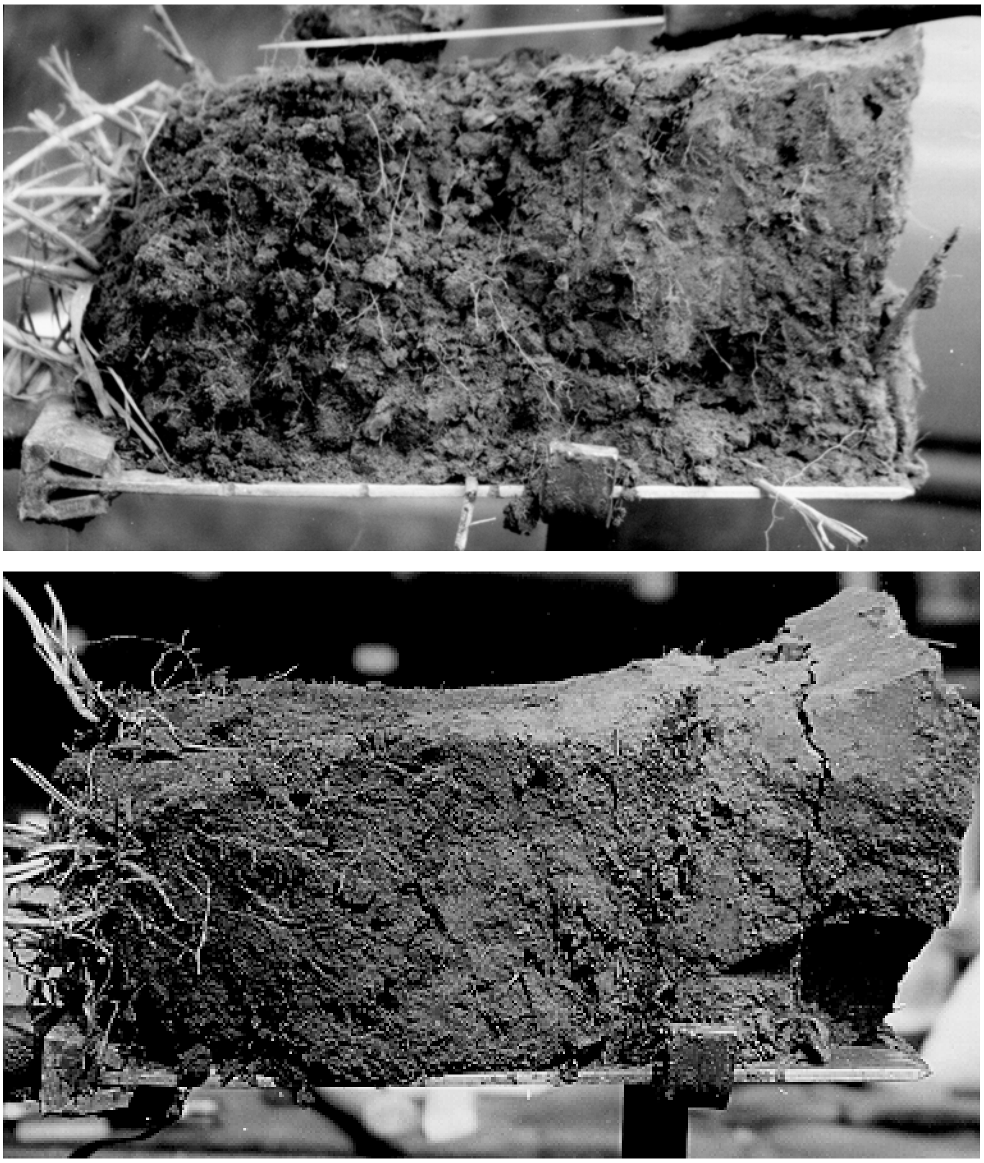

Figure 11. Soil samples (0-30 cm) from dairy farming cropping system soil with grass ley (DFG(2)) (*top*) and continuous cash cropped (CCC)(*bottom)* ready for spade analysis description. The descriptions were performed in the beginning of July (water content: 19.5 and 16.9 m^3 $100m^{-3}$, respectively for DFG(2) and CCC). The crop (Spelt in DFG(2) and Winter wheat in CCC) were in early maturation stage (i.e., growth stage 81 and 79, respectively for DFG(2) and CCC according to the decimal scale).

6.3 Structural binding and bonding mechanisms

The fact that the DFG(1) soil displayed poorer soil fragmentation and stronger aggregates than the DFA soil may be related to a higher content of binding (fungal hyphae and roots) and bonding (polysaccharides) agents created by soil biology (Degens, 1997). Evidence suggests a higher content of biologically derived binding and bonding agents in the DFG(1) soil, i.e. markedly higher biological activity as indicated by a larger soil biomass, biomass-C/total-C ratio, β-glucosidase activity and earthworm activity (Schjønning et al., 2002a). Moreover, the DFG(1) was expected to have more structural binding by old roots derived from the grass/clover crop than the annually cropped DFA soil. A number of other studies have indicated that soil biological activity may increase aggregate tensile strength (e.g. Chenu & Guérif, 1991; Hadas et al., 1994). Especially a high earthworm activity may cause increased strength of dry aggregates (McKenzie & Dexter, 1987; Schrader & Zhang, 1997).

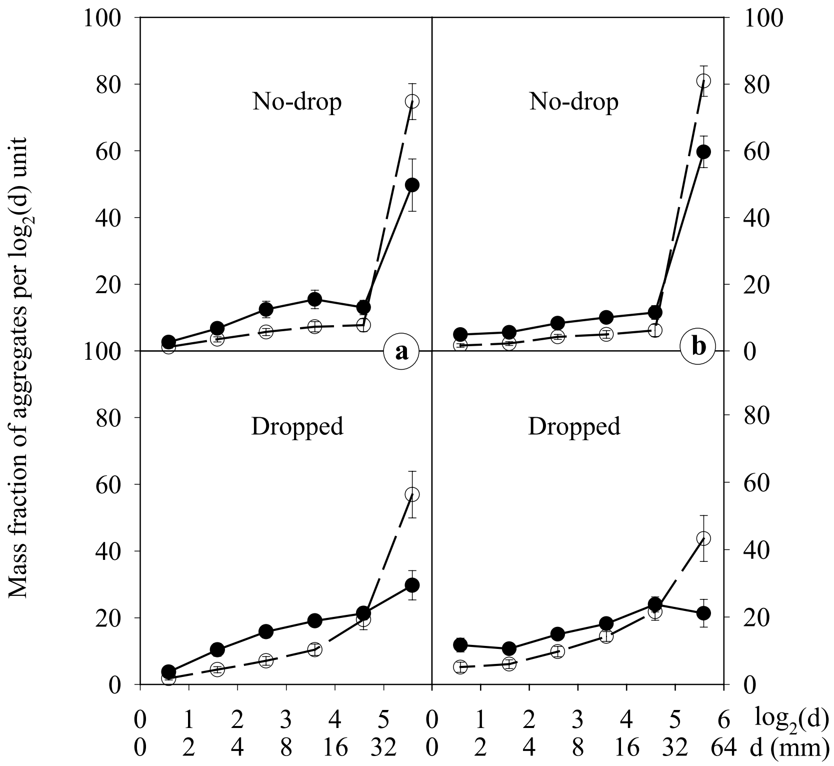

Figure 12. Mass fraction of aggregates per log2(d) size unit vs. aggregate size in log2(d) scale. (a) case study 2 soils spring sampling and (b) case study 2 soils autumn sampling. (—●—) DFG(2) soil, (--○---) CCC. Bars indicate +/-1 standard error (n=9 (grid-point averages)). DFG(2): forage cropping system with grass ley, CCC: continuous cash cropped. (**Paper I**).

In both studies B and D, the soils with higher SOM content (AM and DFG(2), respectively) displayed a tendency to higher Y in wet condition. This may be ascribed to a higher content of binding and bonding agents (e.g. polysaccharides and fungal hyphae) (further discussion in **Papers II** and **IV**). Cementation of clay dispersed under wet conditions can serve as an explanation for the larger increase in Y and E_{sp} with decreasing pressure potential found for the CCC and UNF soils in comparison with the DFG(2) and AM soils, respectively. A lower stability of aggregates in wet condition has been found in other studies for the CCC and UNF soils in comparison with their counterparts (i.e. DFG(2) and AM, respectively) (Schjønning, 1995; Schjønning et al., 2002a). The presented results agree with the findings of Chan (1989). In a study on hardsetting Australian soils he found that a cultivated soil low in SOM content displayed a much stronger increase in aggregate tensile strength upon drying than a permanent pasture soil (pressure potentials in the range oven-dry to -100 hPa). Others have also reported similar effects of SOM and clay dispersibility on tensile strength of dry aggregates (e.g. Kay & Dexter, 1992; Watts et al., 1996; Watts & Dexter, 1997a). The case study 2 results do not allow a clear differentiation between crop rotation and fertilization effects. However, other studies have indicated that monocultural cereal growing may result in increased bulk soil shear strength and aggregate tensile strength (Chan & Heenan, 1996; Watts et al., 1996).

6.4 Soil pore characteristics

The soil pore space was thoroughly examined for the **Paper I** soils by Schjønning et al. (2000b). The study included determination of pore size distribution and a number of pore geometry characteristics. Therefore, one of the objectives in **Paper I** was to evaluate the effect of pore characteristics on soil fragmentation suggested in the tensile fracture theory.

The lower ease of fragmentation and higher aggregate strength shown for the DFG(1) soils could not directly be related to differences in pore characteristics, i.e., the soils displayed very similar pore characteristics) except for a significantly higher number of *habitable* (0.2-30 μm) and *protective* (0.2-3 μm) pores found for the DFG(1) soil.

In contrast, soil pore characteristics may contribute to the explanation of the differences in soil mechanical characteristics found for the case study 2 soils. The CCC soil had a lower total porosity and macroporosity, and a less tortuous and complex pore system than the 'sponge'-like DFG(2) soil. Schjønning et al. (2002b) reported about three times as many large pores proliferating the soil matrix in the DFG(2) soil than in the CCC soil when drained to pressure potentials less than field capacity (~ - 100 hPa pressure potential). This is probably a primary reason for the lower strength and higher ease of fragmentation displayed for the DFG(2) soil. Interestingly, the friability index increased significantly with total porosity characteristics for the case study 2 soils, whereas no correlation was found for the case study 1 soils (Figure 13). No significant correlations were found between mechanical properties and the pore tortuousity characteristics presented by Schjønning et al. (2002b). Air permeability, diffusivity and the derived parameters are expected to show large small-scale variability (cm's) in comparison with more integrating parameters like bulk density and total porosity (e.g. Koszinski *et al.*, 1995). Large small-scale variation may explain the poor correlations found as samples used for measuring mechanical properties were taken about 10-70 cm from the samples taken for measuring pore characteristics. See section 7.2.1 for further discussion on the relationship between tensile strength and pore characteristics.

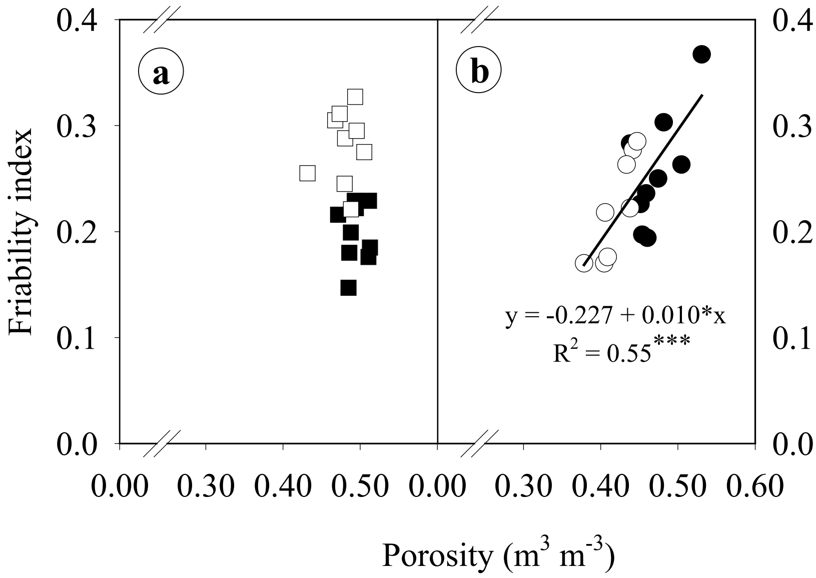

Figure 13. Friability related to total porosity. The points represent grid point means. Significant correlation was found for the case study 2 soils. (a) case study 1 soils and (b) case study 2 soils, ■ DFG(1), □DFA, ● DFG(2), ○ CCC. (**Paper I**).

7. Tillage and traffic effects

The effect of tillage and traffic was studied in field experiments performed on the organically farmed Rugballegård Experimental Station. The field experiments were carried out on a sandy loam soil. In the tillage experiment, a conventional ploughing-harrowing tillage system (CONV) was compared with a non-inversion deep tillage system (NINV), which combined subsoil loosening to 35 cm with a shallow intensive secondary tillage (**Paper III**). In the traffic experiment a compacted treatment, labelled (PAC), was compared with a reference treatment, labelled (REF) (**Papers IV** and **V**).

7.1 Non-inversion tillage

In **Paper III**, effects of non-inversion primary tillage on soil tilth were evaluated. The objective was to investigate the effect of the primary tillage treatments on ease of tillage and penetration resistance and the effect and persistence of non-inversion subsoil loosening. Soil fragmentation and friability were evaluated for the 7-14 cm layer that was affected by primary cultivation but not directly by secondary cultivation. Seasonal effects were investigated by performing field tests and soil sampling at crop emergence in May and after crop harvest in September.

In the visual evaluation of the 0-30 cm soil layer an upper layer with crumbs as structural units was observed for both the NINV and the CONV treatments above a denser layer that reached to the bottom of the ploughed or formerly ploughed soil (Figure 14). Below ~ 22 cm, a compacted plough pan was observed in the CONV treated soil and the remains of an old plough pan were detected in the NINV treated soil. The visual evaluation revealed no substantial differences between the treatments at the 0-20 cm soil depth. However, cone penetration measurements in the field and annulus shear strength measurements performed in the laboratory indicated higher strength in NINV soil than in the CONV soil in the 7-14 cm layer.

Results from the soil drop test showed a tendency to poorer soil fragmentation for the NINV soil (Figure 15) at all times of measurement. Significant differences for dropped samples were found when including all data in the statistical test. The difference in the specific surface area of the dropped samples was produced by the energy input in dropping, since no difference between the treatments was found for the non-dropped reference samples.

Figure 14. Soil samples (0-30 cm) from non-inversion tillage (NINV) (top) and conventional (CONV) (bottom) ready for the spade analysis description. The tests were performed early July 1998 in a pea/spring barley crop (growth stage: 71 and 68 for spring barley and pea, respectively, in both treatments according to the decimal scale. The water content at sampling was 22 m^3 100 m-3 for both treatments. (**Paper III**).

The tensile strength measurements also indicate that it was more difficult to fragment the NINV soil (Figure 16), although significant differences were only found for 2-4 and 8-16 mm aggregates for the September sampling. The NINV treated soil had also the smallest friability index for the September sampling time (i.e. k = 0.16 and 0.22, respectively, for the NINV and CONV soils) (Figure 16), whereas no differences were found for the May sampling time. The lower friability index for the NINV treatment is consistent with the lower ease of fragmentation observed for this treatment in the soil drop tests.

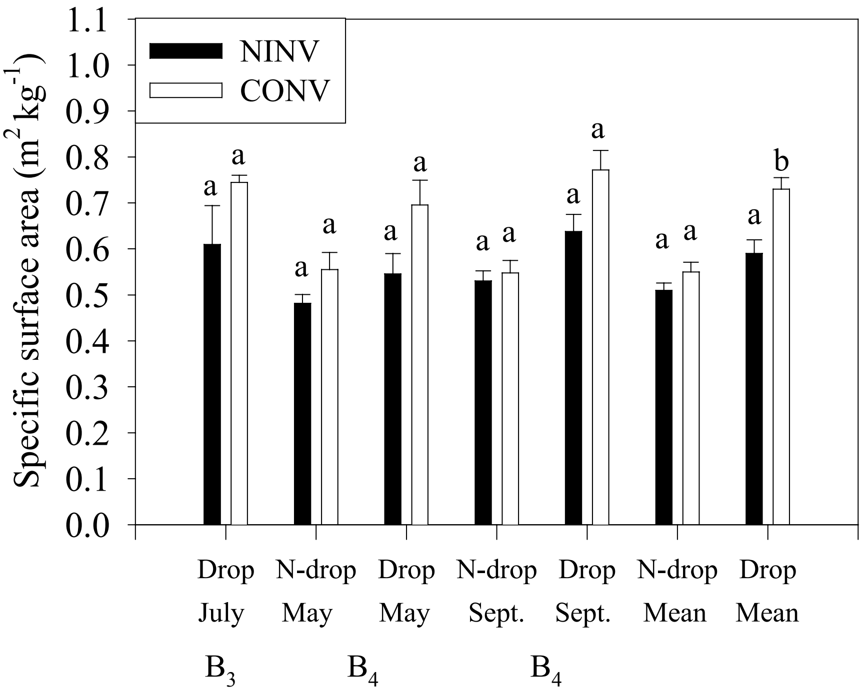

Figure 15. Soil drop test results. Specific surface area (m^2 kg^{-1}) for dropped (Drop) and non-dropped (N-drop) samples taken from the B_3 and B_4 field. Vertical bars indicate +1 standard error (n= 4 (plot averages)). NINV: non-inversion tillage, CONV: conventional tillage. Water content at testing: B_3 July: 22.3 m^3 100 m^{-3} for both treatments; B_4 May: 23.5 and 25.1 m^3 100 m^{-3} for CONV and NINV, respectively; B_4 September: 21.5 m^3 100 m^{-3} for both treatments. (**Paper III**).

The slightly stronger soil at 7-14 cm in the NINV treatment may be the result of a less effective soil loosening by the non-inversion deep loosening treatment. Generally, tine cultivation has been found to loosen the soil less effectively than mouldboard ploughing (Bowen, 1981; Larney & Kladivko, 1989; Sommer & Zach, 1992; Carter, 1996; Carter et al., 1998). The stronger NINV treated topsoil observed in this study may also be due to compaction from the rotovator although bulk density data showed no significant difference between the treatments (**Paper III**). However, a number of studies have reported that tillage pans may develop below a rotovated soil layer (e.g. Schjønning & Rasmussen, 1989). Noticeably, poorer ease of fragmentation and friability was found for the non-inversion loosened 7-14 cm soil. It was supposed that a higher energy input in mouldboard ploughing as in non-inversion tillage (Tebrügge & Düring, 1999) would result in increased aggregate tensile strength and decreased friability due to the breakdown of a larger proportion of weak aggregates (Watts & Dexter, 1997b). However, this statement is based on the assumption that tensile failure was the dominant mode of failure for both primary tillage treatments. Compaction and shear failure may have played a larger role for the studied 7-14 cm soil layer under non-inversion tillage as a direct effect of the tine subsoil loosening or as an indirect effect of the rotovator used for secondary tillage. Difference in the mode of failure may also explain why Watts et al. (1996) found no clear difference in aggregate tensile strength for soil subjected to either low intensive cultivation (mouldboard ploughing) or high intensive cultivation (rotary harrowing) on a loamy soil. Furthermore, in this study, the higher energy input in mouldboard ploughing may have produced micro-cracks within the aggregates rather than excessive fragmentation, i.e. resulting in subsequently weaker aggregates. This would be in accordance with the principle of storage of volumetric strain energy proposed by Chancellor et al. (1969).

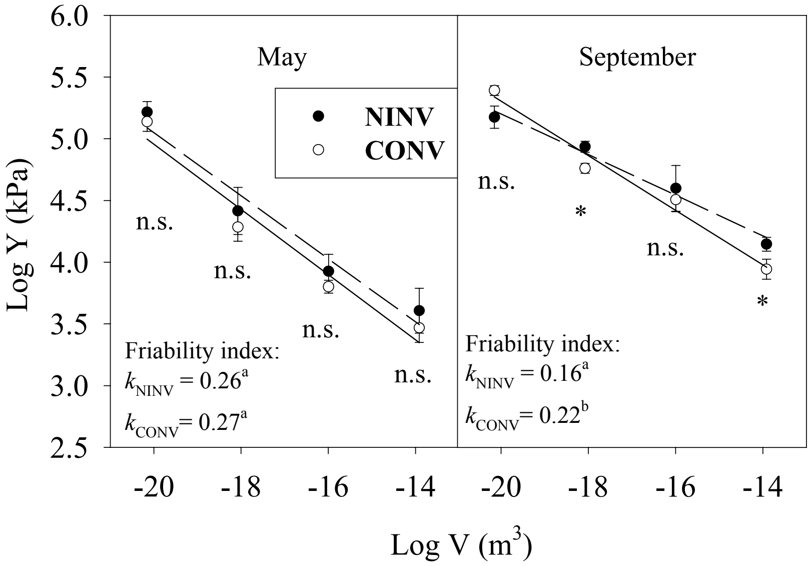

Figure 16. Aggregate tensile strength, *Y*, for aggregate size fractions with different volume, *V*, sampled in the B_4 field (May and September). Soil friability index determined as -1*slope of the linear regression lines. NINV: non-inversion tillage, CONV: conventional tillage. *: =0.05, n.s.: non significant. (**Paper III**).

Interestingly, the soil aggregates became stronger and the soil less friable during the growing season (Figure 17). This was somewhat unexpected, as natural soil processes occurring during the growing season (e.g., wetting/drying cycles) usually result in reduced aggregate tensile strength and increased friability (Utomo & Dexter, 1981; Kay & Dexter, 1992). However, sampling in September was carried out only a week after a wet period lasting 8 days with a total of 44 mm rain whereas sampling in May was carried out almost two months after the latest wet period with more than 40 mm rain. Therefore, cementation of clay dispersed during the wet period (Kay & Dexter, 1992) may explain the higher tensile strength measured in September than in May. The difference between treatments was only significant in September although the results from May displayed the same trend (i.e., highest tensile strength of aggregates larger than 1-2 mm for the NINV treatment). This implies that natural soil processes occurring during the growing season did not eliminate differences between the tillage treatments. This was somewhat surprising as Watts & Dexter (1997b) found some recovery of tillage-induced effects on tensile strength and friability within three weeks after tillage for a loamy soil. The present results highlight that aggregate tensile strength and friability are dynamic soil characteristics.

7.2 Traffic and intensive tillage

The effect of 'extreme tillage/traffic' in the form of heavy compaction (PAC) or kneading (INT) was studied in a field experiment using a normally treated soil as a reference (REF). Both of the extreme tillage/traffic treatments were carried out early spring on wet soil. Driving a 6-8 tonne tractor (inflation pressure 125 kPa) wheel by wheel performed the PAC treatment. Using a rotary harrow with high rotary speed compared to forward speed accomplished the kneading treatment. Results from the experiment are reported in **Papers IV** and **V**. Munkholm et al. (1999) have reported results from all three treatments.

The results regarding tensile strength of soil cores were discussed in Chapter 3 and results regarding tensile strength of aggregates at different water contents were discussed in Chapter 4. However, a significant effect of soil compaction on bulk soil and aggregate tensile strength was also found. Interestingly, no clear treatment effect was found on the specific rupture energy of aggregates as discussed in Chapter 5. Soil from the 7-12 cm soil depth was used in **Papers IV** and **V**. A strong effect of soil compaction on aggregate tensile strength was also found when using soil from the seedbed (0-5 cm depth) (Figure 17) (Munkholm et al., 1999). The demonstrated effect of soil compaction on aggregate tensile strength corresponds with results by Chan (1989), Guérif (1990) and Watts & Dexter (1998). Notice that also the kneading effect of intensive rotary cultivation on wet soil (INT) resulted in increased strength of air-dry aggregates to the same level as for the PAC soil.

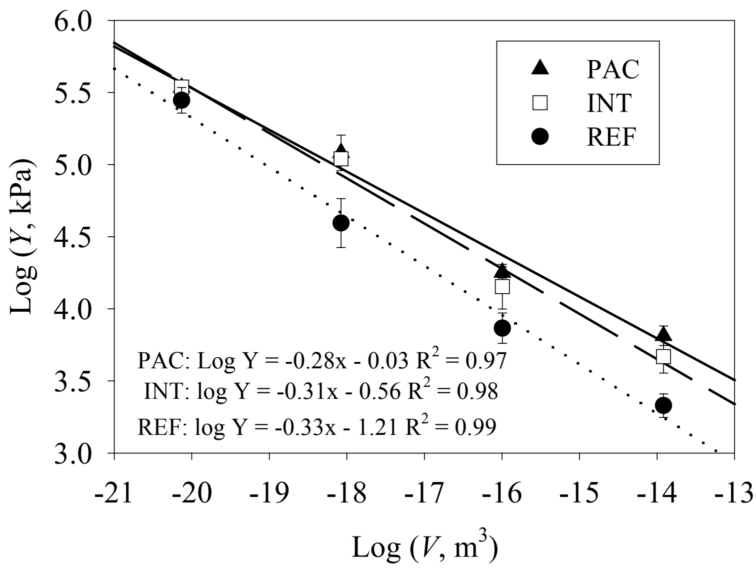

Figure 17. The effect of treatment on aggregate tensile strength (geometric mean values) and friability index for air-dry soil sampled from at 0-5 cm depth 1998. Vertical bars indicate +/- 1 standard error (n=3 (geometric means of 15 determinations for each plot)). Lines are linear regression lines. PAC: compacted soil, INT: intensive rotary harrow cultivation, REF: reference.

The **Paper V** study showed that data obtained in the laboratory correspond well with the observed soil behaviour in the field. The PAC soil had significantly higher shear strength at all the tested normal loads. In addition, the PAC soil fragmented poorly when performing the soil drop test (Figure 18). The PAC soil displayed almost no fragmentation at all (GMD 44.1 and 38.7 mm for non-dropped and dropped samples, respectively) whereas the REF soil fragmented into a broad range of aggregate sizes when dropping the soil cubes (GMD: 30.2 and 14.2 mm for non-dropped and dropped samples). The relative change in geometric mean diameter from reference treated to dropped ($\Delta GMD/GMD_N$) was considered as an empirical index of ease of fragmentation and a large difference was found between the treatments (i.e. $\Delta GMD/GMD_N$ = 53 and 13% for REF and PAC, respectively). The results in **Paper V** agree with results reported by Schjønning et al. (2002a) who related soil fragmentation to traffic intensity. Two intensely trafficed, diversely cropped and animal manured soils showed poorer soil fragmentation than a mainly cereal cropped soil with no input of animal manure. For the **Paper V** study, the energy input in the soil drop test was obviously too low to induce substantial fragmentation of the PAC treated soil (i.e. approximately 8.9 J kg^{-1} dry soil). Based on the rupture energy of the aggregates, much higher soil fragmentation would have been expected in the soil drop test, i.e. the rupture energy was <2 J kg^{-1} dry soil for all aggregate sizes at -100 hPa (Table 2 in **Paper IV**). The relatively low fragmentation implies that also a substantial amount of the energy input in the soil drop test did not dissipate into soil fragmentation. It was supposedly stored as volumetric strain energy (Chancellor et al., 1969) and/or lost as fragment rebound and heat evolution related to plastic deformation. It is also noticeable that there was no difference between the treatments in specific rupture energy of soil aggregates (see discussion in Chapter 4.1). The findings in this study imply that caution must be taken in predicting soil fragmentation in tillage from measurements of rupture energy of single aggregates.

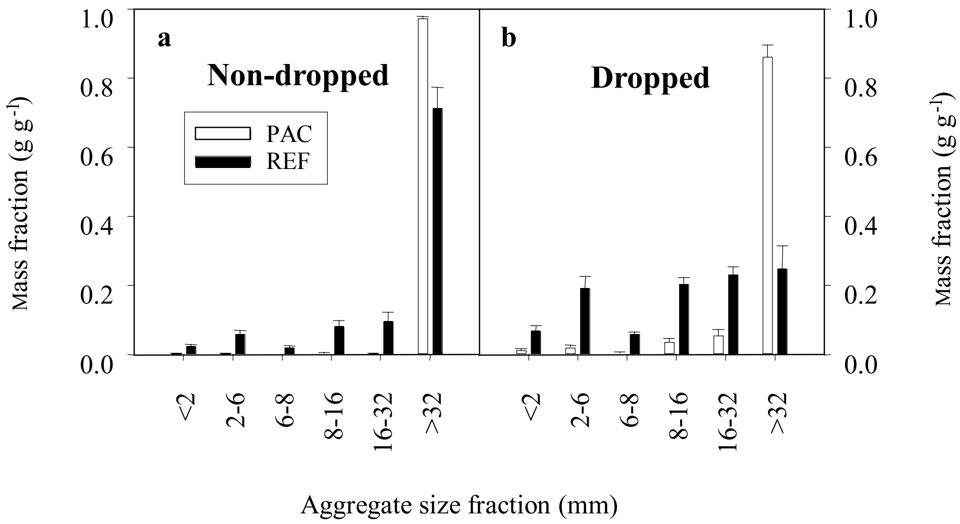

Figure 18. Aggregate size distribution for the soils when subjected to the soil drop test at approximately –300 hPa in the field. Bars indicate +1 standard error (n=9, i.e. averages for each sampling surface). PAC: compacted soil, REF: reference. (**Paper V**).

It was remarkable that both treatments showed approximately ten times higher apparent soil cohesion than tensile strength of soil cores even though the measurements were performed at fairly similar pressure potential (e.g. cohesion =31.6 kPa and tensile strength =3.1 kPa for the PAC soil) (**Paper V**). A higher cohesion than tensile strength was not unexpected. Koolen & Kuipers (1983) have – under a number of assumptions – theoretically estimated the relationship between soil cohesion and tensile strength (i.e., Y = 0.48*cohesion). Later, this theoretically determined relationship was supported by empirical data (Koolen & Vaandrager, 1984). They determined soil cohesion (annulus shear test), unconfined compressive strength (soil cores) and tensile strength in a direct tension test on soil cores and they used remoulded soil from four soil types ranging from silty clay loam to sand. Shear failure involves larger parts of the soil volume and internal friction may to some extent have been included in the estimate of apparent soil cohesion. Although the torsional shear test operated at low normal loads (<32 kPa) allows the soil to fail along "natural" weak planes, the mode of failure will be different from pure tensile failure. The soil is confined within the soil matrix and shear box and sheared in specific horizontal planes. In addition, tensile failure in torsion loading is less effective than tension loading at inducing crack propagation (Anderson, 1995). The fact that soil failed along the horizontal and the vertical plane, respectively for the torsional shear and tension tests, may also have played a role.

7.2.1 Soil pore characteristics

The difference between the treatments may be related to the difference in soil density and pore characteristics. The soil pore characteristics were dramatically affected by the compaction as indicated by an increase in bulk density and aggregate density and a decrease in macroporosity (Table 3 and Figure 5 in **Paper V**). The PAC treatment also caused a significant reduction in the ability of the soil to transport gas by convection (i.e., lower air permeability) and in pore continuity at -30 and -100 hPa pressure potential (Table 4, **Paper V**).

The two-piece cores for the direct tension test were taken horizontally in the soil whereas the cores for pore characterization were taken vertically. This procedure was undertaken in order to characterize the vertically oriented cracks and pores that were expected to influence the tensile failure of the cores.

The tensile strength of the soil cores was significantly negatively related to macroporosity (Figure 19). Similar good correlations were obtained when correlating tensile strength with total porosity. However, the effect of porosity on tensile strength may be attributed to the effect of large pores as the treatments showed similar number of pores smaller than 10 μm (see Table 4 and Figure 5 in **Paper V**). Others have also shown a significant influence of macroporosity on tensile strength (Guérif, 1990; Hallett et al., 1995a). The correlation between tensile strength and pore characteristics was not improved by including the index of pore continuity (PO) in the statistical model (data not shown). In itself, there was no significant correlation between PO and tensile strength within the treatments (data not shown). This is in agreement with findings in **Paper III**.

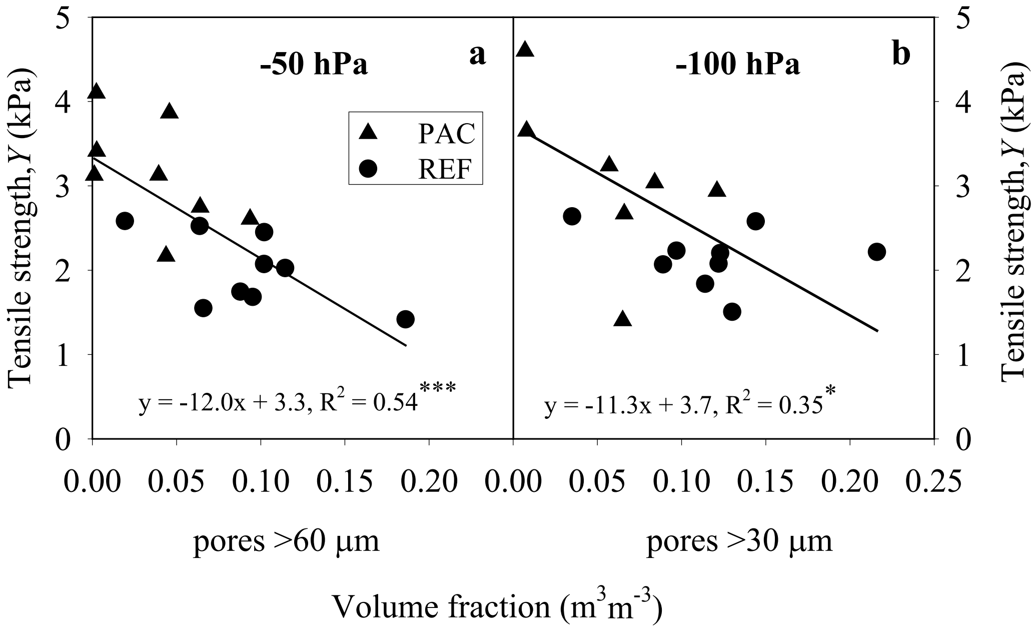

Figure 19. Tensile strength of soil cores measured at –50 and –100 hPa as related to the volume fraction of pores >60 μm and >30 μm, respectively. The symbols represent a mean value for each sampling surface. Lines represent linear regressions. PAC: compacted soil, REF: reference. (**Paper V**).

8. Conclusions

Experimental strategy and methodology

- The direct tension test method developed during this study allows measurement of tensile strength in moist soil without making assumptions on the mode of failure.
  - The presented method was applicable at high matric potentials (-50 and -100 hPa) but not at -300 hPa.
  - The direct tension test results corresponded well with the predicted values determined from the indirect measurements of aggregate tensile strength. This suggests that indirect measurements of tensile strength can be performed at high water contents despite some plastic deformation.

- The energy input in the soil drop test was low in comparison with the energy input in tillage but high compared with the specific rupture energy of single soil aggregates. This suggests that a considerable amount of the energy input in tillage and in the soil drop test is stored as volumetric strain energy, lost to plastic deformation or dissipated into shear failure. Furthermore, the low specific rupture energy of single soil aggregates in comparison with typical energy input in tillage implies that caution must be taken in predicting soil fragmentation in tillage from measurements of rupture energy of single aggregates.

- The friability index presented by Utomo & Dexter (1981) showed in general a low sensitivity to long- and short-term differences in soil management. However, a clear effect of soil water was found, i.e. maximum friability index values at -300 to -1000 hPa pressure potential.

- A fairly good correlation was generally found between results obtained by different methods in the hierarchy of methods applied. This indicates that sophisticated laboratory methods for determination of soil strength and fragmentation characteristics may well be useful for evaluating soil behaviour at soil conditions prevailing in the field at tillage. Nevertheless, it is recommended that laboratory methods are evaluated by using simple field methods.

Soil water and pore characteristics

- A paramount influence of soil water regime on tensile strength and specific rupture energy of aggregates and on friability indices was shown.
  - Interaction between soil water and treatments was found for cropping system soils and the fertilization treatments but not for the compaction treatments.
  - A range in water regimes was necessary in order to reveal long-term treatment effects of fertilization. This could be obtained by applying laboratory analysis on soils adjusted to different pressure potentials.

Seasonal effects would probably confound the results if applying field tests of soil mechanical properties at different water contents during the growing season.

- Macroporosity was related to tensile strength and friability index. Surprisingly, no clear correlation was found to pore geometry characteristics. This may be due to large small-scale variations in these properties.

Soil management

- Marked long-term effects of cropping systems and fertilization were found.
    - For two neighbouring soils with a high input of organic matter, poorer soil mechanical characteristics were found for a soil with grass in the rotation (DFG(1)) than for a soil solely grown with annual crops (mainly cereals). This difference in strength and friability characteristics may be related to a higher amount of biological structural binding and bonding agents in the soil with grass included in the rotation.
    - Two soils with high inputs of organic matter (DFG(2) and AM) displayed more desirable aggregate strength and soil fragmentation characteristics than their counterparts (CCC and UNF, respectively) receiving low inputs of organic matter. The DFG(2) and AM soils showed similar or higher mechanical stability at high pressure potentials and lower aggregate tensile strength at low pressure potentials in comparison with CCC and UNF, respectively. Evidence suggests that cementation of dispersed clay was a determining factor for the observed difference.

- Significant effects of tillage and traffic were shown.
    - The non-inversion tillage resulted in a poorer soil tilth in the topsoil layer (i.e. higher soil strength and lower ease of fragmentation and friability index). Surprisingly, the effect of tillage on topsoil tilth was clearer by the end of the growing season in September than in May. This indicates that natural soil processes occurring during the growing season were not able eliminate the differences between the primary tillage treatments.
    - Soil compaction resulted in strongly increased aggregate tensile strength at all the measured pressure potentials (-100 hPa to -166 MPa). However, soil compaction did not significantly affect the specific rupture energy of the aggregates.
    - Aggregates from the compacted soil failed at higher stress but at lower strain than aggregates from the reference soil, which resulted in a higher Young modulus, (Y/ε), for the compacted soil. This was characteristic for all size-classes and at all pressure potentials.

9. Perspectives

Worldwide the awareness of the environmental impact of modern agricultural production systems has increased tremendously among farmers and consumers during the last decade. This increased awareness has caused a change to more sustainable use and management of pesticides and nutrients in Denmark. This development has also been forced by governmental legislation restricting the use of pesticides, animal manure and mineral nitrogen in the crop production, and supporting the conversion to organic farming practices. However, the use of heavier machinery, intensified tillage and amalgamation of small fields has resulted in less sustainable soil management in Denmark with problems such as subsoil compaction and erosion occurring. The focus on sustainable soil management has meant that low-input farming systems, as e.g. organic farming have gained ground in Denmark. In low-input farming systems plant production relies more closely on the intrinsic properties of the soil, as sub-optimal plant-growth conditions cannot be compensated by an extra input of pesticides and fertilizers. Therefore, an optimal soil tilth has become of vital importance in Danish plant production systems.

The results in this thesis show that soil management to a high degree affects soil fragmentation and friability characteristics. Further research is needed in order to differentiate the relative effects of crop rotations and fertilization. The suggested mechanisms for explaining the tilth differences in this study ought to be studied in controlled experiments. Input of organic matter was generally found to have beneficial influence on soil fragmentation and friability. However, a soil (DFG(1)) with a high input of organic matter and biological activity displayed poorer soil fragmentation and friability characteristics than its counterpart (DFA). This brings into question whether the optimal level of biological activity in the soil is equal to the maximum level? The role of soil biology in soil structure formation and stabilization needs to be investigated in further detail.

Intensive tillage and traffic on wet soil was shown to have a negative effect on soil fragmentation and friability properties. Unfortunately, the development in practical plant production in Denmark has rapidly gone towards more intensive secondary tillage with PTO-driven cultivators and traffic with increasingly heavier machinery. In addition larger tractors and improved tires have made it possible to traffic wetter soils than before, with the potential of making matters even worse. It appears that we are in a “vicious circle” where intensive tillage and traffic on wet soil leads to stronger and less friable soil, which again increases the demand for more intensive tillage. Future research must evaluate the consequences of this development and the persistence of the effects discovered. This is a very reactive approach, which cannot stand alone. A much more proactive approach should be followed as well.

Reduced tillage practices have gained interest in the last couple of years in Denmark. However, the spotlight is pointed on reduced primary tillage (e.g. omitting mouldboard ploughing) and not reduced input in secondary tillage. It is necessary to also introduce reduced secondary tillage management practices that are able to fragment the soil to a desirable aggregate size distribution with a minimum energy input. The development of tillage implements and concepts is to a great extent handed over to agricultural engineers employed in private companies who in many cases use the trial and error principle. A proactive multidisciplinary approach is needed that includes agronomy, soil mechanics and agricultural engineering in the design of new tillage implements and concepts. The knowledge accumulated over the last couple of decades on tensile failure in soil should be applied in the design of tillage implements (Hettiarachi, 1990). Much more work is needed to evaluate the efficiency of different tillage implements to fragment the soil, as done by e.g. Berntsen & Berre (2000).

Soil water was shown to strongly affect soil fragmentation and friability. Even though this was not surprising it appears that the influence of soil water on the soil fragmentation process has not drawn the deserved attention. The importance of soil water was highlighted by Dexter (2000) in a recent paper where he defined the optimal water content for tillage as the "the water content at which tillage produces the greatest proportion of small aggregates", i.e. the greatest soil fragmentation. I would suggest including the quality of the soil fragmentation (i.e., the size distribution of the soil produced) in the concept as well. It is important to define the optimal water content for tillage but it is also of interest to define the range in water content where high quality tillage is possible to perform. Farmers would value this information. However, they would also like to know how they should manage the soil in order to expand this range. A more comprehensive understanding of how soil management affects the optimal level and range in water content for tillage is needed.

As pointed out by Dexter (2000) it is not easy to take tillage machinery to fields with different soil types on many different dates and water contents to obtain information on the resulting tilth. The development of new methods and application of well-known methods for quantifying soil fragmentation and friability of soil at conditions similar to soil conditions at tillage (including water content) has been a primary aim in this thesis. However, there is still a strong need to develop new methods and modify existing methods in order to quantify soil fragmentation and friability under controlled conditions. The modelling of soil fragmentation from a priori information on soil properties (e.g. tensile strength, pore characteristics) was not included in this thesis. However, the results obtained in this thesis indicate that the prediction of soil fragmentation from tensile strength properties of soil elements may be very complex. We need more basic understanding of the failure of "unconfined" soil at different size-scales under applied stress to improve our predictions of soil fragmentation at tillage.

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