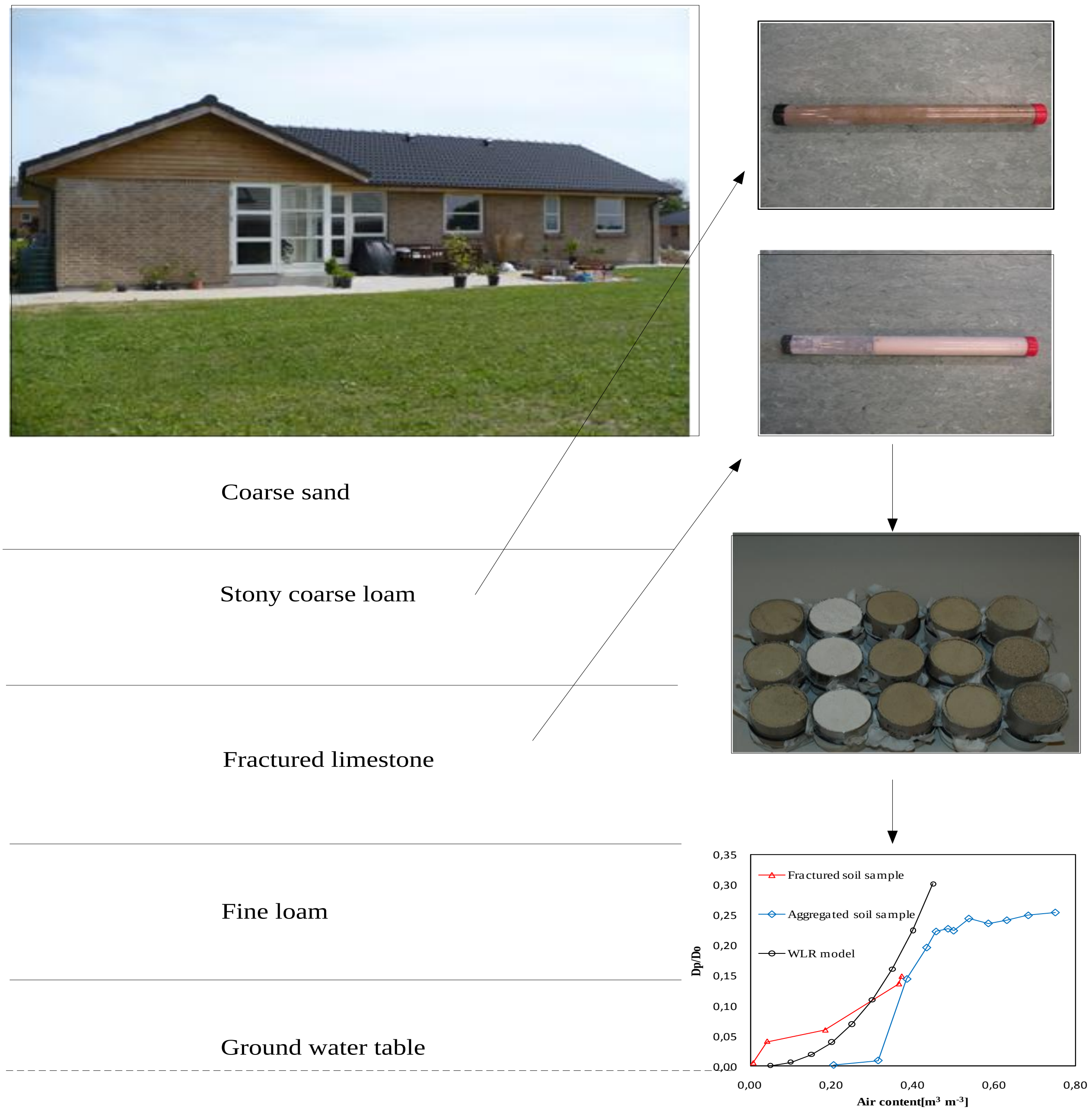
Gas diffusivity in urban vadose zones

- The effect of texture, compaction and structure and the consequence for risk assessment



Aalborg University

June 2009

Maria Pilehave Jensen

Aalborg University

Department of Biotecknologi, Chemistry and environmental engineering

Title

Gas diffusivity in urban vadose zones

- The effect of texture, compaction and structure and the consequence for risk assessment

Gas diffusion i den urbane vadose zone

- Effekten af textur, compactering og struktur og konsekvensen af disse i forbindelse med risiko vurdering

Project period: Sep. 2008-Jun. 2009

Semester: Long Master thesis

Supervisor:

Per Møldrup, Alborg university

Dept. of Biotechnology, Chemistry and environmental engineering

Co-supervisor:

Kate Scow, University of California, Davis

Dept. of Land Air and Water Resources

Written by:

Maria Pilehave Jensen

Main report: 100 pages

Appendix: 2

Enclosure: 1

Gas diffusion is an important parameter when dealing with volatile soil pollution in urban vadose zone, especially regarding risk assessment.

In this project has the focus been soil texture, compaction and structure and the effect on the gas diffusivity.

New measuring equipment for measuring the gas diffusion coefficient in 100 cm3 soil samples has been set up and tested and was found easier to use and more flexible than the so far used equipment. The system was also found applicable for equipment to measure on larger samples.

Furthermore has the gas diffusivity been measured for 100 cm3 samples with different texture, compaction and structure and it is concluded that especially structure has a great impact on the gas diffusivity in the vadose zone.

The Water Induced Liner Reduction model suggested by Moldrup, P. et al., 200 was also tested and it was concluded that as a predictive model was applicable, but it had limitations regarding very fine texture, and structure.

Regarding risk assessment is the WLR model concluded useful but with the exception of highly structured soil and fine textured soil

Resumé

Dette projekt omhandler gas diffusiviteten in den vadose zone i urbane jorde, samt effekten af textur, kompaktering og struktur, hvor agenda er risiko vurdering. Diffusions coefficienten er blevet målt på intakte såvel som pakkede prøver med varierende textur, kompakteringsgrad og strukur i form af aggregering og revner.

Projektet har ikke fokuseret på at opstille en prediktiv model, men på at undersøge fingeraftryk og ”Dp/Do, ε kurve tendenser i jordprøver fra ”våd” til ”tør”. Igennem projektet er den Water Induced Linear Reduction (WLR) model blevet anset for at være gyldig for en mellem én kornet textur med en én regions opførsel. WLR modellen er derfor igennem projektet blevet brugt som en “reference” model til de målte Dp/Do, ε værdier for jordprøver med forskellig textur, kompaktering og struktur.

Studiet viste at specielt fin kornet textur, of struktur dannelse i form af aggregering og revner havde en betydning for diffusion i den vadose zone, og at WLR modellen dermed havde begrænsninger i forhold til disse parametre.

Det er dog konkluderet at WLR modellen er brugbar til at beskrive diffusiveten i den vadose zone når det gælder risiko vurdering. Dette begrundes i at WLR modellen i de fleste tilfælde over estimerede diffusions koefficienten hvilket stemmer overens med at risiko vurdering i Dnamark er baseret på konservative beregninger. Det er dog vurderet at, hvis jorden er meget struktureret i form af aggregering ag revner at WLR modellen ikke tilstrækkelig.

En konceptuel model for beregning af diffusiviteten i den vadose zone er derfor opstillet med udgangspunkt i WLR modellen, men hvor der tages forbehold for de nævnte parametre der har indflydelse på diffusiviteten.

Preface

This thesis is the ending of my final project for my environmental engineer education at Aalborg University. It deals with the gas diffusion in the vadose zone and the effect of texture, degree of compaction and structure where the agenda is risk assessment.

The thesis consists of a main report followed by appendix and enclosure. The appendix is given by letters and the enclosure by numbers. Along with this report is also a CD-rom containing electronic enclosure with data from the measurements performed.

Tables and figures are sequentially numbered and commented text above below respectively.

In connection with the completion of this project a great thanks to:

- Kelum Chamindu for sparring and help in the lab and for making long lab days more fun
- Helle Blenstrup for help in the lab and for making long lab days more fun
- Dianne Toy Louie for help in the lab at UCD and for making my trip a great experience
- Andreas Houlberg Kristensen and Rambøll for intact soil samples and soil data
- Henrik Kock for building the new diffusion equipment

Furthermore would I like to especially thank my parents and my family for support, help and tolerance in connection with my education and this final thesis.

Also a special thanks to Professor Kate Scow and my supervisor Per Møldrup for making my stay at UCD possible and a great experience with a high professional profit, I would not have been without. Also thanks to my supervisor Per Moldrup for very motivating directions and a great involvement.

Aalborg 06-10-09 Maria Pilehave Jensen

Summary

This project deals with diffusion in urban vadose zone and the effect of soil texture, soil compaction and soil structure, where the agenda is risk assessment. Measurements performed on soil samples which differs in texture, degree of compaction and structure have been used to study the effect of the mentioned parameters.

The project has not focused on predicting a descriptive model, but on studying the “fingerprints” and the Dp/Do vs. ε curve behaviors. The Water Induced Linear Reduction (WLR) model suggested by Moldrup, P. et al., 2000 has in this project been assumed as being a model that is valid for intermediate, homogeneous single grained soil. And throughout the project has this model been used as a “reference model” to the Dp/Do, ε measurements performed on samples with different texture, degree of compaction and structure.

The study showed that especially very fine textured soil, highly structured soil in the form of aggregation and fractures and soil with a high content of stones had an impact on the diffusion in the urban vadose zone.

This therefore indicates that the WLR model being a descriptive model for the diffusion in the vadose zone, will have some limitations regarding the parameters mentioned above.

The WLR model is however concluded useful for describing the diffusion in the urban vadose zone regarding risk assessment. This is with the argument of the conservatism in the Danish risk assessment. And for all measurement was it seen that the WLR model was over predicting the Dp/Do in an acceptable degree. However, if the soil is highly structured and has a high content of fine particles or stones are it concluded that the WLR model is not useful.

A conceptual model for predicting the diffusion in the vadose zone has therefore been set up based on the WLR model, where the mentioned parameters affecting the diffusion have been taken into account.

Table of content

1 Introduction

Soil as a general term usually denotes the unconsolidated thin variable layer of minerals and organic material that covers most of the earth's land surface. But what many people do not think of is that soil is one of the ultimate and vital resources here on earth as well as water and air. Soil is essential for growing plants for food as it provides the plants with support, water, nutrients and air. But soil is not only a source that provides food for the human population. It is also fundamental for the foundations of buildings, waste disposal, ground water purity and recharge and climate impact among other things (Allaire et, al., 2008; Singer, 2006). The world's population has increased from less than one billion people in the beginning of the 19^{th} century to more than six billion people in the early part of the 21^{th} century, and compared to the fact that soil is a slowly renewable source and the intensified agriculture and urban use, it is important that we have the right knowledge in terms of chemical, physical and biological processes that takes place in the soil. Knowledge, that is important for being able to manage this resource and thereby secure and preserve it so it can serve and provide for the requirement of humans life. But it is also important for being able to find solutions to local and global problems including e.g. agricultural use, soil pollution and emissions of green house gases that contribute to the global warming. All issues that influences the economic, the environment and the human health. Seen from a global perspective these are problems that are present in less or higher degree in the different parts of the world (Singer, 2006).

In Denmark urban soil pollution is a great problem and has been a topic where focus has increased more and more in the last decade (AVJ, 2004). At the end of year 2006, about 24.000 polluted or possibly polluted sites had been registered by the Danish Counties. From these, 11.812 sites were completely or partly mapped at level 2, which means that pollution has been found, and 11.574 sites were mapped at level 1 which means that activities that could have caused pollution had taken place at the site. These pollutions are caused by a large spectrum of activities. But petrol stations and other sites that do activities with oil and petrol makes up one of the largest groups of sites that has been level 2 mapped and thereby are polluted (WEB 2). This meaning, that many of the common types of soil pollution in Denmark contains volatile compound that through the gas transport can be spread within the soil, to the soil surface or the groundwater and thereby cause exposal to humans, animals and plants. Volatile pollution can spread in many directions and cause many problems, such as the situation where volatile compounds are transported into houses and other buildings causing a bad indoor climate. To prevent this and evaluate the environmental and health related consequences of volatile soil pollution, is it important to understand and be able to predict the gas transport as well as the governing parameters. An illustration of the gas spreading can be seen in the figure 1 below where petrol has been leaking from a petrol storage tank in the ground.

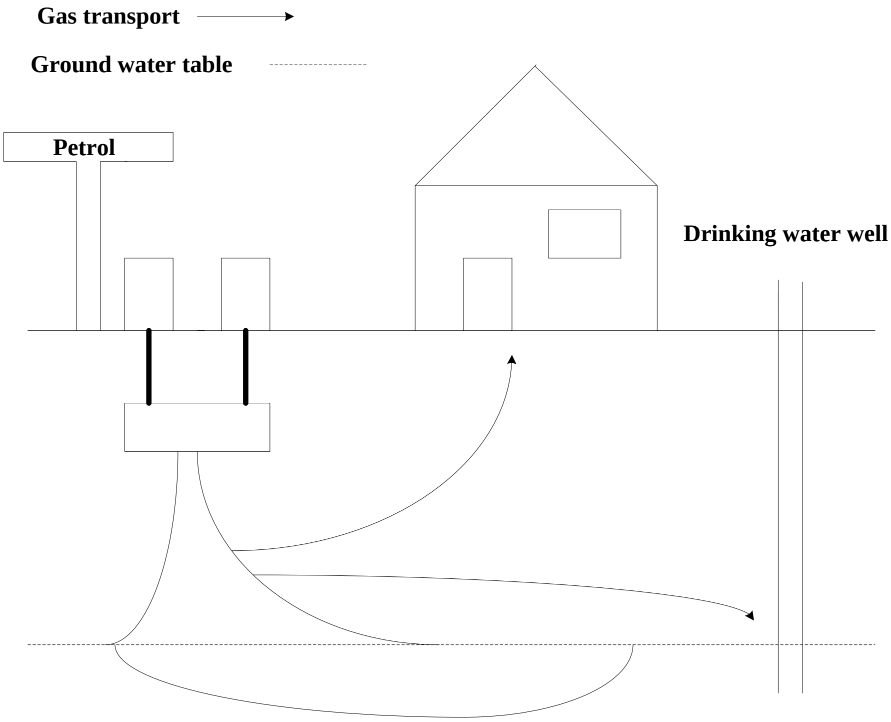


Figure 1 The spreading of volatile pollution in the vadose zone.

In Denmark is risk assessment of urban polluted soil sites based on the PC-based spreadsheet JAGG (Soil, Evaporation, Gas and Groundwater) which is a calculation tool made in accordance with guidelines issued by the Danish Environmental Protection Agency. Guidelines, that deals with the risk assessment of soil, groundwater and vaporisation of soil contaminants and their migration to e.g. outdoor and indoor air (Miljøstyrelsen, 1998). The calculations of the indoor climate contribution regarding volatile soil pollution, is in JAGG based on the matter that the evaporation contribution from a soil pollution may not exceed a given evaporation criteria. Furthermore, it is based on stationary pollution and conservative calculations, using equations for the gas transport, where some is not sufficiently supported experimentally. The gas transport from the pollution and into a building is based on vertical diffusive transport of the contaminated soil pore gas from a contaminated area to the lower side of the floor in a house or building. The further transportation of contaminating compounds into a house or building is calculated as the sum of the diffusive and convective transport. Calculating the diffusive transport through the soil are, as a minimum requirement, that the soil type and layer length must be known and based on this, standard soil parameters such as e.g. bulk density, porosity and air content is used in the calculations (Miljøstyrelsen, 1998). Soil parameters, that is often not in accordance with the actual urban site. The calculations in JAGG is therefore often not in accordance with reality and often exceeds the evaporation criteria even though they are conformed. If the calculated indoor climate contribution exceeds the given evaporation criteria, measurements of the pore air or indoor air must be made or in some cases clean up must be initiated. Steps that are expensive and time consuming (AVJ, 2004; Miljøstyrelsen 1998).

A renewed JAGG model is at the time being completed. One of the changes in the new model is that the Water Induced Linear Reduction (Marshall) Model (WLR) suggested by Moldrup et al., (2000a) is used for predicting the gas diffusivity in the vadose zone, a parameter that is important to know about as it is the most controlling parameter for the gas transport in the vadose zone outside the zone of influence (Partridge, et al., 1999). Furthermore is it also rare that soil pollution causes a gas production that will result in convective transport (Miljøstyrelsen, 1998). So far has the general accepted Millington and Quirk prediction model from 1961 (MQ1961) been used, but the WLR model has proven better than MQ1961 even though it is still not sufficiently supported experimentally and is only tested for single grained, intermediate homogeneous and isotropic 1-regions soils as most prediction models are (Moldrup et al., 2000a). As the soil at urban sites as well as many others sites is often not single grained but aggregated (2-region soils) this can mean that the WLR model is not sufficient for the prediction of the gas diffusion coefficient when dealing with 2-regions soils (Singer, 2006). Furthermore, the model has not been tested sufficiently on compacted soil as well as all soil types.

2 Literature study

The gas transport is overall controlled by a driving force and the most accessible path. The gas can in principle move in all three dimension and will in principle just as well move in the vertical direction as well as the horizontal direction depending on the size and direction of the driving force and accessible path (AVJ, 2004) The driving force is the basis for initiating the gas movement whereas to which extent this will result in a flux is depending on how unhindered the gas can move in the soil. The two mechanisms responsible for the movement of gases within the soil vadose zone and further way up to the surface or down to the groundwater, are advection and diffusion, where diffusion is the most controlling mechanism outside the zone of influence (AVJ, 2004; Pers. Com Moldrup, 2009)

2.1 Gas diffusion

Gas diffusion occurs when molecules of a given gas moves from a zone of high concentration (high partial pressure) to a zone of low concentration (low partial pressure). This continues until an equal concentration of gas throughout the soil atmosphere has occurred. Because this equilibrium condition rarely occurs, gases are constantly diffusing through, into and out of the soil. Gas diffusion in soil can be separated into three different types of mechanisms. The Knudsen diffusion (1), that occurs, when the mean free gas path is much greater than the pore radius. Molecular diffusion (2), that occurs, in pores that are greater than that of the mean free path of the gas molecules and under isothermal and isobaric conditions, when equimolar pairs of gasses counter-diffuse. Bulk diffusion (3), that besides, molecular diffusion includes non-equimolar diffusion and the resulting pressure build up due to different velocities of the molecules (Warrick, 2003).

In this project, only molecular diffusion (2) has been taken into account as neither the Knudsen diffusion nor the non-equimolar diffusion is considered occurring.

Molecular diffusion of a conservative gas can be described by the 1 dimensional empirical expression shown in eq. 2.1 (Rolston and Moldrup, 2002)

$$J_g = -D_p \cdot \frac{dC_g}{dz} \qquad (2.1)$$

Where,

z is the distance [m]
J_g is the diffusive gas flux [g gas m^{-2} soil s^{-1}]
C_g is the concentration in the gas phase [g gas m^{-3} soil air]
D_p is the diffusion coefficient in soil [m^3 m^{-1} s^{-1}]
ε is the volumetric air content [m^3 m^{-3}]

Eq. 2.1 is also known as Fick’s law and was originally developed to describe molecular diffusion of solutes in the liquid phase, and when used for gasses Fick´s law is strictly applicable to molecular diffusion of equimolar gases in isothermal and isobaric systems and exclude the effect of Knudsen diffusion and non-equimolar diffusion. Combined with the continuity equation for a conservative gas given as eq 2.2 below (Loll and Moldrup, 2000)

$$\frac{d\varepsilon \cdot C_g}{dt} = \frac{dJ_g}{dz} \qquad (2.2)$$

Where
t is time [s]

the gas diffusion can be described as eq 2.3 also known as Fick's second low (Rolston and Moldrup, 2002).

$$\frac{dC_g}{dt} = \frac{D_p}{\varepsilon} \cdot \frac{d^2 C_g}{dz^2} \qquad (2.3)$$

The diffusion coefficient of a given soil is most often given compared to that of free air, Dp/Do.

Overall can it be said, that it is the pore space phase that is the most important parameter regarding gas diffusion as it is here the gas is transported. And dependent on the amount of pore air space and the pore space connection will transport of the gas occur by diffusion in a given extend. Depending on the concentration gradient also. Texture that can be described as the other fraction of a soil unit – the solid phase, and the water has a great influence on precisely this – the pore air space and the pore connection (Singer, 2006; Warrick,, 2002).

2.2 The three phase system

When dealing with soil one can distinguish this into three phases. The solid phase, that consists of minerals and organic matter and make up the soil matrix. The liquid phase that consist of water and liquid and the gas phase that consist of gas – together making op the soil pore space. Each of these phases occupies a certain volume and various mass. A hypothetic illustration of a unit soil is shown in figure 2.

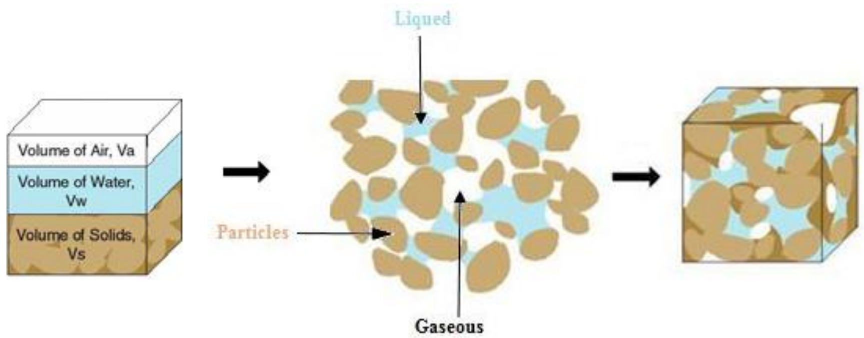


Figure 2 A hypothetic illustration of a unit soil (after Tuller and Ferré, 2009)

As seen on the figure, are the proportion between the volumetric pore space and the volume of solids around equal with sometimes higher volumetric pore space and sometimes less, than the volume of solids. It is also seen that the soil particle sizes differs as well as some pores are occupied by water and some by gas. All this is expressed through different physical properties such as, particle density, bulk density, porosity, water content, air content and particle size distribution – all important for the gas diffusion.

The quantification of the pore space is given as the porosity that expresses the volumetric fraction of pores. The porosity is given as in eq. 2.4.

$$\phi = \frac{V_a + V_w}{V_t} = 1 - \frac{\rho_b}{\rho_s} \qquad (2.4)$$

Where,

V_a is the volume of air [m^3]
V_w is the volume of water [m^3]
V_t is the total volume [m^3]
ρ_b is the bulk density [Mg dry matter m^{-3}soil volume]
ρ_s is the mean density of solids [Mg dry matter m^{-3}dry matter]

The pores will be occupied by either water or air, a distribution that is varying over time and very much depended on precipitation, surface cover and land use. In very rainy periods, it is not unusual to have the pores filled with water and thereby have water content, θ equal to the porosity. Much of this water will however be quickly drained be gravity, studies have showed that pores with a size of 30 μm in diameter or larger can be drained by gravity. Water content in pores smaller than 30 μm is also called field capacity which equals a suction level of -100 cm (pF 2). The remaining water can then be drained by the plants which can drain the water out of pores smaller than 30 μm down to 0,2 μm. This water content is called wilting point which equals a suction level of -15848 cm (pF 4,2) (Loll and Moldrup, 2000).

When the water is drained from the pores, air will be replacing the pore space and the more the pores are drained the higher air filled porosity becomes. The air filled porosity, also denoted air content, ε is given as in eq. 2.5.

$$\varepsilon = \frac{V_a}{V_t} = \phi - \theta \qquad (2.5)$$

Where,
θ is the volumetric water content [m^3 soil water m^{-3} soil vol.]

The porosity is generally between 0,3 and 0,6 m^3 pore space/m^3 soil volume, depending on the texture. Coarse textured soils (e.g., sandy soils) tend to have less total porosity than fine textured soils (e.g., silt or clay soils). This is due to the fact that coarse textured soil can have a higher degree of compaction of the soil particles and thereby a high bulk density than fine textured soil. The bulk density is normally varying between 1,4-1,7 Mg/m^3, but higher and lower bulk densities is not unusual (Loll and Moldrup, 2000). The governing parameter for both total porosity and air filled porosity can be said to be the bulk density as it result in a high or low porosity depending on the degree of compaction of the soil. The degree of compaction is also responsible for the pore size distribution and thereby the drainage level of the pores and thereby also the air filled porosity. But as mentioned above bulk density depend on the texture which is therefore also governing for the porosity, the air filled porosity and this pore space connection.

2.3 The solid fraction - Soil texture

Particle size distribution and shape are important characteristics affecting pore size distribution, pore geometry and total solid surface area. The particle size distribution is also the basis of the soil texture and thereby the soil type. In terms of soil texture, refers soil type to the different sizes of mineral particles in a particular soil. Most soils consist of mineral particles of different sizes: large particles called gravel, smaller ones sand, still smaller ones silt and finally the smallest size clay. The proportions of each size fraction combine to determine the soils texture and thereby the soil type, be it coarse (gravelly or sandy), intermediate (loamy) or fine (clayey). As mentioned, makes the solid particles up the soil skeleton and between the skeleton is the soil pore space. The soil type and thereby the particle size distribution therefore has a great influence on the gas diffusion as it is one of the soil properties that determines the pore size and connectivity and thereby the gas diffusion – this together with the water content and water distribution. Most soils will have pores of all sizes, but as mentioned varies the pore size distribution with texture (Warrick, 2002). On figure 3below is shown the pore size distribution for a coarse, intermediate and fine texture.

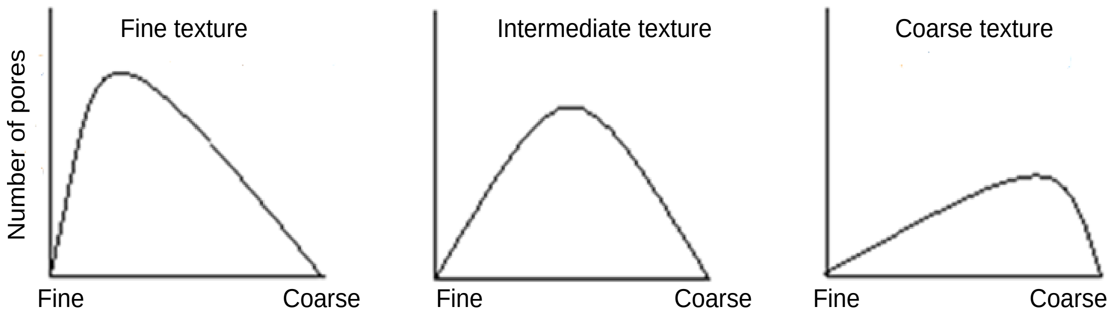


Figure 3 the pore size distribution for a fine (clay) texture, a intermediate (Loam) texture and a coarse (sand) texture. (After singer, 2006)..

A coarse texture consists of mainly large particles and large pores that are easily drained which are optimal for the gas transport. But at the same time is the surface area of coarse particles often not so high which causes a higher tendency of water blockage in wet soils and thereby “blind alleys” for the gas transport. Having a fine textured soil on the other hand which partly consists of fine particles and thereby small pores has a high surface area where the water can be distributed and the tendency of water blockage is not in the same degree as for coarse textured soils (Singer, 2006). This phenomena is also called water induced pore disconnectivity and together with solid induced tortuosity will this be described in the following as these two are governing for the pore connection and thereby the diffusion.

2.4 Tortuosity and pore disconnectivity

The diffusion rate through a porous media is less than that through free air due to the decreased cross-sectional area available for gas movement, the increased path length due to solid induced pore tortuosity and water induced pore disconnectivity due to water blockage (Water bridges). Regarding soil diffusion it is therefore an important goal to understand and describe the tortuosity and pore-disconnectivity.

Tortuosity can be thought of as the average distance a molecule must travel through a network of air filled pores to move a unit distance through a porous media. The increased path length is created by the shapes of both the particles and the pores, and can therefore be denoted as solid induced tortuosity, (T) (Moldrup et al., 2001; Partridge et al., 1999).

Pore disconnectivity, can, as the tortuosity also be thought of as increasing the path length. Pore disconnectivity is a phenomena occurring in wet soil as it the placement of the water that is the controlling parameter, and it can therefore be denoted as water- induced disconnectivity, (C). The two phenomena is illustrated in figure 4 below.

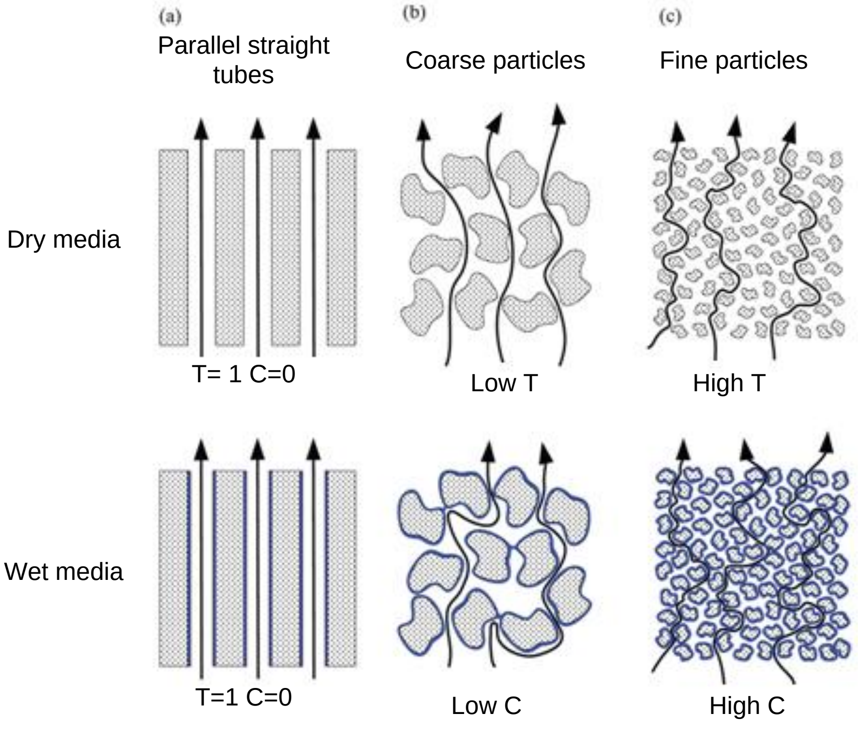


Figure 4 The magnitude of T and C in wet and dry media having fine and coarse particles (After Thorbjørn, et al.,2008a).

As seen on figure 4 the pore space will be in the form of parallel straight tubes if T and C is zero regardless of whether the soil is dry or wet. A situation where $D_p/D_o = \varepsilon$ is reflecting the resistance to gas diffusivity due to only the reduction in soil air (Thorbjørn et al., 2008a).

The presence of particles between each other induces a tortuosity, $T > 0$ and causes the pore space to deviate from parallel straight tubes. And according to Shimamura, (1992) will this vary depending on content of fine particle. And T will be higher in fine textured soils than in coarse textured soils (Thorbjørn et al., 2008a; Shimamura, 1992).

Having a wet soil an additional mechanism in form of the water induced disconnectivity can contribute to an increased path length and resistance to gas diffusivity. Again there is a difference between fine textured material and coarse textured material. Due to the lower surface area for larger particles than for small particles will this result in higher water induced disconnectivity and in some cases will these water bridges block the diffusion completely (Thorbjørn et al. 2008a).

2.5 Particle arrangement and soil structure

Soil structure is the arrangement and organization of primary particles. It is rare that particles, is separated from other particles. Except from dunes and beaches, the sand particles are usually attached to silt and clay particles, forming groups of particles called aggregates. In figure 5 an aggregated soil sample be seen.

Figure 5 An aggregated soil sample(left) and the sample after sieving and crushing (right).

Particle arrangement in the soil varies depending upon soil texture coarse or fine, surrounding conditions like chemical and biological activity, water content (matric potential), overburden and confining pressures and loading history. Aggregates may vary in size, shape and stability and furthermore has aggregates both inter and intra pores. The particle shape and orientation define the intra aggregate pore space and connectivity whereas the aggregate shape and orientation define the inter aggregate pore space and connectivity (Singer, 2006). An illustration of aggregated soil and the difference in inter aggregate and intra aggregates pores are seen in figure 6.

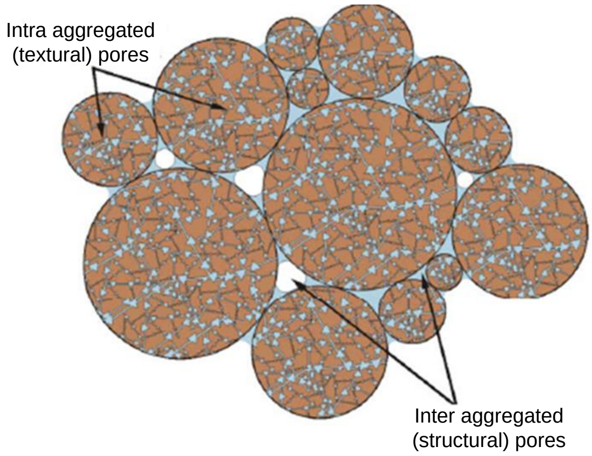


Figure 6 Illustration of aggregated soil and the difference in inter aggregate and intra aggregates pores.

Aggregates are not permanent and undergo modifications due to drying and wetting and they vary besides that also as mentioned in stability depending on the different aggregate stabilizing agents such as silicate clay, organic matter and oxides of Fe and Al (Singer, 2006). Aggregation increases the total pore space and also the pore size distribution where aggregated soil will have more larger pores in the inter pore space and more small pores in the intra pore space which influence the physical processes primarily through their control of the soil hydrology and thereby the air content and the gas diffusion path. The large pores in the inter pore space will transmit water more quickly and furthermore will they infiltrate water in the intra pores than soils with no or little aggregation. This means that the gas diffusion will be increased in the inter pore space but then decreased in the intra pore space. Of course, depending on the pore size distribution and pore connectivity (Warrick, 2002). Besides aggregation, the soil can also be fractured in higher or less degree. This can be due to the drying and wetting processes that in some cases also lead to swelling and shrinking of the soil. Besides this crack and fractures can also be a consequence of the soil root system or the soil animal life as e.g. earthworms. The fractures result in continuous macrospores that are often consisting of air and thereby is optimal for the gas diffusion of course depending on the size and numbers of fractures (Singer, 2006).

2.6 Modelling the gas diffusion - The WLR model

A universal description of the soil gas diffusivity and the governing parameters has been a main research objective in soil gas physics since the ground-breaking work of Buckingham in 1904. Besides being an important parameter regarding risk assessment and human health e.g. here in Denmark it is also a fundamental aspect of many environmental, engineering, ecological, agricultural and biological problems. For example, biodegradation and exchange of greenhouse gasses, aeration of agricultural soil, emission of fumigants but also in connection with plant growth projects in microgravity environment in outer space (Augustus,2008; Steinberg et al., 2005) Buckingham pioneered the research on soil gas diffusion and suggested that the gas diffusion coefficient is related to the air filled pore space in the form of a power function, ε^x, where x is a total parameter for tortuosity and pore connectivity. Since then numerous empirical expressions have been developed that relate the diffusion coefficient of the gasses in soil, to their diffusion coefficient in free air, the tortuosity factor and pore connectivity factor in some way. The tortuosity and pore connectivity factor is generally correlated with air filled porosity, or combinations of air filled and total porosity; Marshal 1959, Millington 1959, Millington and Quirk 1961, Currie 1960, Lai et al. 1976, Moldrup et al. 1999,Moldrup 2000, Moldrup et al. 2005 (Allaire et al., 2008).

So far the Millington Quirk 1961 model (MQ 1961) has been a generally accepted model for predicting the gas diffusivity in soil. Also Regarding risk assessment here in Denmark, has this model been used so far. But in connection with the new Risk assessment tool JAGG 2 has it been suggested to use the Water Induced Linear Reduction model proposed by Moldrup et al. 2000. A model tested primarily on single grained, homogeneous and isotropic soils with an intermediate texture (Moldrup et al., 2000a). The eq. for the WLR model can be seen in eq. 2.6 below.

$$\frac{D_p}{D_o} = \frac{\varepsilon^{2,5}}{\phi} \qquad (2.6)$$

Where,
Dp/Do is the relative diffusion coefficient.

The WLR model is a modification of Marshalls 1959 classical model for completely dry soil, The Marshall 1959 model has been modified with an additional linear reduction in gas diffusivity with relative air-filled porosity (Moldrup, et al., 2000a).

$$\frac{D_p}{D_o} = \varepsilon^{1,5} \cdot \left(\frac{\varepsilon}{\phi}\right)^1 \qquad (2.7)$$

The WLR model describes the solid-induced tortuosity by the term $\varepsilon^{1,5}$ and the water-induced pore disconnectivity by the term $(\varepsilon/\phi)^1$, and the model can therefore be written as eq. 2.8.

$$\frac{D_p}{D_o} = \varepsilon^T \cdot \left(\frac{\varepsilon}{\phi}\right)^C \qquad (2.8)$$

Where,

T is the solid-induced tortuosity
C is the water-induced disconnectivity

As mentioned, the WLR model is primarily tested for single grained intermediate soils. Having compacted soils, very coarse textured soil or fine textured soil as well as aggregated and fractured soil will all this affect porosity, pore- and particle size distribution and surface area of a soil – all affecting the tortuosity and the pore disconnectivity cf. section 2.4. This means that the parameters T and C probably will have to be adjusted to be able to predict Dp/Do. In figure 7 and 8 is illustrated how the WLR curves changes with changing T and C.

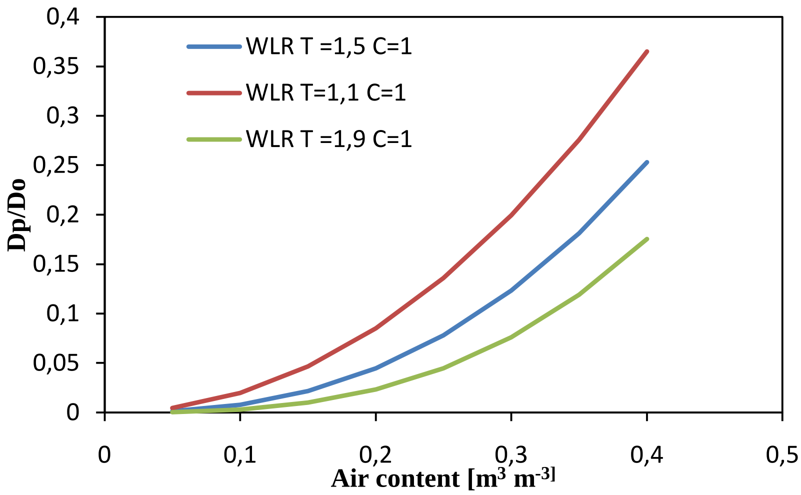


Figure 7 Illustrates how the WLR curves changes with changing tortuosity factor, T.

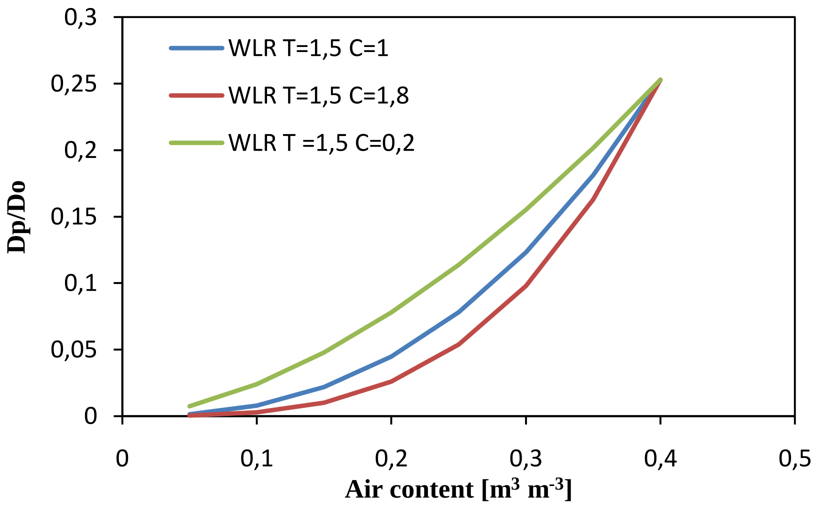


Figure 8 Illustrates how the WLR curves changes with changing pore connectivity factor, C.

As it is seen on figure 7 and 8 will the change in T and C result in varying WLR curves. Where if T is changed will this especially result in differences in the dry area as it is here the term (ε^T) will be controlling as ε is high. Whereas, if C is changed will the area in the middle of the curve be most affected as it is here the greatest value of $(\varepsilon/\phi)^C$ is. In other words will a change in T and C be able to predict WLR curves with higher tortuosity and water blockage if T and C are changed.

Looking at a specific site, which is the case when working with risk assessment, it is the soil hydraulic properties and more specific the matrix potential, ψ that is focused on as air content is never the same through the soil profile. Dp/Do can therefore also be expressed through ψ. This can be done by using the parametric van Genuchten SWC model that describes the θ(ψ) relationship (Van Genuchten, 1980). See eq. 2.9.

$$\Phi = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1+(\alpha|\psi_m|)^n}\right]^m \qquad (2.9)$$

(Van Genuchten, 1980)

Where,
θ, is the water content [cm^3 cm^{-3}]
θ_s, is the water content at saturation [cm^3 cm^{-3}]
θ_r, is the residual water content [cm^3 cm^{-3}]
Ψ_m, is the matric potential [cm]
n, is a shape parameter
m, is a shape parameter (m=(1-(1/n)))
α, is a shape parameter [1/cm]

α, n and θ_r are parameters that can be obtained by fitting the model to a few measured data pairs. However if measurements has not been made, typical van Genuchten SWC model parameters (α, n) including the residual (θr) and the saturated (θs) water contents compiled from the UNSODA database (Unsaturated Soil Hydraulic Property Database) can be used (Tuller and Ferré, 2009). See table 1.

Table 1 Typical fitting Van Genuchten parameters (n and α) including φ_r and φ_s , N indicates the number of soils or samples of a given soil texture from which the mean values are compiled.

Soil texture	N	N	θs [cm^3/cm^3]	θr [cm^3/cm^3]	α [1/cm]
Sand	126	3,19	0,37	0,058	0,035
Silt loam	101	1,39	0,43	0,061	0,012
Clay	25	1,20	0,51	0,102	0,021

The variable parameter, ε in the WLR model can then be replaced the Van Genuchten expression and thereby vary with the matric potential. See eq. 2.10 below.

$$\frac{D_p}{D_o} = \left(\phi - \left[\frac{1}{1+(\alpha|\psi_m|)^n}\right]^n \cdot (\theta_s - \theta_r) + \theta_r\right)^{1,5} \cdot \left(\frac{\phi - \left[\frac{1}{1+(\alpha|\psi_m|)^n}\right]^n \cdot (\theta_s - \theta_r) + \theta_r}{\phi}\right)^1 \qquad (2.10)$$

In this way it is possible to compare the Dp/Do at a given matric potential and thereby at a specific site. In figure 9 is illustrated the relationship between Dp/Do and pF for different textures. The Van Genuchten parameters have been used from table 1.

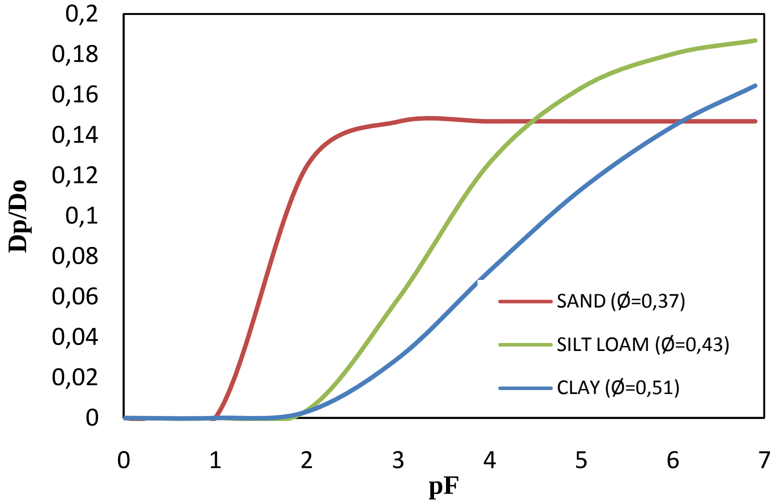


Figure 9 The relationship between Dp/Do and pF based on a combination of the WLR model and Van Genuchten (SWC) model.

On figure 9 it is seen that the Dp/Do values can be compared at a specific matric potential-and thereby specific hydraulic site condition. On the figure is illustrated the curves for Sand, silt Loam and clay that all has a more s-shaped curve then the Dp/Do, ε curves.

3 Objectives

As mentioned in section 2.1 is the gas transport is governed by Fick's law of diffusion which identifies concentration gradient (dc/dz) as the driving force initiating the gas movement. However, the extent to which this will result in a flux depends on the amount of pore air space, the pore network and how unhindered the gas can move in the soil. This can be said to be expressed by the diffusion coefficient, Dp. Fig. 10 illustrates how Dp is controlled by the before mentioned parameters.

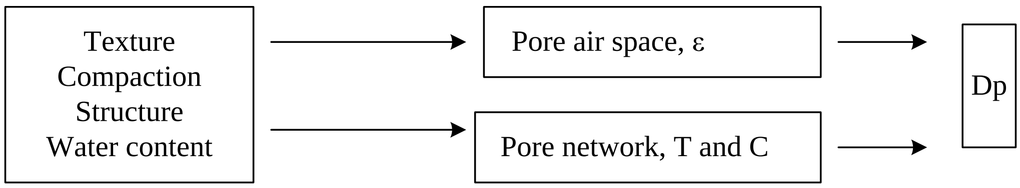


Figure 10 The overall parameters that are controlling the amount of pore air space and the pore network, and thereby Dp.

As it is shown in the figure **texture, compaction, structure and water content** basically controls the amount of pore air space, ε and the pore network in form of T and C which together is controlling the diffusion coefficient, Dp. The main objective of this project will therefore be to analyse and evaluate the effect of texture, compaction and structure on Dp in soils from near water saturation to air saturation. The parameters for which this will be analyzed and evaluated will be ε, T and C. The project will not focus on finding and setting up a model that would be able to predict Dp based on the given effect from texture, compaction and structure. But instead will focus be on clarifying the fingerprints for these effects on soil going from wet to dry.

It is however important to find a reliable descriptive model for Dp/Do which can accurately predict gaseous phase contaminant transport (e.g., emission of methane from landfill site, migration of VOC from leaky underground repositories) as well as a useful tool for risk assessment. WLR model was found to be such a promising tool but it is only tested on intermediate non structured one region soils. Testing and validating limits of this model is also another essential part of this study.

The agenda for the project and the focus on gas diffusion in the vadose zone, is risk assessment and the environmental and health related problems that the gas transport in the vadose zone can cause. The effect of texture, compaction and structure on Dp/Do and consequently for risk assessment is also studied and evaluated.

A condition for studying and evaluating the above is reliable and well functioning measurement equipment. This area will therefore also be studied and new equipment will be set up and tested.

In the table below is given a presentation of the objectives for this project.

The objective of this project is:

- To set up and test new equipment for measuring the gas diffusion coefficient on 100 cm^3 soils samples – and evaluate the validity of the equipment.

- To obtain a system insight of and evaluate the gas diffusion in the vadose zone, based on measurement of the gas diffusion coefficient in:

  - Soil samples with different texture
  - Soil samples with varying compaction
  - Soil samples of structured soil in the form of aggregation and cracks

The measurements will be performed on urban soils and porous media, at different air content and matric potentials to see the effect of texture, compaction and structure in both dry and wet samples.

- To study and evaluate the validation limits of the WLR model regarding, soil texture, compaction and structure (aggregation and cracks) as a descriptive model.

- To study and evaluate the validation of the WLR model regarding risk assessment. This will be based on Case study for an urban polluted.

4 Hypotheses for parameter effect on gas diffusivity

Based on the theory previously presented, the following describes a number of hypotheses regarding the effect of soil texture, compaction and structure on soil gas diffusion. This effect of texture, compaction and structure can in some cases be difficult to predict, especially if more than one of them is varying, as they can often be opposing. The hypotheses are therefore set up based on a coupling between the theory given in the literature study and the WLR model, where the WLR model is considered fully validated for an intermediate single grained textured soil. The hypotheses are set up based on stringent condition according to the WLR model meaning that only the tortuosity and pore disconnectivity as well as porosity are the parameters that are adjusted when setting up the hypotheses.

The air content at a specific site is not the same throughout the soil profile, whereas pF is more likely to be. Hypotheses for the relationship between the relative gas diffusion coefficient, Dp/Do and the suction level, pF and the effect of **soil texture**, **compaction** and **structure** variations in the soil profile have therefore also been set up. Again are the hypotheses based on the WLR model but here combined with the van Genuchten SWC model, as pF is part of this equation (c.f. eq 2.10 section 2.6).

For both the Dp/Do vs ε plot and the Dp/Do vs pF plot should they not be seen as finally results but more as examples of overall expected curve trends for especially soils going from wet to dry. The Dp/Do vs ε plot and the Dp/do Vs pF plot are based on different data and should not be compared directly, but again more according to curve trends.

4.1 Hypothesis for the effect of soil texture

It is expected that soil texture has an influence on the relationship between Dp/Do and ε, and that for some soil types will the WLR model differ from the measured Dp/Do vs ε plots.

- In soil samples with high volumetric water content it is expected that Dp/Do will be higher for a fine textured soil than for a coarse textured soil due to the lower water induced pore disconnectivity, as a consequence of the difference in surface area and thereby distribution of the water which result in less water blockage (c.f. section x).
- In dry soil samples it is expected that the Dp/Do is higher for a coarse textured soil than for a fine textured soil due to the higher solid induced tortuosity because of the high content of fine particles (c.f. section 2.4).
- It is expected that the WLR model will be in accordance with the Dp/Do, ε relationship intermediate textured soil both in the dry and wet area as also mentioned in the beginning of this section.

This result in a WLR model where it is expected that T and C differs as follows:

Fine textured soil → T < 1,5 and C > 1

Intermediate textured soil → T = 1,5 and C = 1

Coarse textured soil → T > 1,5 and C< 1

On figure 11 below is shown the hypothesis for the relationship between Dp/Do and ε and pF and the effect of soil texture. For a fine textured soil has T been chosen to be 1,3 and C to be 3. For a coarse textured soil has T been chosen to be 1,8 and C to be 0,5. The hypothesis for the Dp/Do Vs pF plot has been set up based on the van Genuchten-SWC model eq. 2.10 where the van Genuchten parameters in table 1 has been used for a fine, intermediate and coarse texture respectively. As the two plots are constructed based on different data, they cannot be compared directly as they will not have the same Dp/Do values.

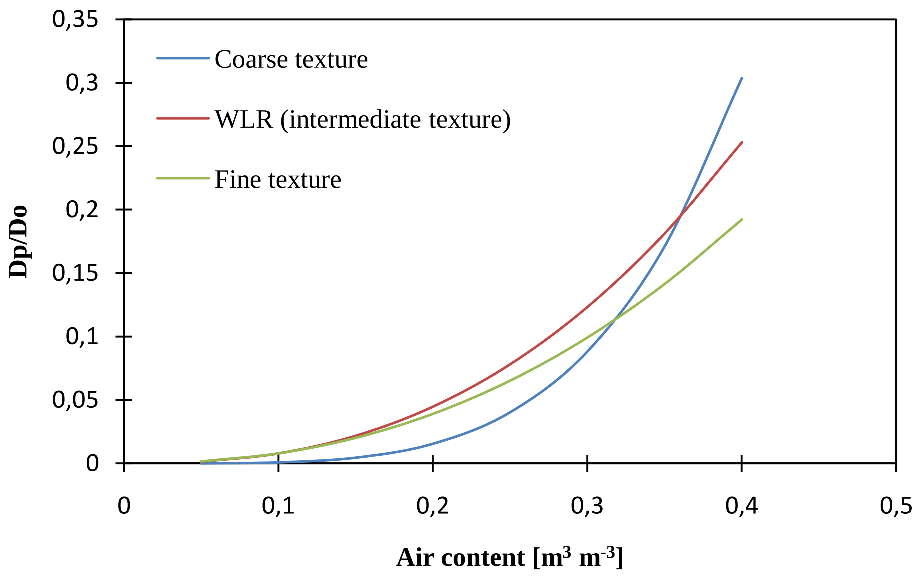


Figure 11 The expected Dp/Do as a function of (a) air content for a fine, coarse and intermediate texture.

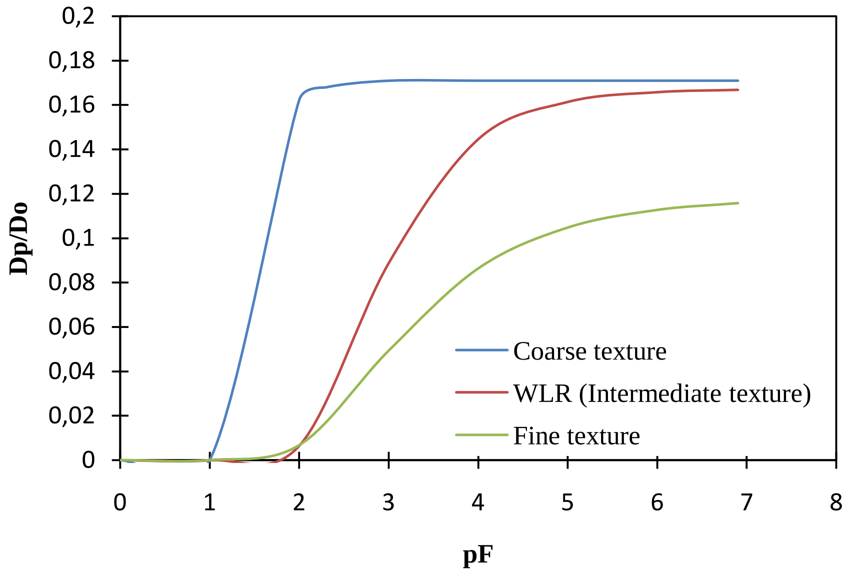


Figure 12 The expected diffusion coefficient as a function of pF for a fine intermediate and coarse texture.

On figure 12 it is seen that the area of low pF values does the WLR model predict a great difference in Dp/Do, which is also in accordance with the theory as the coarse texture will be more drained than the fine texture due the higher content of large pores, and the diffusion coefficient will therefore be higher. It is also here the greatest difference in Dp/Do values will be seen. As the pF increases, does the WLR/van Genuchten model predict that the difference in Dp/Do decreases which is also in accordance with the theory as most of the water is drained and the controlling parameter will be the tortuosity. The Dp/Do will be highest for the coarse textured soil and lowest for the fine textured soil will as was also seen on the figure above.

4.2 Hypothesis for the effect of compaction

It is expected that compaction of the soil also has an influence on the relationship between Dp/Do and ε and pF and that for some degree of compaction will the WLR model differ from the measured Dp/Do Vs ε plots. Two parameters that are changing due to compaction are porosity and pore size distribution and as a consequence of this possibly also the phase distribution.

- High compacted soil has a lower total porosity than low compacted soil and according to Papendick and Runkles, (1965) will soil at the same air content have a higher diffusion coefficient for a dry soil (low compaction) than a wet soil (high compaction). This is due to the change in air filled pore configuration, in addition to water-blocked pores being more effective in preventing diffusion than pores blocked in other ways (Thorbjørn, et al., 2009a).
- The pore size distribution will also change as the amount of small pores will increase in high compacted soil compared to a low compacted soil dealing with the same soil type (cf. Section 2)

In addition to the change in parameters such as porosity and pore size distribution will the change in these parameters due to compaction also be governed by texture. And how both compaction and texture will result on these parameters is difficult to predict. The hypothesis for compaction is therefore made on the basis of the WLR model where the porosity has been changed and the T and C parameters according to a fine and coarse texture. The WLR model will therefore represent a fine, intermediate and coarse texture according to the chosen T and C values given above, and the porosity will be 0,3 (high compacted) and 0,5 $m^3\ m^{-3}$(low compacted). In figure 13 is illustrated the hypothesis for the effect of compaction based on the WLR model.

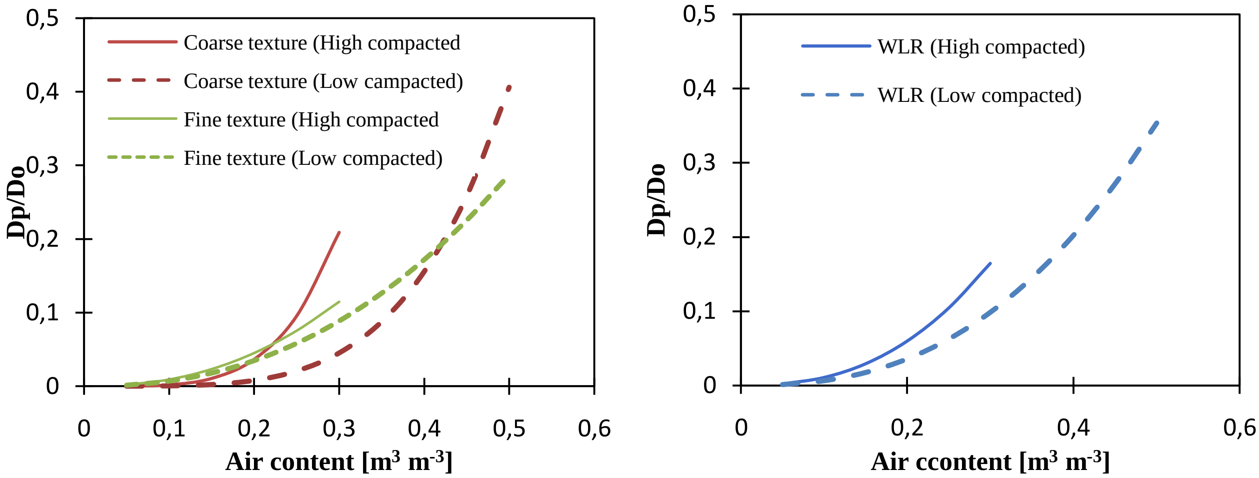


Figure 13 The expected diffusion coefficient as a function of air content for a high and low compacted soil (left). The two curves are compared to the WLR (right). On the left figure are coarse and fine textured soil shown and on the right curve are the intermediate textured soil presented in the form of the WLR model

On figure 13 it is seen that the hypothesis based on the WLR model, for the effect of compaction is that the diffusion coefficient is higher for a high compacted soil than for a low compacted soil for all three textures at the same air content. This is also in accordance with the theory that says that high compacted soil has a lower volumetric water content than the low compacted soil at the same air content and the high compacted soil “act” as a more dry soil compared to the low compacted soil that therefore is more effected by water blockage. When the soil samples are dry the low compacted soil will of course have a higher diffusion coefficient as it has a higher porosity and also larger pores, all optimal for the gas diffusion. The difference in diffusion coefficient of course differs depending on the soil type as also seen in the figure.

Based on the figure and theory is the hypothesis for the WLR model validation limits that for dry soil samples will there be a difference on Dp/Do for both high and low compaction compared to the WLR model. The Dp/Do will in dry soil samples be higher for the coarse texture and lowest for the fine texture at each compaction as was seen in the hypothesis for the effect of texture. For wet soil samples will the difference in Dp/Do compared to the WLR model not be high for either high or low compaction for the two textures, except for the low compacted coarse texture, which is probably due to the effect of the water blockage.

On figure 14 are the Dp/Do compared regarding the hydraulic conditions, pF. The plot has been constructed on the basis of eq. 2.10 where the van Genuchten parameters from table 1 has been used representing a fine, intermediate and coarse texture, and the porosity has then been chosen to be 0,3 and 0,5 $m^3\ m^{-3}$.

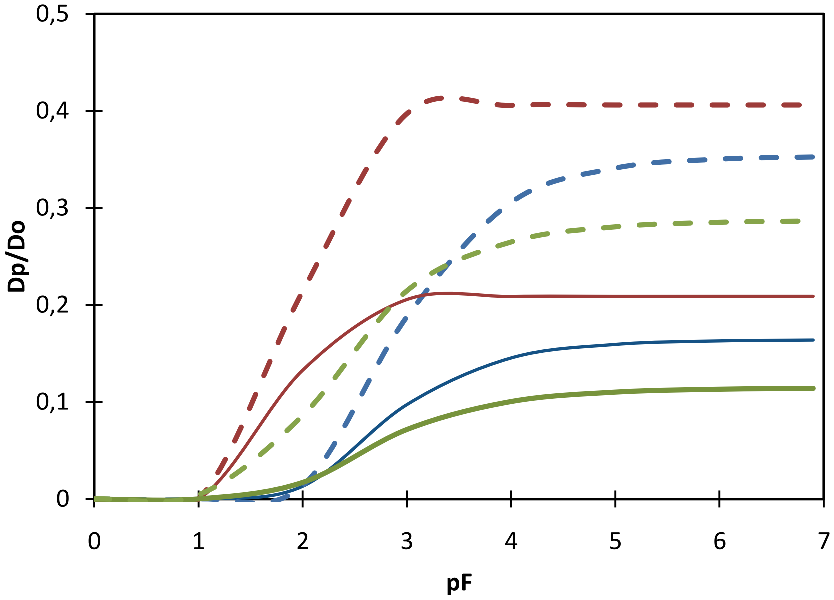


Figure 14 The expected Dp/Do, ε relationship for a high and low compacted coarse and fine textured soil soil . The curves are compared to an intermediate textured soil represented by the WLR model for the two compactions respectively. For conditions and symbols see figure 13.

As seen on the figure is the hypothesis based on the WLR model combined with the SVC- van Genuchten model that having a high compacted soil will result in lower Dp/Do than a low compacted soil at the same pF. This is in accordance with the theory that says that compaction results in higher content of small pores for which a higher pF is needed to drain the pores which is the opposite for a low compacted soil which is drained at lower pF due the higher content of large pores, which therefore results in higher Dp/Do

It is also seen that the difference in Dp/Do for the same texture is most clearly at high pF values (pF > 3). This is also in accordance with the theory as at low pF values will it only be the largest pores that are drained. And as the high compacted soil contains some large pores that will be drained at that pF will it act more as a dry soil than the low compacted soil that will still be so affected by water blockage.

4.3 Hypothesis for the effect of structure - aggregation

It is expected that structure in form of aggregation also has an influence on the relationship between Dp/Do and ε and pF and that for some degree of aggregation will the WLR model differ from the measured Dp/Do Vs ε plots. Two parameters that are changing due to aggregation are porosity going from single to dual porosity but also pore size distribution. The hypothesis for the relationship between Dp/Do and ε for aggregated soil is beside the literature study also based on Currie (1983) who stated that when there is a spatial separation of two groups of pores, as for example, between the system of inter-aggregate pores and the discrete zones of smaller intra-aggregate pores, is the relationship between Dp/Do and ε in two parts. On figure 15 is illustrated the hypothesis for the relationship between Dp/Do and ε. The hypothesis is based on the WLR model in the inter pores, where the porosity and T are the same and only C has been changed as it is expected that water induced disconnectivity has a great influence due to the difference in pore size distribution. The Dp/Do, ε relationship in the intra pores is sketch based on Currie (1983). This plot is just one example on the relationship. Again can compaction and the composition of the aggregates also have an influence on the parameters controlling for the gas diffusion. But again will this be too difficult to predict.

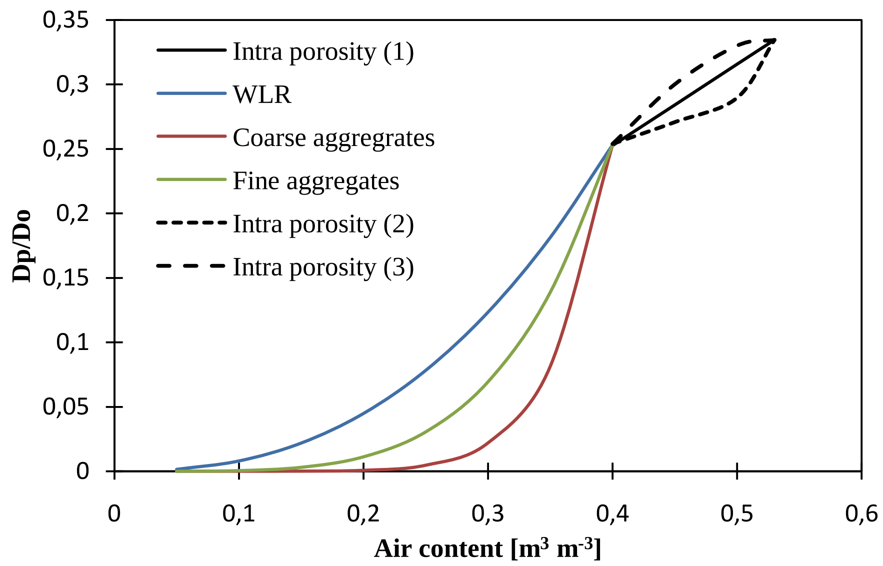


Figure 15 The expected Dp/Do, ε relationship for aggregated soil with fine and coarse aggregates. On the figure is also seen the three curve behaviours for the Dp/Do vs ε relationship suggested by Currie (1983)

As seen on figure 15 is the hypothesis for aggregated soil based on the WLR model that in the outer pore space will the relationship between Dp/Do and ε be equal to that for single grained soil, where it again is seen that for small aggregates will the curve follow the fine textured soil. For large aggregates the relationship between Dp/Do and ε will follow a coarse textured soil. This is in accordance with the theory but will not be due to difference in surface area as what was the case for texture, but due to the pore network that will be easer blocked by water for large aggregated soil than small aggregated soil

When the outer space is drained and the inner space is started draining is the hypothesis based on Currie (1983) that the further tribute to the gas diffusion depends very much on the inner structure, pore size distribution and connectivity and three different curves for describing the relationship between Dp/Do and ε is set up. For all three curves is it expected that there will be a decrease in effectiveness for Dp/Do per extra air content.

1. A linear extension of the curve will occur when the pore size distribution is homogeneous and there is moderate pore connectivity.

2. If the pores are not well connected will this result in a curve where an increase in Dp/Do will not appear until a great part of the intra pore space is drained.
3. Are the pores well connected with a content of both large and small pores will there be an increase in Dp/Do which will fade out in the end as the small pores that will be drained as the last is not quite as connected as the larger pores.

Regarding the WLR model and its validation for aggregated soil is that, it is expected to fit the curve pretty well in the outer space, though again depending on the aggregate size where it on the figure seen to fit fine aggregated soil best.

Depending then on whether total porosity or total macro porosity is used in the WLR model is it expected not to fit either way for the total Dp/Do. Using total porosity will result in over predicting in Dp/Do due to a too low tortuosity that occurs in the intra pore space. Of course depending on the intra porosity and the pore network, will the difference be significant in higher or less degree. Using total macro porosity results in a too low total Dp/Do due to the too low porosity. Again is this depending on the intra pore space.

The relationship between Dp/Do and pF is again very dependent on the aggregate size and on the inter pores and intra pores and the curve trend will form much depending on that. No figure of the hypothesis has been made as it will not give a realistic based if it based on the WLR and SWC- van Genuchten model. It is however expected that the Dp/Do increases very much within a very little range in pF. The range of pF is expected to vary with aggregate size and be more or less steep. It is then expected that the curve will be more or less stabile and have only a little increase in Dp/Do starting at the pF where the inter pores are drained. This is though depended on the inter- and intra-porosity distribution. Is the intra porosity high will this of course result in a higher increase in Dp/Do and is the intra porosity low will the increase be little. This of course, depending on the pore network for both situations.

4.4 Hypothesis for the effect of structure - fractures

It is expected that structure in form of fractures also has an influence on the relationship between Dp/Do and ε and pF, and that for some degree of fractions will the WLR model differ from the measured Dp/Do Vs ε plots. Two parameters that are changing due to fractions are the tortuosity and pore size disconnectivity as cracks forms as almost straight parallel tubes where C will be 0 and T depending on the tortuosity of the cracks will be close to 0. In figure 16 is illustrated the hypothesis for the effect of structures in the soil. The hypothesis is set up based on the WLR model where for both high and low fractured soil are the values used for T and C the same, The part of the curve that differs is the first part which is set up based on Penman, 1940 where Dp/Do $=0{,}66\cdot\varepsilon$ depending on the tortuosity of the fractures.

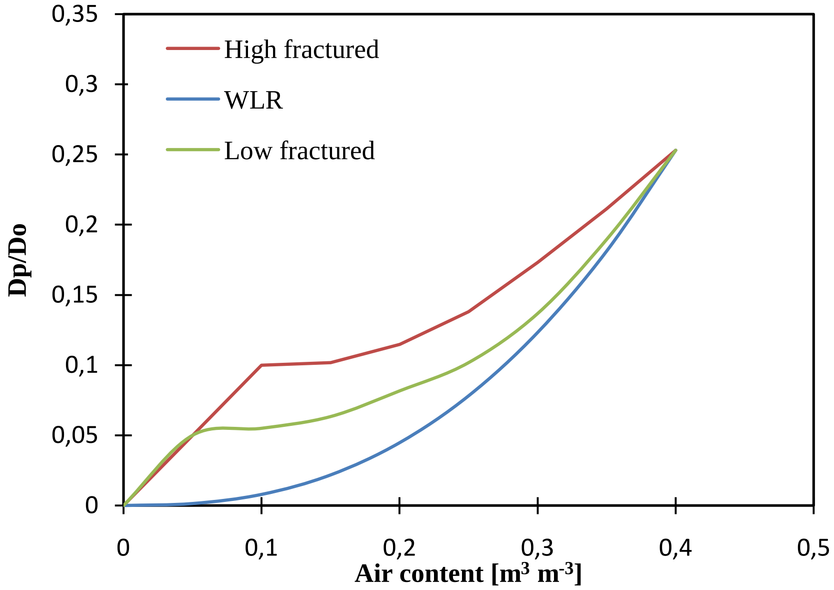


Figure 16 The expected Dp/D, ε relationship for high and low fractured soil samples compared to the WLR model.

The hypothesis based on the WLR model is as seen on figure 16. Having a structured soil will mean that water will easily be drawn out these pores and the Dp/Do will increase very fast in the beginning, and as seen will this depend on how fractured the soil is. It is seen that having a high fractured soil will result in the highest Dp/Do in the first part of the curve. This is also in accordance with the theory that says that the Dp/Do is calculated based on Penman, 1940 for a higher amount of air space. When the large cracks are drained from water the Dp/Do then follow curve for an unstructured soil. These curves will then again depend on texture, aggregation and compaction. And the curve in figure 16 is just an example on how the curve could look. Depending on the tortuosity of the cracks a difference in Dp/Do for dry samples can also occur.

The WLR model will not fit in the wet area as both the tortuosity and the disconnectivity will be greater. But in the dry area will the curves be more alike and can result in the same Dp/Do when totally dry. Of course given that the porosity is the same. Dp/Do will probably be a little higher for the fractured soil as the disconnectivity and tortuosity is smaller.

In figure 17 is illustrated the hypothesis for the effect of structures in the soil. The hypothesis is set up based on eq 2.10 in section 2.6. And is again just one example of the relationship.

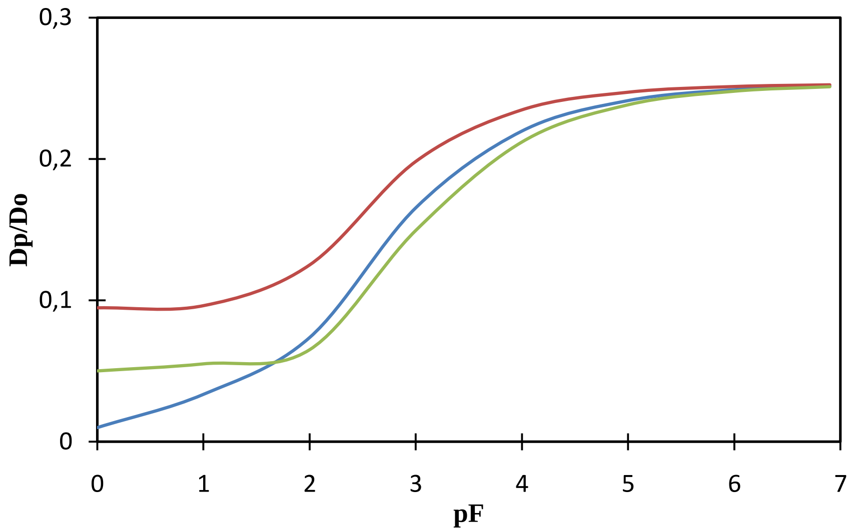


Figure 17 The effect of structure on Dp/Do as a function of ε and pF. For symbols and conditions see figure 16

In figure 17 is it seen that the fractured soil will from the beginning have a high Dp/Do as the pores will be drained be gravity and as there is no disconnectivity in these pores formed by the cracks will this be optimal for the pores. At the pF where the air content will be the same the curves will follow the WLR curve. Again depending on the texture and the additional pore space and pore connectivity.

5 Development of new measuring equipment and analysis procedure

5.1 Measuring the gas diffusivity in soil.

Through time there has been developed several methods and equipment to measure the gas diffusion coefficient in soil (Allaire, et al. 2008). In this project the gas diffusivity has been measured using gas diffusion equipment at University of California at Davis (UCD) that is based on a system that has been used since 1987, where it was introduced in Japan (Pers. Com. Moldrup, P., 2009). Furthermore has a new modified gas diffusion equipment at Aalborg University (AAU) been used, equipment that has been set up and tested in this project. The measuring equipment at UCD and AAU is based on the same method, a method known as the Currie method, which was originally proposed by Taylor, 1949 (Rolston and Moldrup, 2002).The method is a one chamber method based upon establishment of a concentration gradient through a soil sample producing a diffusion process. The principle of the method is illustrated in figure 18 below.

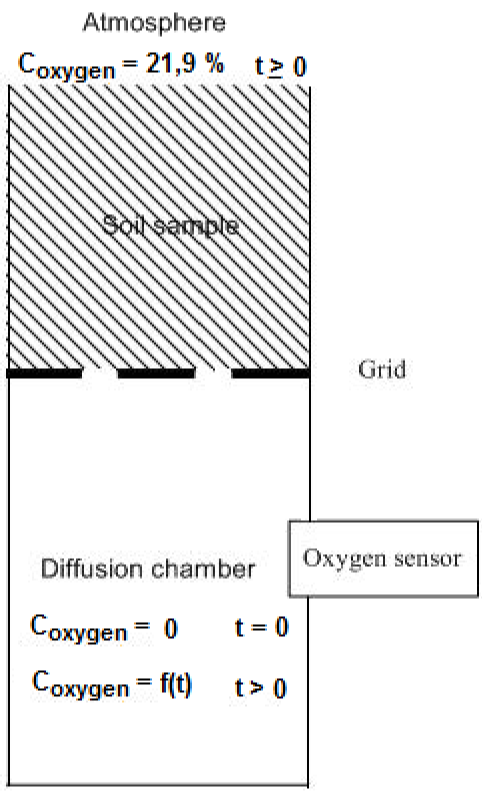


Figure 18 The principle of the method for measuring the gas diffusivity in soil.

As can be seen on figure 18 one end of the soil sample is in contact with the atmosphere making the method a partly open system where the gas transport is between the atmospheres and the closed chamber that is in contact with the other end of the soil sample. The tracer gas used in this method is molecular oxygen which is naturally occurring in the atmosphere in a concentration of 20,9 %. The concentration gradient through the soil sample is created due to flushing of the diffusion chamber with nitrogen, N_2 making it free of oxygen. The created concentration gradient is monitored during time and becomes an indirect measure for the soil gas diffusivity. The method is a non steady state method, as the concentration gradient is decreasing during time.

5.2 The measuring equipment

The measuring equipment at UCD and AAU consist, in principle of the same two parts. Diffusion chambers with a closing mechanism, a manifold and an oxygen sensor attached to it and as the second part, a data logger that is connected to the oxygen sensor and computer, to monitor and collect the data during the measurements. The measuring equipment used at UCD is developed based on equipment which is used on the Saitama and Tokyo universities in Japan and is set up and tested by Nielsen, 2004 in connection with his Master Thesis project. A picture of the equipment can be seen in figure 19 below.

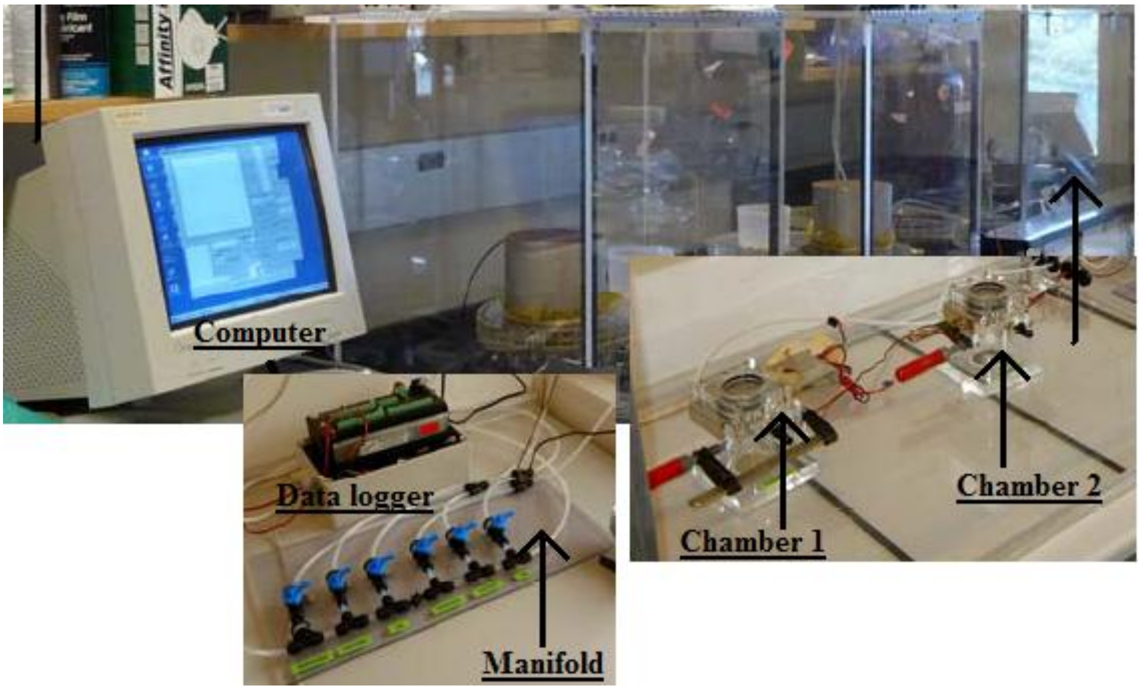


Figure 19 The laboratory arrangement of the diffusion equipment used at UCD

The new equipment at AAU is developed here at AAU and is based on the equipment at UCD and thereby the Saitama and Tokyo Universities. A picture of the equipment can be seen figure 20 below.

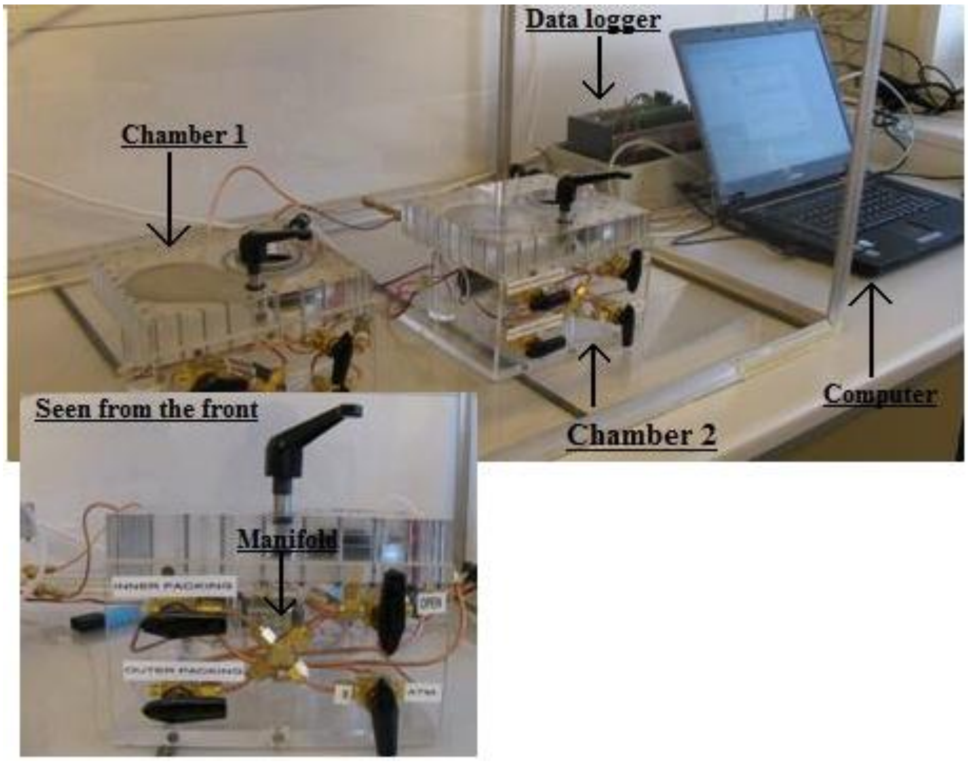


Figure 20 The laboratory arrangement of the diffusion equipment at AAU

As seen on figure 19 and 20 does the two laboratory arrangements look the same. But there has been made some modifications on the new system in the form of modified chambers. Making it more easy to use and more optimal regarding the tightness of the system. The parts that have been improved on the new equipment is the gas controlling system, the manifold, that has been mounted on the chambers instead of being a separate unit which can be seen on figure 19 and 20. Furthermore has the open/closing mechanism between the chamber and the sample been modified, as well as the sample holder. The open/closing mechanism for both chambers is a slide that can be moved forth and back. In figure 21 below are the open/closing mechanism for the two chambers pictured.

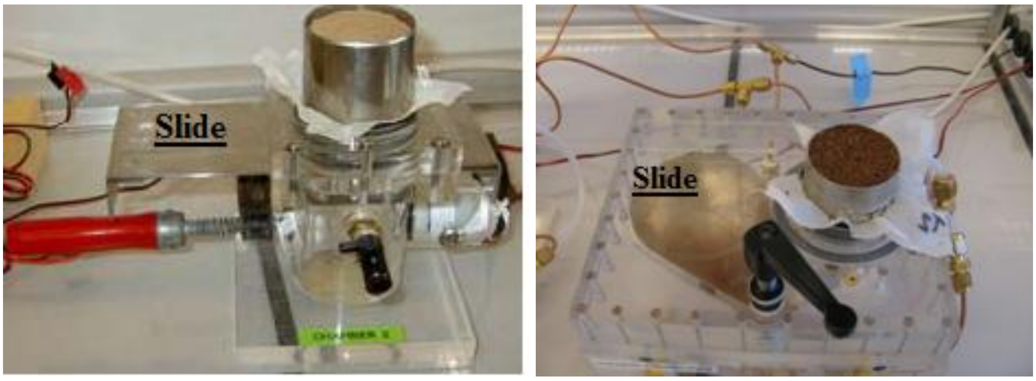


Figure 21 The open/closing mechanism for the two chambers respectively. The left picture shows the chamber at UCD and the right picture shows the new modified chamber.

As for the equipment at UCD, should the slide be pushed forth and back between to o-rings. A procedure that often could be difficult because the slide easily could get stocked between the two o-rings as they are very closely spaced to keep the system airtight. As for the new modified equipment should the slide also be pushed forth and back, but a handle has been attached to the slide contemporary with that the o-rings has been replaced with hallow packings that can be blown up and thereby keeping the system airtight and emptied again giving more space for the slide to move forth and back.

As mentioned has the sample holder also been modified for the new equipment. In the figure 22 below is pictured the sample holder mechanism for the equipment at UCD and AAU.

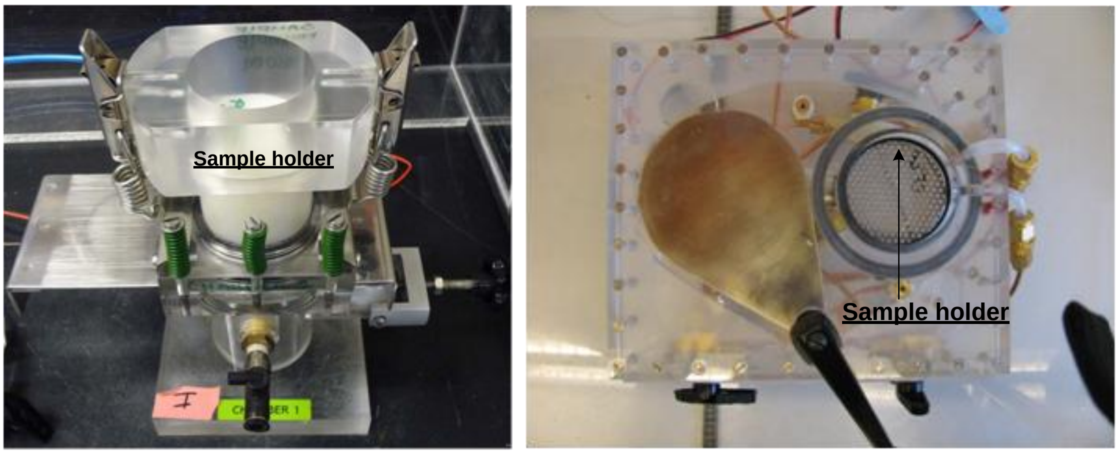


Figure 22 The sample holder for the equipment at UCD (Left) and for the equipment at AAU (Right)

For the equipment at UCD is the sample held air tight to the sample holder by a open block that can be attached to the sample and removed again by two hinges and to springs. This could often be difficult as the hinges often were very tight. As for the equipment at AAU, has this feature also been modified and made simpler. This is done by again using a hallow packing that can be blown up when the sample has been placed in the sample holder holding it airtight to the chamber and then emptied when the sample should be removed. This is a simple process that is controlled on the manifold.

In the following, will the construction of the new equipment, be described more detailed. Furthermore will the calibration, as well as the testing of the equipment, be presented.

5.3 The modified measuring equipment at AAU

The laboratory arrangement is mainly build up from PMMA eq. plexiglas and consists of two identical units. As the system is partly open, pressure differences in the room can interfere on the gas transport making it not only diffusive but also advective. To avoid this, the equipment is placed in a box that is closed during measurements c.f. Figure 20. Each unit consist of a diffusion chamber with a sample holder on the top only separated by a grid. The sample holder is constructed to fit 100 cm^3 soil samples (height 5,1 cm; diameter 5 cm). The contact between the chamber and the soil sample can be disconnected by turning a slide over the grid as can be seen on figure 23 below

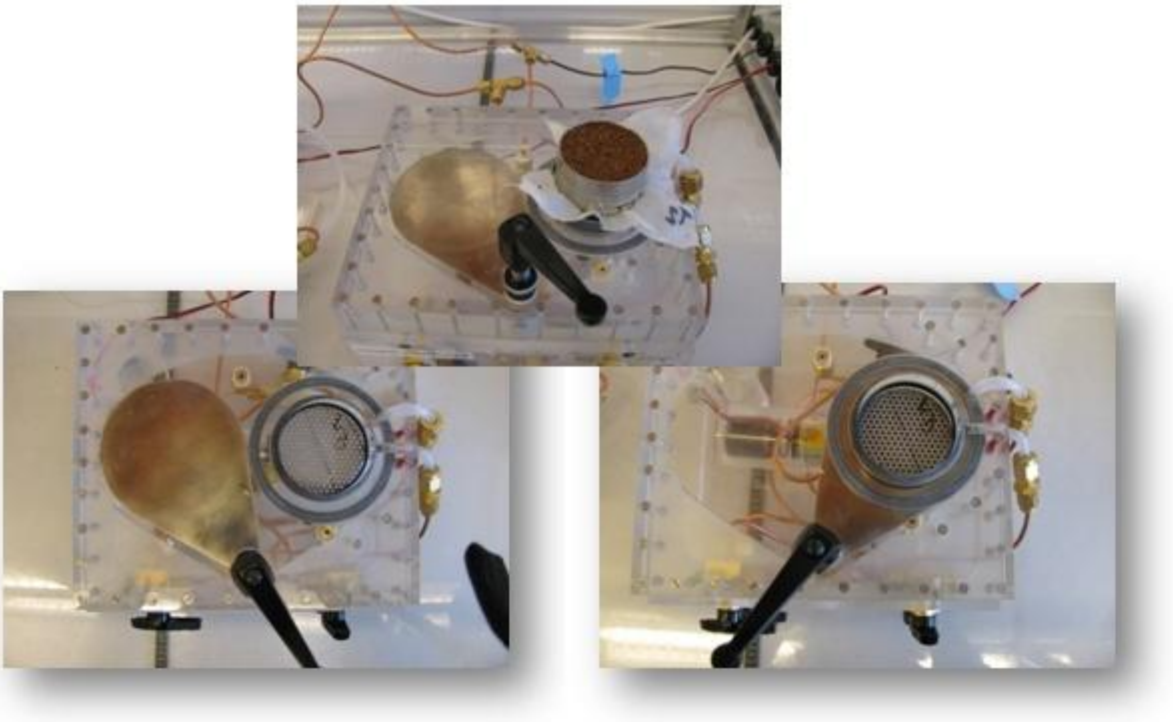


Figure 23 The closing mechanism that can disconnect the contact between the chamber and the soil sample.

Figure 23 also shows two packings - an inner packing and an outer packing. The inner packing holds the soil sample airtight to the sample holder and the outer packing prevents air seepage from the closing mechanism area into the chamber when measuring. But also has a function for the movement of the slide as mentioned earlier. The packings are hollow and air can be blown into them. Nitrogen is used for this purpose as it results in the least error in the measurements if the packings are leaking, compared to the use of atmospheric air. The open and closing mechanism for the packings is controlled by tabs on the manifold c.f. figure 20.

There is on the chambers also mounted a holder for the oxygen sensor as well as a gas inlet and a gas outlet consisting of cobber pipes mounted with little fittings and tightened with teflon tape . The open and closing mechanism for the inlet and outlet is controlled by the tabs on the manifold (see figure 20). The open tab for the gas inlet is connected to nitrogen, N_2 and atmospheric air.

5.4 Calibration

Before using the new equipment, the oxygen sensor is calibrated for each of the two diffusion chambers. The oxygen sensor is produced in Japan by Storage Battery CO., Ltd and is of the type KE-12. The oxygen sensor is connected to the data logger that collects the output signal from the oxygen sensor that is in mV. The procedure for the calibration is performed by logging the output signal from the oxygen sensors when the concentration of oxygen in the chamber is 0 % and 20,9 %. The first mentioned concentration is achieved by supplying the chamber with N_2 while the second concentration is achieved by supplying the chamber with atmospheric air. Two output signals in the unit mV are achieved, corresponding to the oxygen concentration in percent that the oxygen sensor is registering. As the oxygen sensors output signal is a linear function of the oxygen concentration, every output signal in mV can be translated to an oxygen concentration in percent. This is done by linear regression between the two points. (Nielsen, 2004) The linear regression of the data point and thereby the calibration graph can be seen in figure 24 below.

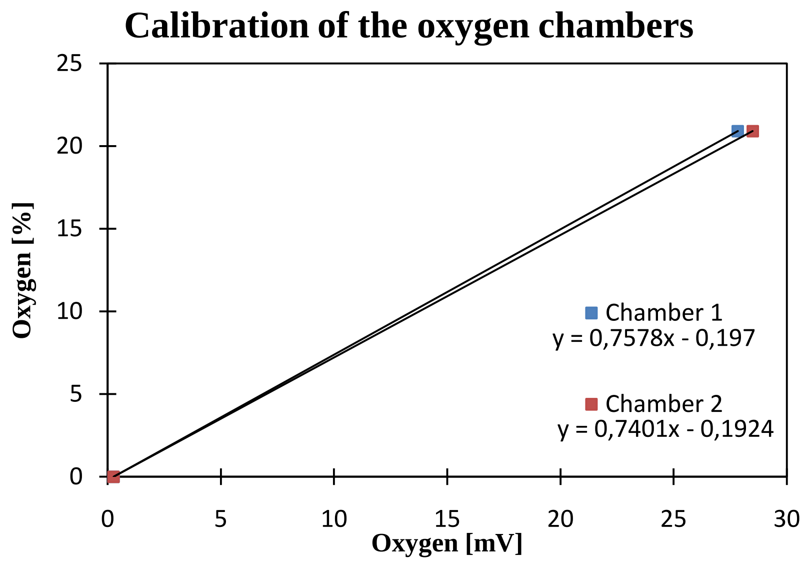


Figure 24 The calibration graph of the oxygen sensor in chamber 1 and chamber 2.

The procedure for achieving oxygen concentration of 0 % and 21,9 % respectively has until now been as follows: Flushing the chamber with nitrogen for three minutes, then flushing the chamber with atmospheric air for three minutes and then use the mean value concentration during the three minutes for 0 % and 21,9 % respectively. But as the oxygen sensor is sensitive to the flow of atmospheric air into the chamber and thereby the pressure in the chamber, different output signals for 20,9 % oxygen was seen depending on the flow as more oxygen molecules is pushed through the membrane of the oxygen sensor at high flow. Variations between 28 mV and 38 mV were seen caused by only little differences in flow. A variation which result in relative diffusion coefficient, Dp/Do of 0,045 and 0,026 respectively, which is a difference on 45 %. The new procedure for achieving oxygen concentration of 21,9 % is therefore to open the slide so the chamber is open to the atmosphere and wait until the signal is stabile. This value can then be used in the calibration of the sensor. If one should perform many measurements in one day and the samples measured on are very wet the oxygen concentration in the chamber is low, when opening the slide after a measurement. It can then take some time before a concentration of 21,9 % is achieved. The chamber can then be flushed with atmospheric air for about one minute after which a stabile signal should be registered before using the value for calibration. If the chamber is flushed with atmospheric air, it is important that the flow is not too high as this can break the membrane of the oxygen sensor. The procedure of flushing the chamber with nitrogen is the same as the previous calibration procedure: the chamber should be screened by the slide while flushing, which should occur for about three minutes until the signal is stabile. Again the flow should not be too high. In the previous calibration procedure the chamber was first flushed with nitrogen and afterwards with atmospheric air. In the new procedure is the order the opposite to avoid flushing of the chamber with nitrogen again after the calibration procedure as the chamber should be oxygen free before starting a measurement. Both time and N_2 is hereby saved.

It is very important that the oxygen sensors are calibrated before measuring as if not it can result in wrong results of the diffusion coefficient. As a guide line the output signal corresponding to an oxygen concentration of 21,9 % is about 28,1 mV ± 0,1 for chamber 1 and 28,6 ± 0,1 for chamber 2 and for an oxygen concentration corresponding to 0 % about 0,3 ± 0,03 for chamber 1 and 2 for the oxygen sensors used in this project. These guide lines should however not be expected to be useful in other project as the oxygen sensors performance is decreasing during time and as the output signal varies depending on the specific oxygen sensor.

5.5 Testing the chambers

To make sure that the equipment is tight and is measuring correct, tests of the chambers were performed. For this purpose, three blocks were made. One block with no holes used for testing if the chambers are tight and two blocks with four holes in each used to test if the equipment is measuring correct, see figure 25.

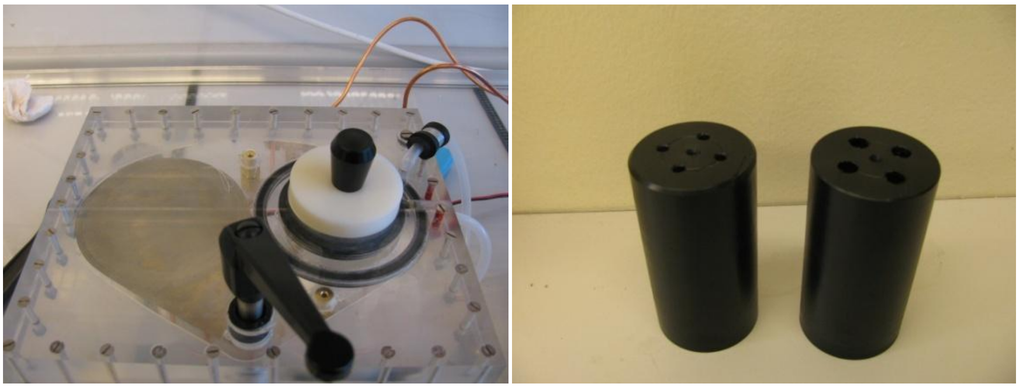


Figure 25 The equipment used for testing the chambers. The left picture shows the chamber with the block used for the test of tightness. The right picture shows the blocks used to test if the chambers measures correct.

The test that was made to make sure that the chambers are tight was done by placing the block in the sample holder, see figure 25. Then flush the chambers with nitrogen until the chamber was oxygen free and then start monitor the oxygen concentration in the chamber during three hours. If the concentration has not exceeded an increase of 0,1 % oxygen during three hours the chambers are assumed tight. The reason for the maximum increase of 0,1 % is, that when measuring on very wet samples the increase in oxygen level, due to diffusion, can be only 2% during three hours. And a too large increase in oxygen level due to a leaking chamber will make the measurements of especially for very wet samples uncertain. On figure 26 below is shown a result from a test of chambers tightness.

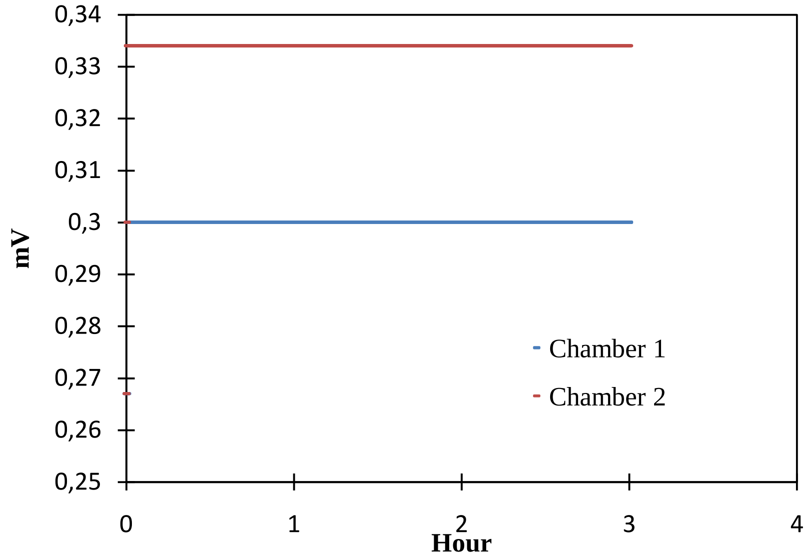


Figure 26 The result of tightness test of the chambers

As can be seen on figure 26 neither of the chambers exceed an increase of the oxygen concentration of 0,1 % and is stabile around 0,3 mV and 0,33 mV for chamber 1 and 2 respectively. Both chambers are therefore considered tight in the period of three hours that is the longest measuring period used in this project. In this project the chambers has been tested continually during measurements to make sure that the chambers remained tight (see CD-rom “The measuring equipment”).

The test for making sure that the equipment was measuring correct was done by using the two black blocks with holes, see figure 25. The length of the block is 100 mm and the perimeter of the holes is 5 mm (Block 1) and 8 mm (Block 2) respectively for the two blocks. The total surface area of the four holes make up 4 % and 10,6 % respectively, of the total surface area of the blocks, making the blocks represent soil samples with an air content of 0,04 cm^3/cm^3 and 0,106 cm^3/cm^3 respectively. The chambers were tested individually but also against each other. Firstly the chambers where tested individually to see if measurements could be reproduced for each chamber making sure that the equipment could perform stabile and identical measurements of the same sample. Measurements on the same block were carried out twice on each chamber. The result can be seen on figure 27 and 28 below. On figure 27 and 28 measurements of the oxygen concentration in the chamber is showed as a function of time. This plot is chosen as it gives the best basis for comparison.

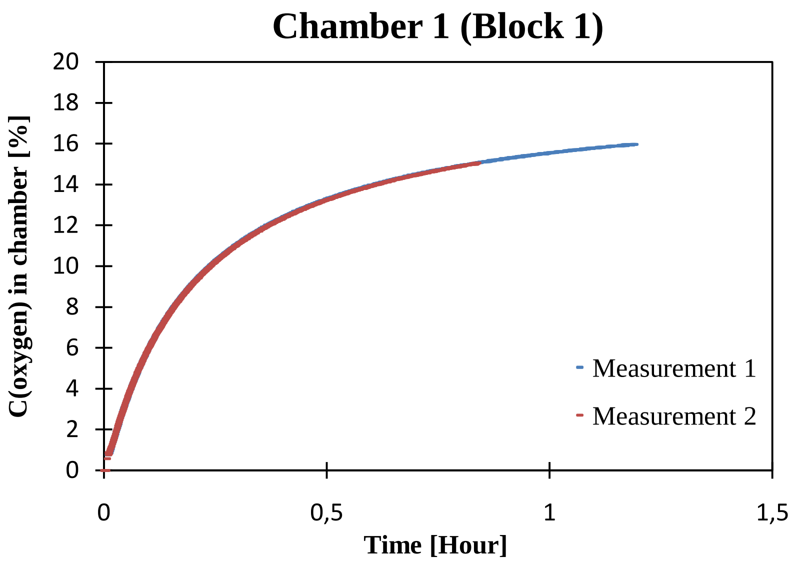


Figure 27 Two measurements performed using chamber 1 and Block 1

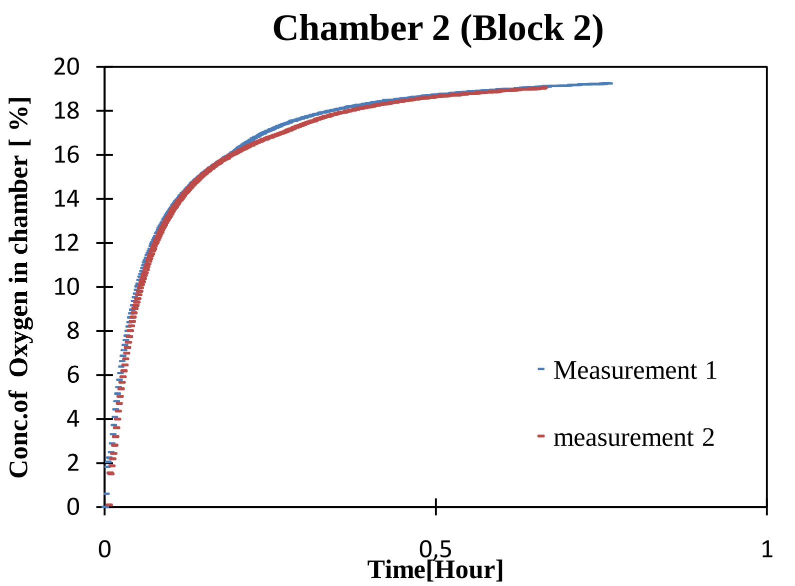


Figure 28 Two measurements performed using chamber 2 and Block 2

As can be seen on figure 27 and 28 both chamber 1 and chamber 2 can reproduce measurements using the same block and that is both when using block 1 and 2 that represents a sample with a little air content (0,04 cm^3/cm^3) and a sample with a higher air content (0,106 cm^3/cm^3). To see the results of the test of chamber 1 using block 2 and chamber 2 using block 1 (see CD-rom "The new measuring equipment").

Secondly, the chambers where tested against each other to make sure that the chambers performed identical measurements. Measurements on the same block for the two chambers were compared. The results of the comparison can be seen in figure 29 below. Again the plot of the oxygen concentration in the chamber as a function of time is shown. Only the plot of the test using block 2 is showed, as the plot of the test using block 1 shows the same.

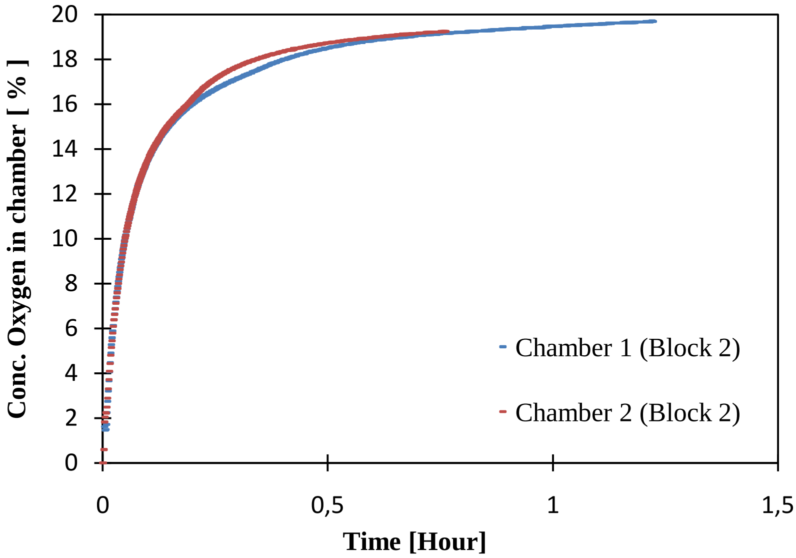


Figure 29 Diffusion measurements in chamber 1 and chamber 2 using Block 2

As can be seen on figure 29 the chambers measures the same using block 2. To see the results of measurement performed on chamber 1 and 2 using block 1 (see CD-rom "The new equipment").

5.6 Validation

Finally, the chambers were validated to see whether the measurements resulted in the right and expected diffusion coefficients. Measurements performed on soil samples of the same soil, bulk density and air content using the already tested equipment at UCD and the new equipment at AAU where therefore compared. Results from measurements performed on the fine granular soil called Profile and the more coarse granular soil Zeoponix are shown in figure 30 below.

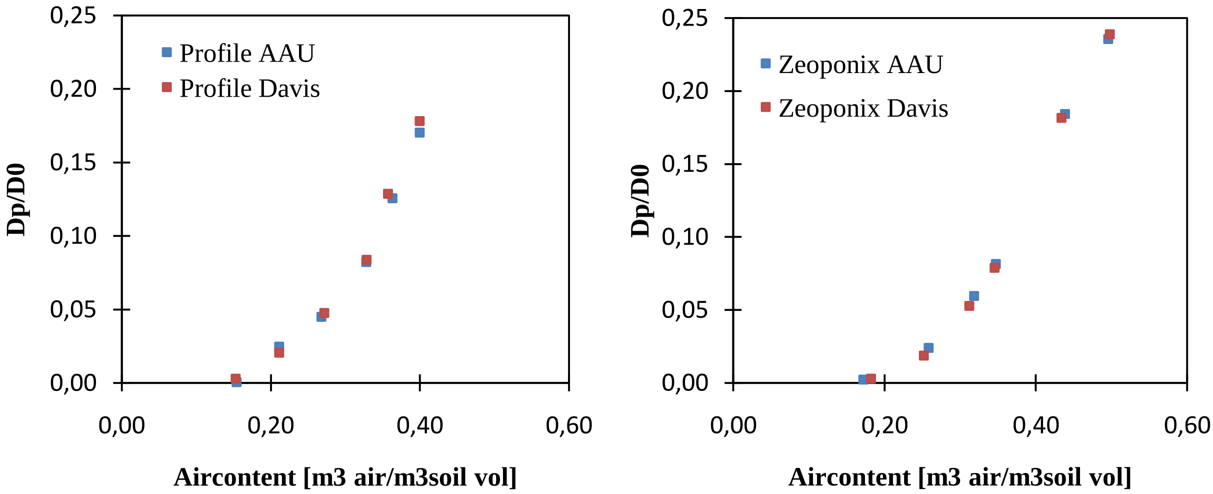


Figure 30 Measurements of Profile and Zeoponix, packed at the same bulk density.

As seen on figure 30 the measurements performed at UCD and AAU results in the same relative diffusion coefficients for the two soils respectively at different air contents. Figure 30 also shows that the modified equipment at AAU measures correct in wet samples as well as in the more dry samples.

5.7 Analysis procedure

The measuring procedure and the calculation of relative diffusion coefficient can be seen in app. A. as this follow the standard procedure. However, there has been made some changes in the standard calculation method that is described in the appendix.

To be able to calculate the relative diffusion coefficient, Dp/Do, h·L and α·L is needed. h·L can be calculated, where L is the height of the sample and h is equal to

$$h = \frac{\varepsilon}{\alpha \cdot \varepsilon_c} \qquad (5.1)$$

where,

α is the height of the chamber [m]

ε_c is the air content of the chamber [1 m^3/m^3 chamber]

Having h·L, α·L can then be determined from a converting table. Only some values of α·L is given in the table and values in between has to be estimated. Thorbjørn (2005) found that an expression of the correlation of α·L and h·L (see app. x). In this project it was found that using this expression resulted in to low values of Dp/Do in wet samples up to 4 % and to high results of Dp/Do in dry samples, up to 6 %. This expression is therefore not found useful in this project. But seen from an engineer perspective it would be optimal to find an expression that can be used in all calculations instead of having to estimate the α·L of each measurement. It is therefore tested whether an expression can be found that can be used in all calculations in this project. This is done by finding the highest and lowest value of h·L appearing for the measurements performed in this project and then find an expression that fits the table values of the corresponding α·L values. In figure 31 is shown a plot of the table values of αL and the fittet expression of the αL values corresponding to the lowest and highest values of h·L.(see calculations on CD rom “The new measuring equipment).

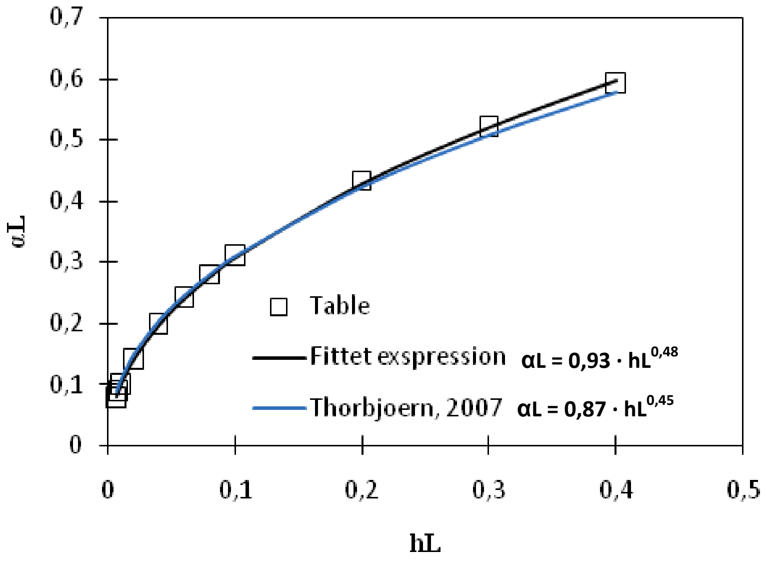


Figure 31 The plot of table values of aL and hL and values of aL and hL found from the fitted expression and Thorbjørn, 2005.

As seen in the figure is there a very good correspondence between the table values and the fitted expression. Testing the expression it is seen that the expression is useful for almost all measurements performed in this project. However the expression results in an error in relative gas diffusion on up to 2 % for wet samples. Based on the test of the expression it is though decided to use the found expression in this project. Calculation of the relative diffusion coefficients made for very wet samples is however checked according to the table in Rolston and Moldrup (2002). To see the test of the new expression (see CD-rom “The new measuring equipment).

6 Materials and measuring series

In this project the diffusion coefficient has been measured on both intact and packed samples. Seven soils/media have been selected with the purpose of studying the given objectives of this project. The seven soil/media, has been collected in Denmark and the USA and are divided in two groups, **Focus soils** and **Cosmos media** and they will be presented in the following section.

6.1 Focus soil

FOCUS is the acronym for "Fate Of Contaminants in Urban Soils" and the soils included in this group are from urban sites in Denmark. In the group are the Lyøvej soil and the Hjørring soil. These soils have been selected with the aim of studying the effects of soil type and compaction on the diffusion in the vadose zone. In the following the soil will be described together with a short description of the location.

The Lyøvej site

The Lyøvej site is located in Nyborg at Fyn in Denmark. It is a former gas station and is grossly contaminated with gasoline and diesel due to leaching from underground storage tanks. The site was operating almost 30 years until 2001 when the tanks were removed. The field site geology is characterized by high carbonate contents and heterogeneous stratigraphy. On figure 32 below is shown a typical geological stratigraphy from the site

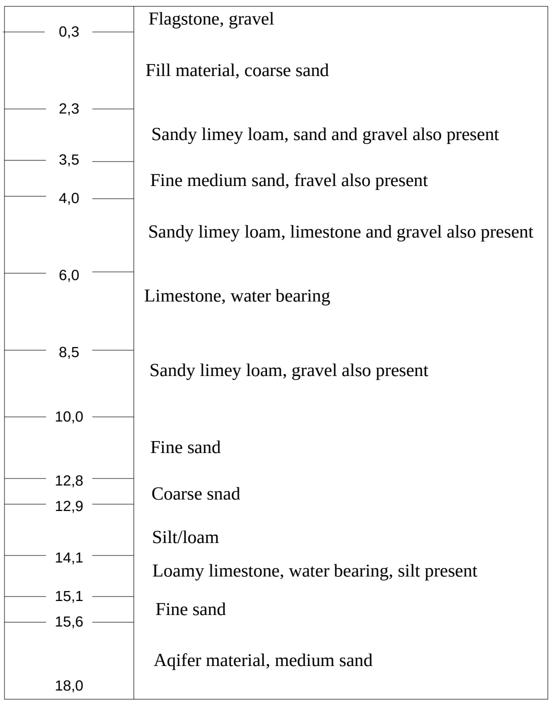


Figure 32 Borehole B301 at the Lyøvej site, representing a typical geological profile at the field site (Rambøll, 2008)

As seen on the figure different soil types are represented down through the soil profile. The top 10 m are dominated by gravely sandy loam enclosing a layer of water-bearing limestone around 5-7 m b.g.s. From 10 to 13 m b.g.s. the stratigraphy is mostly fine sand, followed by various layers of silt and limestone just above the groundwater table.

The gas diffusivity has been measured on both intact and repacked soil samples from this site. The intact soil samples has been collected from borehole B316 and the soil for the repacked samples has been collected from borehole B303. An overview of the boreholes can be seen in app. B as well as a borehole profile of B316 and B303.

The Hjørring site

The Hjørring site is at a Statoil petrol station in the eastern part of Hjørring in North Jutland in Denmark. The Statoil petrol station is located in a town area and in 1962 the petrol station was established at the site, and through time the station has been expanded. The pollution was discovered in connection with an installation of a monitoring unit in the five storage tanks (DMR, 2003). Texture analysis carried out at Foulum Research Center, DJF, Aarhus University showed that the Hjørring soil is predominantly sandy containing 9.2 % clay, 4.8 % silt, 86.0 % sand, and 0.3 % organic matter. The gas diffusivity has been measured on repacked soil samples from this site. The soil has been collected in the depht of 2 m

6.2 Cosmos media

Cosmos is the acronym for the topic: "(**C**)ivilization in (**O**)uter (**S**)pace: Design of Artificial Porous (**M**)edia with (**O**)ptimal Oxygen and Nutrient (**S**)upply for Plant Growth". This topic is obtaining a lot of focus these days and artificial porous media have been designed with the purpose of matching certain properties with the aim of plant growth in outer space. Five of the media that have been designed are called Profile, Zeoponix, Turface (1-2 mm), Turface (2-5 mm) and Pumice and are stable aggregated media with dual porosity. These five media have been used in this project, representing aggregated soil of different aggregate size. The five media are pictured on figure 33 below.

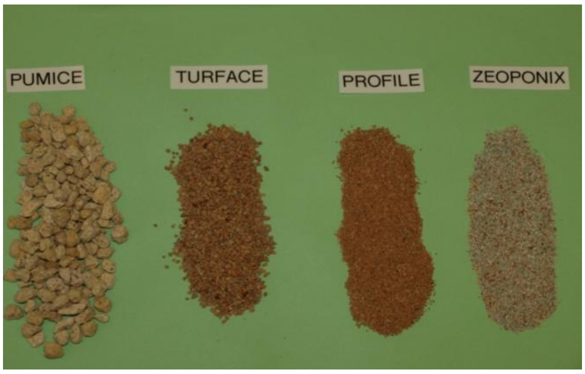


Figure 33 The five cosmos media, Pumice, Turface, Profile and Zeoponix.

The commercial products Profile Turface (1-2 mm) and Turface (2-5 mm) are stabilized backed ceramic aggregates (frittet clay, arcillite) with an aggregate size of 0,25 – 0,85 mm, 1,0 – 2,0 mm and 2,0-5,0 mm respectively. Both media is manufactured by the company Amicor and differ only in particle size distribution. Zeoponix is a mixture of zeolite and rock phosphate and has an aggregate size of 0,25 – 1,0 mm. The components of the media are from the Rocky Mountains in Colorado, but are composed at NASA in Texas. Pumice is of volcanic origin from the Washington state area and has an aggregate size of 3,2 – 9,5 mm (Blonquist et al., 2006). The chemical composition for the five aggregated porous media can be seen in table 2 below. Only the chemical composition for the Turface media is represented as it is the same for the Profile media.

Table 2 Chemical composition of Zeoponix, Profile and Pumice (Blonquist et al., 2006).

Chemical composition[a]	**Light Zeoponix**[b]	**Dark Zeoponix**[b]	**Turface**	**Pumice**
Si	6,16	36,91	38,55	37,06
O	34,64	45,11	34,46	15,44
Al	<2,00	7,58	10,58	5,64
Fe	2,09	<2,00	2,18	32,04
Mg	<2,00	<2,00	<2,00	7,23
K	<2,00	6,15	11,60	2,59
P	16,68	-	-	-
Ca	32,27	<2,00	<2,00	-

[a]All values are percentages. The detection limits of the measurements are <2,00 %

[b]The dark and light Zeoponix correspond to the two different shades of materials The dark and light materials comprise approximately 70 and 30 % of the total, respectively.

The physical properties for the media can be seen in table 3 below.

Table 3 The physical properties for the media (Blonquist et al, 2006.).

Physical properties	**Profile**	**Zeoponix**	**Turface**	**Pumice**
Particle density ρ_s, g/cm^3	2,5	2,5	2,5	2,1
Surface area m^2/g	56	140	55	18
Macro pore fraction	0,57	0,64	0,56	0,43
Micro pore fraction	0,43	0,36	0,44	0,57

For further information of the cosmos media including retention curves, electron micrographs etc. see app B.

6.3 Measurement series

The diffusion coefficient has been measured on five series of samples. In the following will the series be presented in tables including sample ID, location, physical properties of the sample texture and structure.

6.3.1 Measurement series performed using Focus soils

The following measurements series have been performed using the two Focus soils.

<u>Measuring series 1 "The effect of compaction"</u>

Measured at: AAU
Status: Repacked 100 cm^3 soil samples
Location : Lyøvej site
Drainage level: From water saturated to oven dry
Structural issues: Crusted and sieved through 2 mm sieve before packing

Table 4 The location, physical properties of the sample as well as drying method for the Lyøvej soil samples.

Sample ID	Borehole/depht	Bulk density ρ_b Mg/m^3	Porosity φ m^3 m^{-3}	Drying method
C1	303/9,5-10 m.b.g	1,65	0,38	Air + oven drying
C2	303/9,5-10 m.b.g	1,65	0,38	Air + oven drying
C3	303/9,5-10 m.b.g	1,65	0,38	Air + oven drying
C4	303/9,5-10 m.b.g	1,52	0,42	Air + oven drying
C5	303/9,5-10 m.b.g	1,52	0,42	Air + oven drying
C6	303/9,5-10 m.b.g	1,52	0,42	Air + oven drying
C7	303/9,5-10 m.b.g	1,72	0,35	Air + oven drying

In table 5 below is shown the texture analysis for the intact and repacked soil samples. The soil samples has been sieved through 2000 µm, 500 µm and 200 µm sieves using a sieve tower and based on the texture analysis are they characterized as loamy sand.

Table 5 The texture for the packed soil samples from Lyøvej. Only one sample with a bulk density of 1,72 Mg/m^3 has been measured on. The values are in percentage.

Sample ID	>2000 µm	2000-500 µm	500-200 µm	<200 µm	Organic material
C1	0	4,6	39,9	55,4	0,005
C2	0	4,9	41,1	54,0	0,005
C3	0	5,5	41,6	52,9	0,005
C4	0	3,3	39,0	56,7	0,006
C5	0	3,8	40,9	55,2	0,005
C6	0	4,9	47,0	48,1	0,006
C7	0	2,7	29,2	68,0	0,007

Measuring series 2 “The effect of compaction”

Measured at: AAU

Status: Repacked 100 cm^3 soil samples

Location: Hjørring site

Drainage level: From water saturated to oven dry

Structural issues: Crusted and sieved through 2 mm sieve before packing

Table 6 The location, physical properties of the sample as well as drying method for the Hjørring soil samples.

Sample ID	Depht	Bulk density ρ_b Mg/m^3	Porosity φ $m^3\ m^{-3}$	Drying method
H1		1,65	0,38	Air + oven drying
H2		1,65	0,38	Air + oven drying
H3		1,65	0,38	Air + oven drying
H4		1,52	0,42	Air + oven drying
H5		1,52	0,42	Air + oven drying
H6		1,52	0,42	Air + oven drying
H7		1,72	0,35	Air + oven drying
H8		1,72	0,35	Air + oven drying
H9		1,72	0,35	Air + oven drying

No texture analysis has been performed like the one for the Lyøvej soil samples, but the Hjørring soil is characterized as loamy sand as well based on the texture analysis mady by Foulum Research Center, DJF, Aarhus University.

Measurements series 3 “The combined effect of texture, compaction and structure”

Measured at: AAU

Status: Semi-intact 100 cm^3 soil samples

Drainage level: pF 2, pF 2,7; air dry and oven dry

Table 7 The location, physical properties of the sample as well as drying method for the Lyøvej soil samples

Sample ID	Borehole/depth	Bulk density ρ_b Mg/m^3	Porosity φ $m^3\ m^{-3}$	Structural issues
L1	316/3,6-4,1 m.b.g	1,9	0,27	Many stones
L2	316/3,6-4,1 m.b.g	1,9	0,27	Many stones
L3	316/3,6-4,1 m.b.g	1,9	0,27	Many stones
L4	316/	1,75	0,36	-
L5	316	1,7	0,37	-
L6	316	1,65	0,38	-
L7	316/11,7-12,2m.b.g	1,6	0,40	-
L8	316/11,7-12,2m.b.g	1,6	0,40	-
L9	316/11,7-12,2m.b.g	1,6	0,40	-
L10	316/13-13,4m.b.g	1,6	0,40	Small fracture
L11	316/13-13,4m.b.g	1,55	0,42	Small fractures
L12	316/13-13,4m.b.g	1,7	0,35	Small fractures
L13	316/15,2 m.b.g	1,6	0,39	-
L14	316/15,2 m.b.g	1,7	0,35	-

L15	316/15,2 m.b.g	1,65	0,37	**-**

In table 8 below is shown the texture analys for the intact and packed soil samples. The soil samples has been sieved through 2000 µm, 500 µm and 200 µm sieves using a sieve tower (see Appx A).

Table 8 The texture for the packed soil samples from Lyøvej. Only one sample with a bulk density of 1,72 Mg/m^3 has been measured on. The values are in percentage.

Sample ID	>2000 µm	2000-500 µm	500-200 µm	<200 µm	Organic material
L1	-	-	-	-	-
L2	5,9	5,1	23,9	65,1	2,81
L3	-	-	-	-	-
L4	-	-	-	-	-
L5	-	-	-	-	-
L6	0	1	11,0	87,8	1,23
L7	0	1	5,3	92,3	1,51
L8	0	1,3	9,6	88,6	1,14
L9	-	-	-	-	-
L10	-	-	-	-	-
L11	0	0,4	1	95,6	3,02
L12	-	-	-	-	-
L13	2,5	2,7	57,5	39,6	1,14
L14	0	1,0	7,7	90,7	0,39
L15	0	1,0	29,3	68,9	1,13

The samples have been collected by Rambøll using a GeoProbe® that collects samples in PE-tubes (d_i=50 mm) that subsequently is cut in minor parts of about 100 cm^3 (H5xB5,1 cm)For information on the packing method, phase distribution determination, drying and wetting method and the texture analysis see app. A

6.3.2 **Measurement series performed using Cosmos soils**

The following measurements series have been performed on the Cosmos media.

<u>Measurements series 4 and 5 "The effect of aggregation"</u>

Measured at: UCD and AAU
Status: Packed 100 cm^3 soil samples
Drainage level: From water saturated to oven dry

Table 9 The physical properties of the samples and the drying method.

Sample ID	Bulk density ρ_b Mg/m^3	Porosity φ m^3 m^{-3}	Drainage level
Profile	0,65	0,74	Air + oven drying
Turface	0,62	0,75	Air + oven drying
Turface	0,63	0,75	Air + oven drying
Zeoponix	0,97	0,61	Air + oven drying
Pumice	0,36	0,63	Air + oven drying

No texture analysis has been made for the cosmos media. For information on the packing method, phase distribution determination, drying and wetting method and the texture analysis see app. A.

7 Preliminary experiments and analyses

In this project the diffusion coefficient has been measured on samples, that initially has been water saturated after which they have been dried stepwise between measurements (cf. Drying methods app. A). Two different drying methods have been used. Air/oven drying and drainage on a retention box (see app. A). Air/oven drying is a relative fast way of drying the samples whereas using the retensionbox one should calculate with about two weeks depending on the texture of the soil sample and the drainage level. On the other hand it is necessary to have a retention curve when using air/oven drying if the drainage level of the sample is requested. As the diffusion coefficient, of different soil samples that has been dried using the two different methods, has been compared two each other is it important to check if the water is distributed equally in the soil sample. As if not this would result in different diffusion coefficients due to different water distribution and water bridges and not the parameters that are studied. The diffusion coefficients have therefore been measured on the five aggregated media that has been dried using the two different drying methods. The diffusion coefficients have been compared at drainage level of pF 2 and pF 2,9. As for the samples that has been air dried, the samples has been dried to a given air content corresponding to pF 2 and pF 2,9 according to the retentions curves (see app B.). In figure 34 and 35 can the result of this comparison be seen.

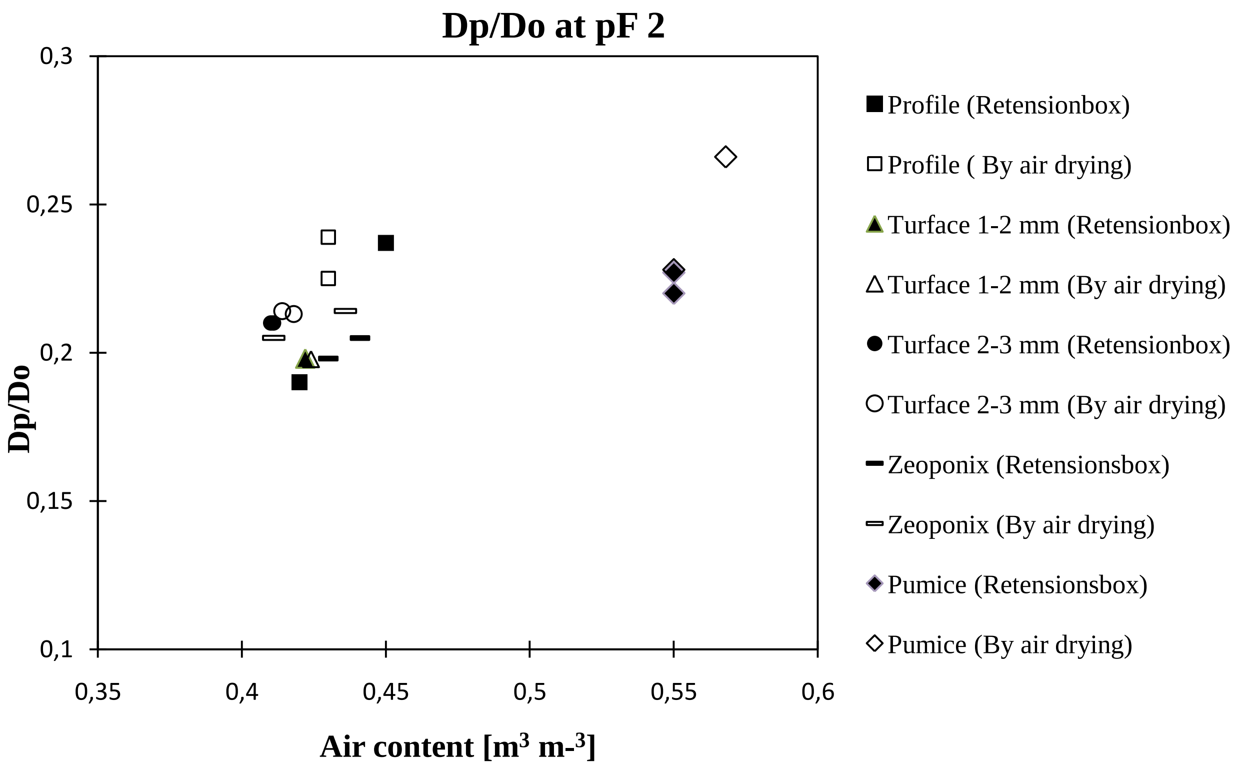


Figure 34 The result of the diffusion coefficient measured on the five aggregated media at a drainage level of pF 2 using two different drying methods.

Overall, it is seen on the figure that there is a good agreement between the diffusion coefficients for the five aggregated media at a drainage level of pF 2, when using the two different drying methods. At a closer look it is especially the case when looking at Turface (1-2mm), Turface (2-3 mm) and Pumice, the three media with the largest particle size. Whereas for Profile and Zeoponix the corresponding diffusion coefficient is a little further apart at the same air content using the two different drying methods. Furthermore is it seen that there is a general tendency for the diffusion coefficient of air dried soil to be higher than for media drained at the retensionbox. In the figure below can the comparison of Dp/Do at pF 2,9 be seen.

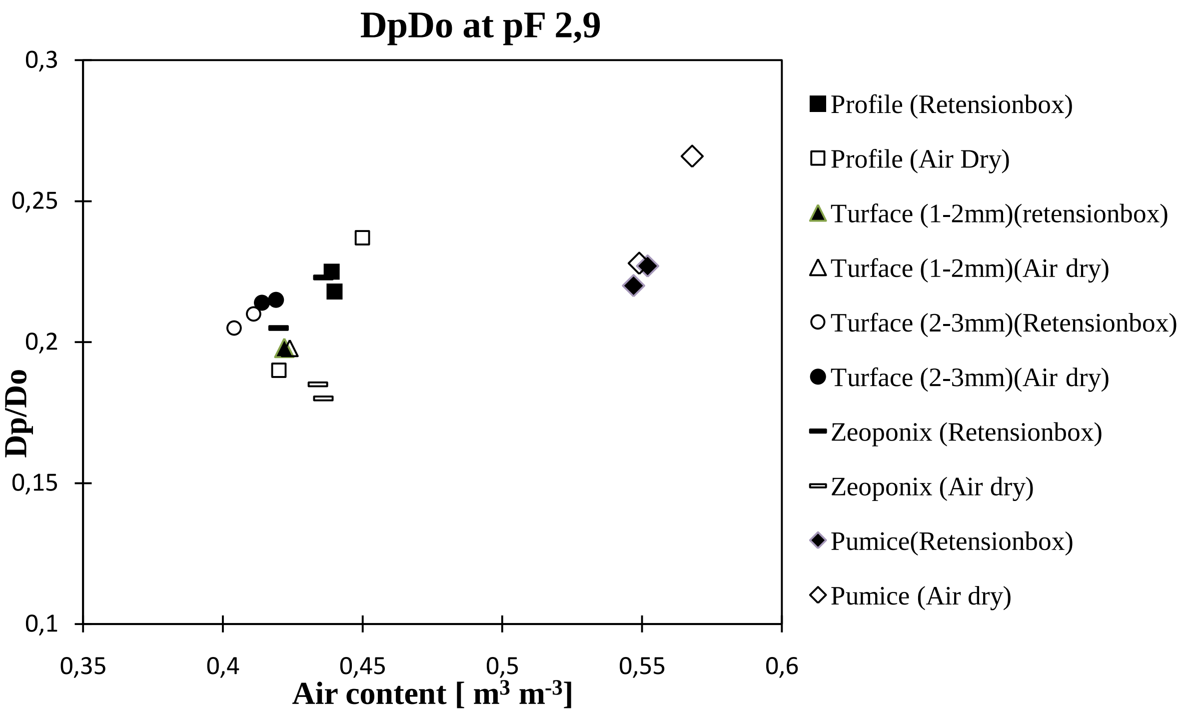


Figure 35 The result of the diffusion coefficient measured on the five aggregated media at a drainage level of pF 2, using two different drying methods.

Again it is seen on the figure that there is a good agreement between the diffusion coefficients for the five aggregated media at a drainage level of pF 2,9 when using the two different drying methods. Again it is also seen that for especially Turface (1-2mm), Turface (2-3mm) and Pumice the agreement is very good, At pF 2,9 it is seen that this is also the case for profile, a tendency that was not so clear at pF 2. For Zeoponix the diffusion coefficients still differs more at the same air content like at pF 2. For both pF 2 and pF 2,9 this tendency is hard to ascribe to the particle size as the water content in the macro pore also plays an important role for the result of Dp/Do. And at pF 2 and pF 2,9 it is only Profile and Zeoponix that is not completely drained in the macro pores (see e.g. inter-intra porosity in table 3 section 6.2). And as Profile is almost water drained in the macro pores at pF 2,9 opposite Zeoponix it is probably more likely to describe this tendency to the water drainage level in the macro pores more than the particle size. At figure 34 and 35 it is also seen that Profile, Turface (1-2mm), Turface (2-5mm), and Zeoponix seems to have some similar behaviour as the diffusion coefficients is lying in the same area at the same air content as well as the air content is also similar at the same drainage level.

7.1 Van Genuchten retention curves

In Measurement series 4 and 5, the diffusion coefficient has been measured for the five Cosmos media where air drying has been used. To be able to convert the air content to a given drainage level a retension curve for the each media is needed. Such one should be made for the specific bulk density at which the samples have been packed and measured at. Blonquist et al., (2006) has made this retension curve from measurements in the drainage levels between pF -2 to pF 7 and fitted those to the bimodal van Genuchten SWC model. As this was not possible with the equipment available at AAU the samples in measurements series 4 and 5 has therefore been packed at the same bulk density as in Blonquist et al., (2006) and the retention curve could therefore be used to convert the given air content to specific drainage level. To make sure that the retention curve was useful for the packed samples it was checked that the same water content was achieved at pF 2 and pF 2,9. The result can be seen in table 10 below.

Table 10 The water content according to Blonquist et al, 2006 and the measurement performed in this project at pF 2 and pF 2,9.

	Water content at pF 2 [m^3 m^{-3}]		**Water content at pF 2,9 [m^3 m^{-3}]**	
	Blomquist et al.	This project	Blomquist et al.	This project
Profile	0,32	0,32	0,31	0,31
Turface (1-2mm)	-	0,33	-	0,32
Turface (2-3mm)	0,34	0,33	0,33	0,32
Zeoponix	0,20	0,19	0,21	0,20
Pumice	0,42	0,29	0,15	0,1

As seen in table 10 there is a good agreement with the measured water content for the samples measured on in this project at pF 2 and pF 2,9 compared to the water content at pF 2 given be the retension curve made by Blomquist et al. This is with the exception of Pumice at pF 2. When placing the Pumice samples at the retension box the water content is below the 0,42 m^3 m^{-3} which it should be at pF 2 according to Blonquist et al., (2006) as it has not been possible to saturate the samples to that water content. The water content of 0,29 m^3 m^{-3} measured in this project should according to Blomquist et al. occur at pF 2,4 and the further loss of water seen for pumice during the time on the retention box at pF 2 could be due to evaporation during the 16 days the samples where in the retensionbox. Based on the results it is therefore decided to use the retension curve made by Blomquist et al. to convert the air content in measuring series 4 and 5. To see the retension curves and calculations see app. B

7.2 Determination of the micro and macro porosity for the Cosmos media.

The five Cosmos media has dual porosity, and when analysing the relationship between Dp/Do and ε is it important to know the right distribution between macro and micro porosity. According to Currie 1983, who said that the relationship between Dp/Do and ε could be seen as two phases, can this Dp/Do Vs ε plot be used to determine the distribution between inter and intra porosity. This is given as the air filled porosity at which a change in curve behaviour is seen (figure 36.1). Furthermore does the relationship between Dp/Do and ε follow a power law in the inter pores (cf. Section 4). This will result in a linear curve in a Log (Dp/Do) Vs Log (ε) plot. The measurements that does not follow the linear curve is measurements of Dp/Do in the intra pores and can therefore also be used to determine the distribution of inter and intra porosity (figure 36..2). The tortuosity factor, X can also be used to determine the distribution. In a ε Vs X plot will the lowest value of X be at the intersection between inter and intra porosity (figure 36.3) (Augustus, et al., 2008). Finally can the Van Genuchten retension curve also be used to determine the distribution of inter and intra porosity (figure 36.4). An illustration of the four plot and how the inter and intra porosity can be determined can be seen in figure 36 below.

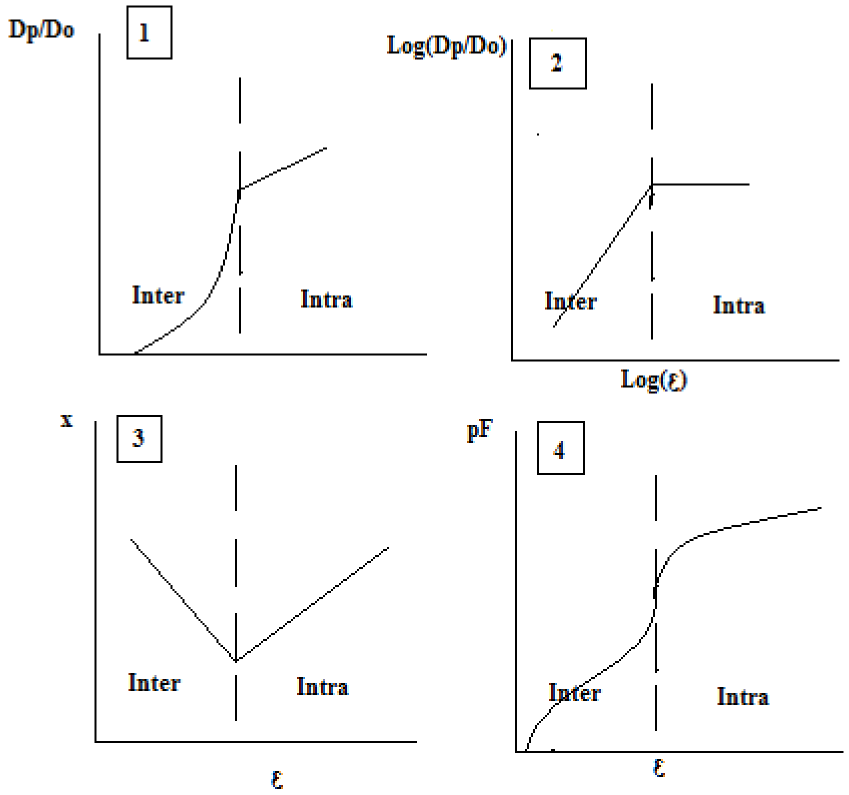


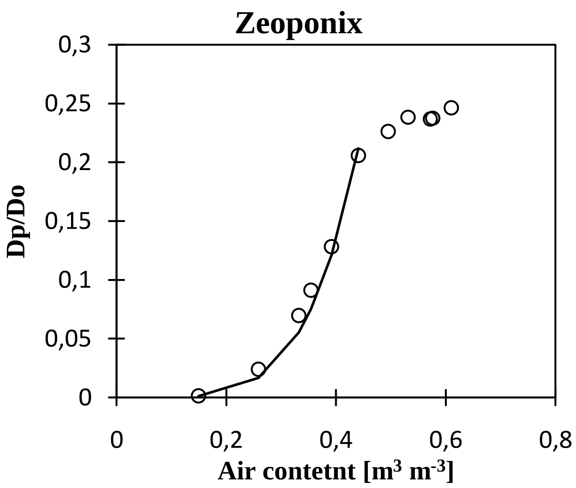
Figure 36 The four plots used for determining the distribution between inter and intra porosity

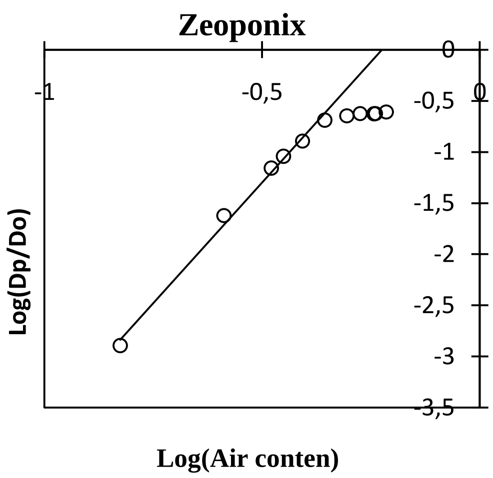
The distribution of the inter and intra porosity have been given by Blomquist et al., (2006) Together with those can the distribution found in this project based on the above plots be seen in table 11 below

Table 11 The distribution of the inter and intra porosity given by Blomquist et al. and given in this project based on the four plots. For Pumice and Zeoponix has the retention curve not been used.

	Inter porosity		Intra porosity	
	Blomquist et al.	This project	Blomquist et al.	This project
Profile	0,42	0,44	0,32	0,30
Turface (2-5mm)	0,42	0,42	0,33	0,33
Zeoponix	0,39	0,44	0,22	0,17
Pumice	0,36	0,45	0,47	0,38

As it is seen in table 11 is the distribution not completely in accordance with Blomquist et al. for the Pumice and Zeoponix. The two media have given some problems when packing the samples and during the measurements has some particles been lost, and as this can explain the higher inter porosity, it is decided to use the distribution of inter and intra porosity found in this project in the following analyses. The four plots for Zeoponix can be seen below, where the plots for the rest of the media can be seen in app B.





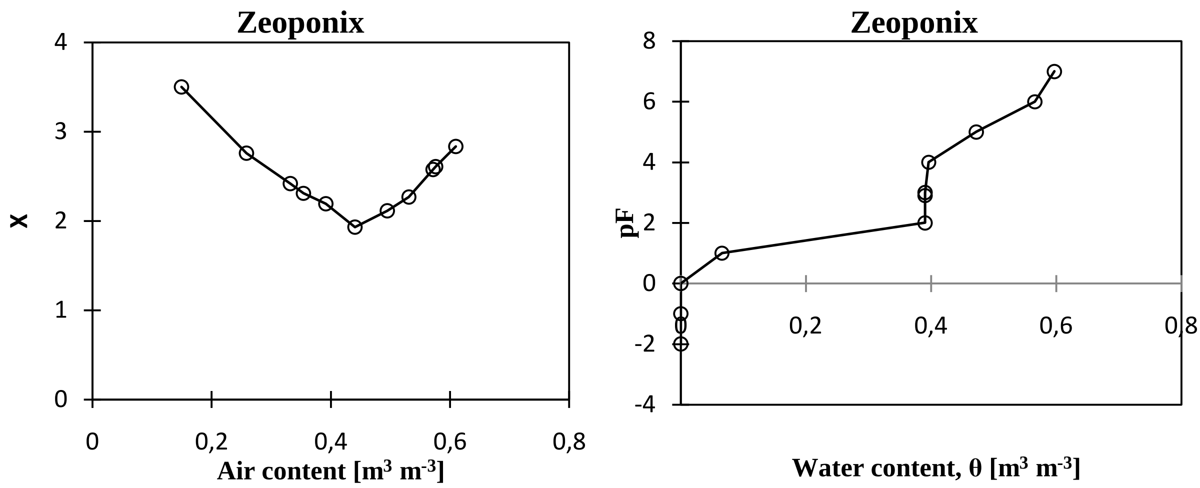


Figure 37 The four plot for Zeoponix, used to determine the distribution between inter and intra porosity,

For Zeoponix the Retensioncurve were not used neither is it for pumice as it considered that these curves is not completely in accordance with the packed samples.

8 Verification of the hypoteses

In the following, will the hypotheses set up in section 4 for the effect of texture, compaction and structure on Dp/Do, be evaluated, together with an evaluation of the validation limits of the WLR model regarding the three above mentioned parameters. Measurements that have been performed on sieved repacked soil samples in this project period have been used (Measurements series 1,2,4 and 5). Calculations of Dp/Do and experimental procedure see section 5 and app, A. Furthermore has measurements on repacked soil samples performed in other projects has also been used.

8.1 The effect of texture

Repacked soil samples containing a sandy soil from Hokkaido in Japan (Hamamoto. S, 2009a), a loamy sand soil from Lerbjerg (Lerbjerg 1) and a sandy clay soil from Lerbjerg (Lerbjerg 5) in Denmark (Moldrup et al., 2000a) and a silty loam soil from Nærum in Denmark (Thorbjørn, A., 2008b) have been used to verify the hypothesis regarding the effect of the texture on Dp/Do. And to evaluate the validation limits of the WLR model. These are soils representing a coarse texture (Hokkaido sand), an intermediate texture (Lerbjerg 1 and 5) and a fine texture (Nærum silty loam) respectively. In figure 38 below can the Dp/Do Vs ε plot be seen for the four soils. As the Lerbjerg soils have only been measured on in a narrow interval of air filled porosity has both of them been used. All soils have a porosity of 0,47 - 0,49 m^3 m^{-3} but measurements of Dp/Do in a completely dry situation is only performed for the Hokkaido sand and Nærum silty loam. The data points are combined by dotted lines in the figure. These lines do not represent a relationship but is only illustrative to better se the trend of the measurements. This is done throughout this section.

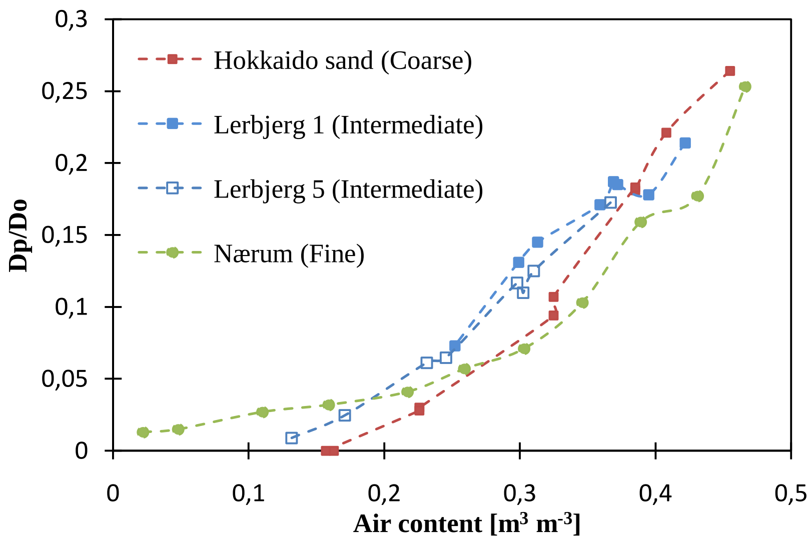


***Figure 38** The (Dp/Do, ε)-plot for the Hokkaido sand, the Lerbjerg sandy clay loam and Lerbjerg loamy sand and the Nærum silty loam. All soil samples has a porosity of 0,47 -0,49 m^3 m^{-3}.*

As it is seen on figure 38 is the hypothesis of the Dp/Do and ε relationship in good accordance with the measured relationship of Dp/Do and ε for the three textures. Especially in the wet area of the curve is the hypothesis in very good accordance with the measurements, where it was assumed that water blockage would have a greater influence on the coarse texture than on the fine texture due to the difference in surface area (cf. Section 2.3). Whereas in the dry area is the difference in Dp/Do not as great as what was expected, due to the difference in tortuosity for the three textures. It has for the intermediate texture not been possible to see where the Dp/Do values is in the dry area as no data have been accessible from the databases with a porosity of 0,47. But from the curve behaviour it seems like it will be in the area as for the fine and coarse texture.

Weather the WLR model fits Dp/Do Vs ε plot for the different textures and if it has limitations regarding textures can be seen in figure 39 below. Here are the measurements of the four soils plotted together with the WLR model.

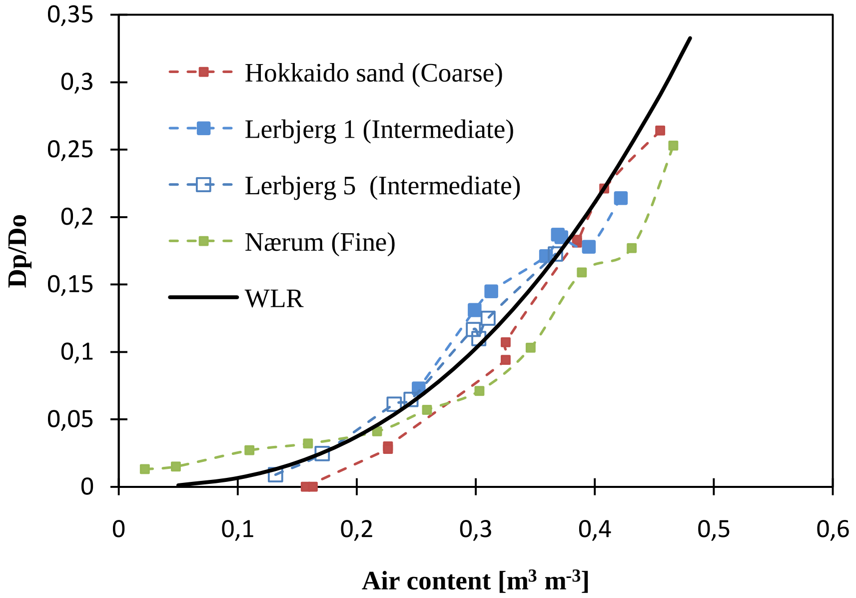


Figure 39 Dp/Do Vs ε plot for the four different textures together with the WLR model.

As seen on the figure is the WLR model in accordance with the Lerbjerg soils - the intermediate texture. This was also expected according to the hypothesis. However in the dry area is it difficult to see if the Lerbjerg soils fit the WLR model as no measurement is performed. It does however look like that the Lerbjerg soil does not fit the WLR model as the measurements in the dry area seems to be laying between the Nærum and Hokkaido measurements. In the wet area the WLR model fit the intermediate texture and also the hypothesis for the three textures in general – under prediction of the fine texture and over predicts the Dp/Do for the coarse texture. Due to the lack of measurements in the dry area, it cannot be evaluated, if the WLR model fits the intermediate texture. It is however seen that for the coarse texture and the fine texture is it only the fine texture that matches the hypothesis whereas for the coarse texture where it was expected to have Dp/D0 values above the WLR model in the dry area, is this not the case for the Hokkaido sand. The WLR model was therefore tested on Dp/Do measurements for another coarse textured soil made by Currie, (1961). This can be seen in figure 40 below.

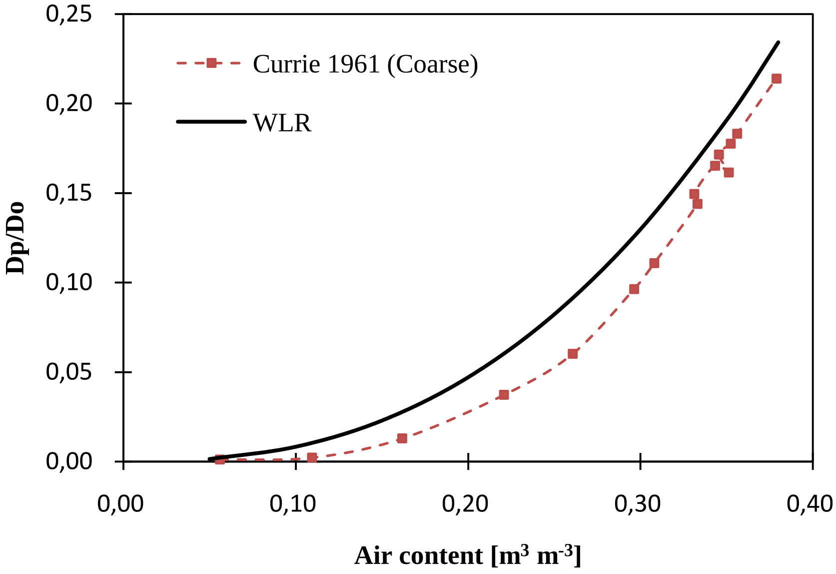


Figure 40 The WLR model plotted against Dp/Do, ε measurements for a coarse textured soil made by Currie 1961. The porosity of the samples are 0,38.

As seen on the figure the WLR model also over predicts the Dp/Do value for coarse textured soil samples measured by Currie 1961 in the dry soil, thereby indicating a too high T factor in the WLR model in general. It is again is seen that it over predicts the Dp/Do values in the wet area which was also expected due to the higher effect of the water blockage. The two course textured soil (Hokkaido sand and Currie, 1961) is packed differently and it is seen that the difference between the measured Dp/Do and the Dp/Do value according to the WLR model is different for the two soil when they are completely dry. This could indicate that the compaction therefore has an influence. This will be accounted for in the next section.

Summary

- In the wet soil are the hypothesis and the measurements of Dp/Do in accordance with the hypothesis meaning that the Water blockage has a higher effect on the coarse textures than on fine textures as expected.

- In the dry soil is the hypothesis regarding coarse texture, lower tortuosity and thereby higher Dp/Do not completely in accordance with the measurements. A parameter that could have an influence on difference in hypothesis and the measurements could be compaction as this can have an influence on the particle alignment and thereby the tortuosity. This will be evaluated in the following section
- The WLR model seems to fit the intermediate texture in the wet area as was also expected. But in the dry area is the model over predicting the Dp/Do for both

thecoarse, intermediate texture, which was not expected and for the fine texture which was expected.

8.2 The effect of compaction

Repacked soil samples containing a loamy sand soil from the Hjørring site and a loamy sand from the Lyøvej site has been packed at different bulk densities (measurement series 1 and 2). Measurements of the Dp/Do, ε relationship on these samples have been used to verify the hypothesis regarding the effect of the compaction on Dp/Do and evaluate the validation limits of the WLR model. On figure 41 is the Dp/Do Vs ε plot seen for the Lyøvej soil samples packed at three different bulk densities – 1,52, 1,65 and 1,72 Mg m^{-3}. In the figure is only shown one of the three measurements performed for each bulk density, as the measurements gave similar results (se enclosure 1) For the sample packed at a bulk density of 1,72 Mg m^{-3} has only one measurement round been performed.

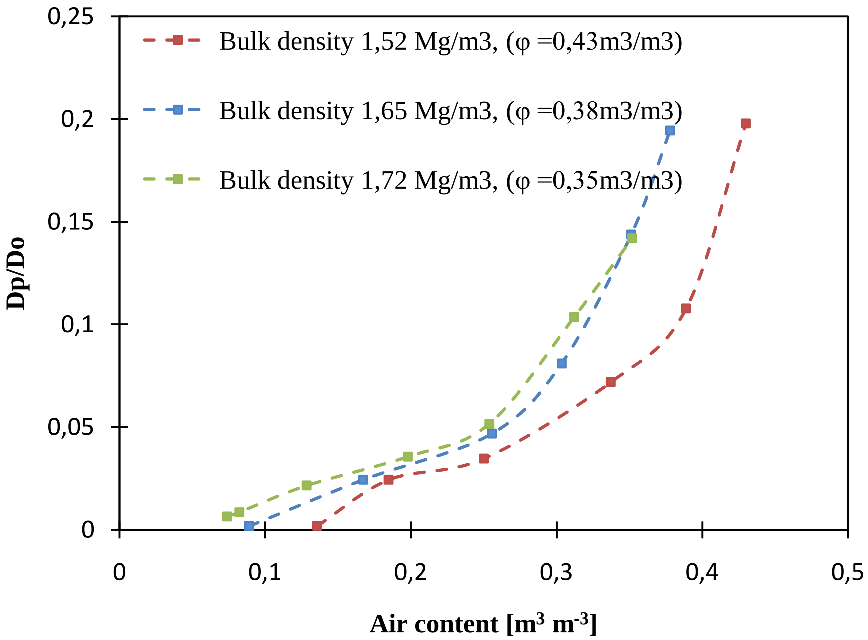


Figure 41 (Dp/Do, ε)-plot for the Lyøvej soil samples packed at three different bulk densities – 1,52, 1,65 and 1,72 Mg m-^{3}

As seen on figure 41 it is the high compaction at 1,72 Mg m^{-3} and 1 ,62 Mg m^{-3} that results in the highest Dp/Do values at the same air content in the dry and wet area of the curve, and the smallest Dp/Do values is for the bulk density at 1,52 Mg m^{-3}. These measurements is in accordance with the hypothesis as it was predicted that the low compacted soil would have a higher porosity and thereby have a higher content of water that can result in water blockage according to Papendick and Runkles, 1965 . This difference in Dp/Do is also seen in the dry area where the explanation could be a more optimal and straight alignment of particles for high compaction than for low compaction also suggested by Hamamoto, S., et al., 2009b. This of course depending on the soil texture. This means that the diffusion path is more unhindered in high compacted soil than low compacted soil

. In general is it seen that there is not such a big difference in the Dp/Do values for the bulk densities at 1,72 Mg m^{-3} and 1 ,62 Mg m^{-3}, compared to the difference in Dp/Do values of low compaction of 1,52 Mg m^{-3} which could indicate some kind of threshold in compaction degree at which the compaction has an influence on the Dp/Do.

In figure 42 is the Dp/Do Vs ε plot seen for the Hjørring soil samples packed also at three different bulk densities – 1,52, 1,65 and 1,72 Mg m^{-3}. In the figure is only shown one of the three measurements, as the measurements gave similar results (se app) The two first measurements for the sample with a bulk density of 1,52 Mg m^{-3} are considered as unlikely as it seems unlikely that the Dp/Do will fall with increasing air content and then increase again. These measurements are therefore not included in the analysis. The measurements has been performed by Chamindu, K., 2009

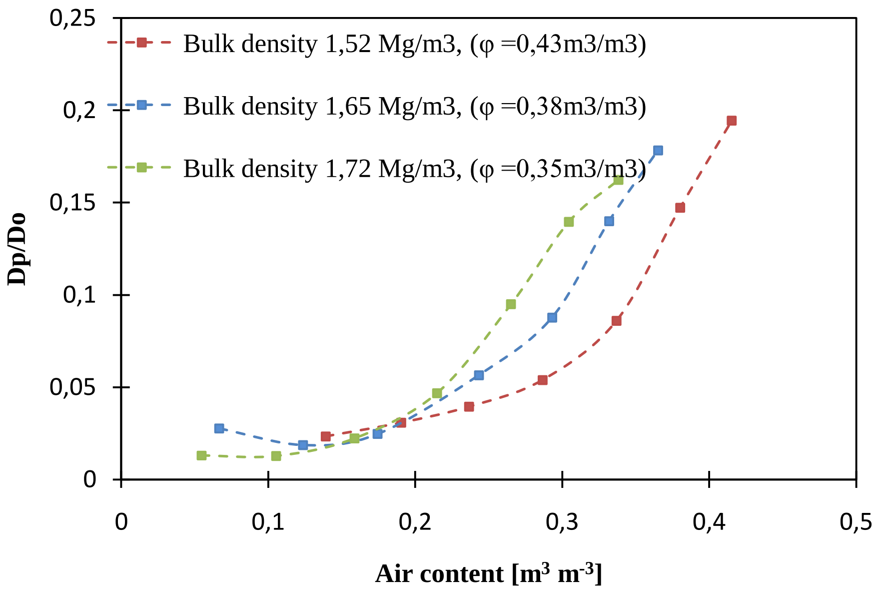


Figure 42 shows the (Dp/Do, ε)-plot for the Hjørring soil samples packed at three different bulk densities – 1,52, 1,65 and 1,72 Mg m^{-3}(Chamindu, K., 2009)

As seen on figure 42 is it the same tendency as was seen for the Dp/Do Vs ε plot for the Lyøvej soil at the three bulk densities – the higher compaction the higher Dp/Do values at the same air filled porosity. Measurements in the wet area are for these measuring series uncertain and it is therefore difficult to evaluate anything based on these regarding the hypothesis. Contrary to this is seen that for the two highest compactions is the difference in DP/Do greater in the more dry area of the curve than what was seen for the Lyøvej measurements. This does not support the suggestion of a threshold in compaction. But at the same time are the soils not completely similar in texture and as three measurements showed this tendency for the Lyøvej soil samples could this therefore still support the theory so it is considered that further measurements must be performed for being able to support or dismiss this suggestion.

For both soils it seems like when 80 % of the water is drained for all three compactions will the soil samples have the same effective diffusion (slope of the curve). For the Low compaction is this percentage a little higher and for the high compacted is it a little lower which it also reasonable as the low compacted soil is more tortuous than the high compacted soil samples. This tendency is also seen for the Hjørring soil. Again this indicates some kind of threshold, this time regarding relative water content and preferential channelling for the diffusion.

In figure 43 below is seen the Dp/Do Vs ε plot for the Lyøvej at the three different compactions. In the plots are also the shown the WLR model as it would predict the Dp/Do, ε relationship for the three different compactions. In the figure is only shown one of the three measurements, as the measurements gave similar results (se app) For the sample packed at a bulk density of 1,72 Mg m^{-3} has only one measurement round been performed.

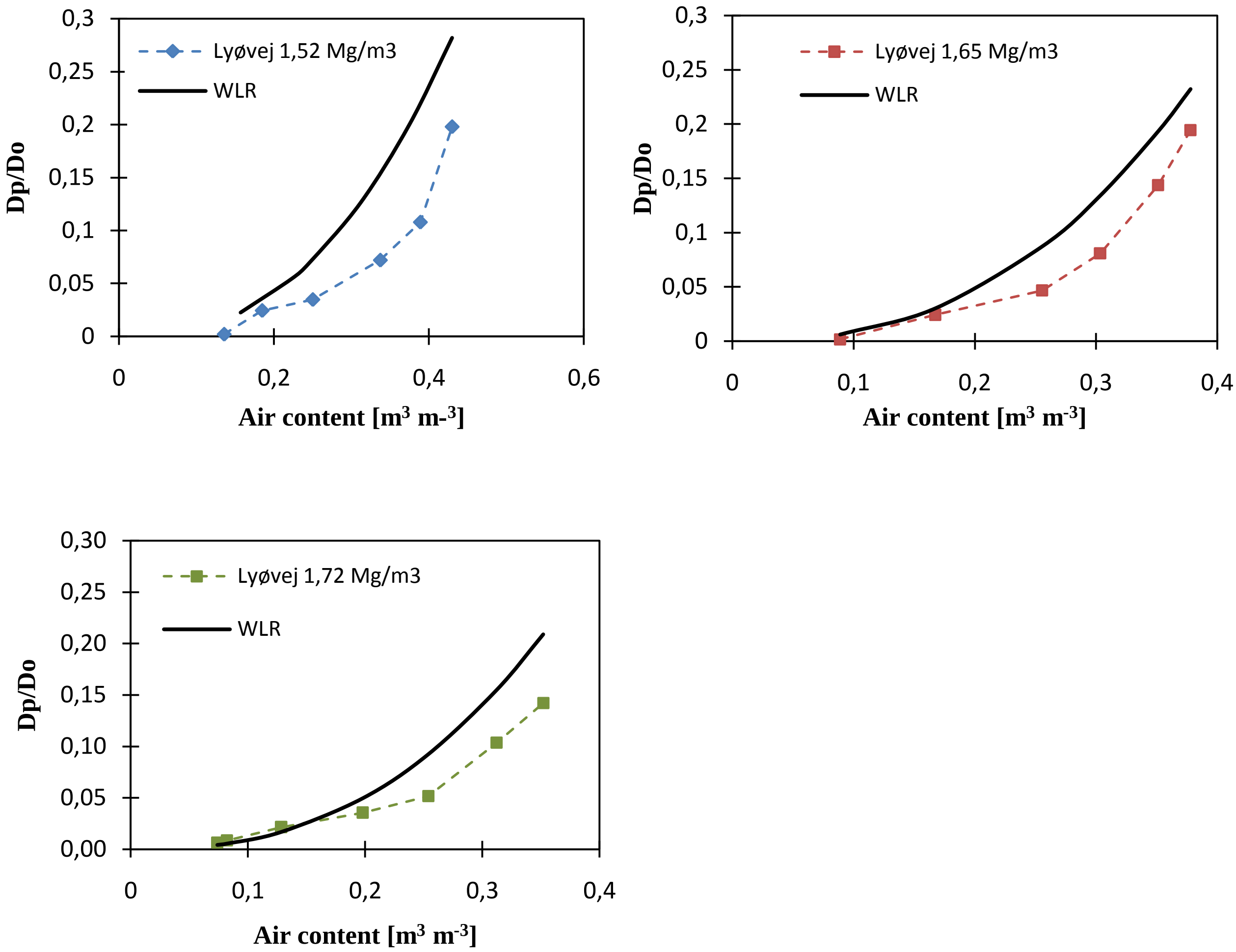


Figure 43 shows the WLR model plotted against the measurements of the three different compacted Lyøvej soil samples

In figure 43 it is seen that the WLR model seems to fit the measurements of the soil samples, having the two highest compaction, best. This is also seen for the Hjørring soil measurements (see CD-rom ”Measurements series 2”). As there are many parameters that have an influence on the measurement due to compaction of different textures such as porosity, pore connectivity, tortuosity and alignment of particles, was it difficult to set up a hypothesis. But according to the prediction based on the WLR model should the WLR model fit measurements performed on intermediate soil at both high and low compaction. And for fine texture the low compaction and coarse texture the high compaction. As the Lyøvej soil has an intermediate texture should it fit all compaction, but it seems like the compaction of the soil effects especially the tortuosity as it is in the dry area the WLR model differs the most from the measurements, which is most clearly seen for the low compaction and high compaction. Based on the entire curve is it the sample packed at 1,65 Mg m^{-3} that fits the WLR model best. This is also the result for the Hjørring samples (See CD-rom "measurement series 2".). It is however seen that for all plots is the WLR model over predicting, but it is considered to okay to use the WLR model as the difference is not so high. It is however considered that more measurements should be performed regarding the effect of compaction combined with different textures.

Summary

- Dp/Do values at the same air filled porosity is highest for the high compacted soil due to higher water induced disconnectivity in the wet area for low compacted soil and due to the higher solid induced tortuosity in the dry area for low compacted soil.
- In the study of the effect of texture it was seen that fine textured soil resulted in smaller pores that again would result in high solid induced tortuosity. This means that the high compacted soil which is also expected to have more small pores should also have higher disconnectivity due to the content of small pores as an effect of compaction. This is not the case and it is assumed to be because of the more straight alignment of the particles that results in a not so high tortuosity.
- The above results are for a fine/intermediate texture and compaction experiments have not been performed for coarse texture and completely fine textured soil. However it is seen that compaction has a result on the pore space and thereby the parameters effecting the diffusion such as the water blockage, pore disconnectivity, tortuosity and particle alignment. Where it for these results for an intermediate soil is seen to especially have an effect on the diffusion in the dry area and thereby the solid induced tortuosity.
- Regarding the WLR model it is the samples packed at a bulk density of 1,65 Mg m^{-3} that fits the best. Furthermore it is seen that the WLR model over predicts the Dp/Do values for all compactions.

8.3 The effect of structure - aggregation

Packed samples using the five aggregated Cosmos media has been used to evaluate the effect of aggregation on the Dp/Do values and the validation limits of the WLR model. In figure 44 below is shown the Dp/Do Vs ε plot for the four aggregated media, Profile, Zeoponix, Turface (2-5 mm) and Pumice (measurements series 4 and 5). Turface (1-2 mm) is not shown as it has shown the same curve trend as Turface (2-5 mm). The macro porosity for Profile is 0,44 m^3 m^{-3} and Turface (1-2 mm) is 0,42 m^3 m^{-3}, for Zeoponix is it 0,44 m^3 m^{-3} and for Pumice is it 0,45 m^3 m^{-3} (see section 7.2).

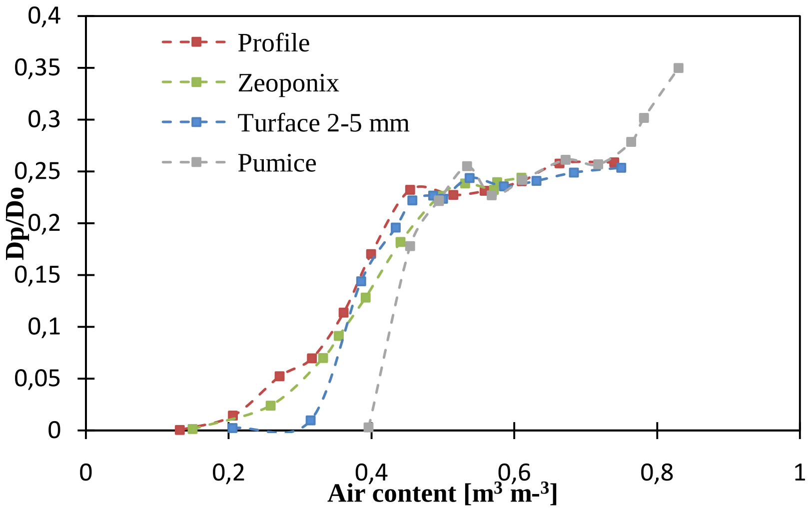


***Figure 44** The (Dp/Do, ε)-plot for the aggregated media Profile, Zeoponix, Turface (2-5mm) and Pumice. The macro porosity for Profile is 0,44 m^3 m^{-3} Turface (1-2 mm) is 0,42 m^3 m^{-3}, for Zeoponix is it 0,44 m^3 m^{-3} and for Pumice is it 0,45 m^3 m^{-3}*

As seen in figure 43 the hypothesis based on Currie (1983) is in accordance with the measurements. The relationship between Dp/Do and ε is in two parts, corresponding to inter and intra porosity. The Dp/Do Vs ε plot in the wet inter pore space is, as expected, like as for single grained particles, effected by the water induced disconnectivity and water blockage. An effect that is more dominant for the large aggregates than the small aggregates. But where it for the single grained particles was because of difference in surface area is this higher effect of water blockage for the larger aggregates due to less pore channels that should be locked by water and thereby hinder the diffusion. This is illustrated in the figure below.

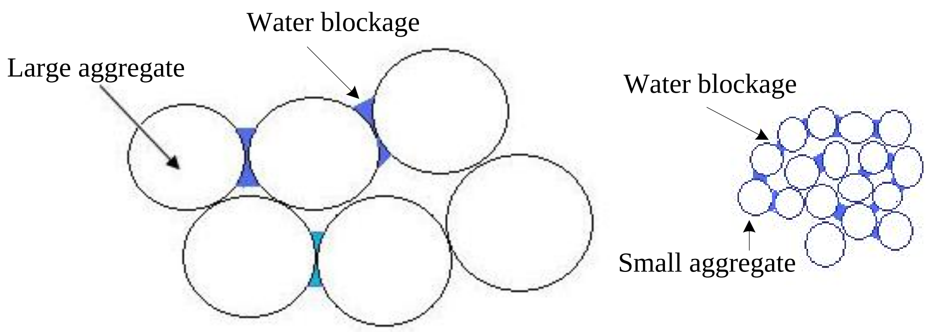


***Figure 45** The amount of pore channels that has to be locked by water, where it is seen that there are several more channels in the small aggregated soil (right), and more water is therefore needed to water loch all channels and hinder the diffusion*

In general this effect is very dominant while the inter pores are still occupying water, and the air content is rather high before an opening in pore space channel occurs - especially for the Turface and the Pumice media.

Looking at the (Dp/Do, ε)-plot for the intra pore space is the curve in accordance with hypothesis 1 for intra pore diffusivity - a linear curve where the effective diffusion is little and does not contribute much to the total Dp/Do (section 4.3). Furthermore this, indicates that the pores are very homogeneous. This is with exception of Pumice. However the curve is linear and equal to the curve for the other aggregates (1) in the first part. But after a certain amount of pores has been drained the effective diffusion is very high and the slope of the curve is very high compared to the slope of the first part of the curve. This could indicate that the large intra pores are not well connected and at the same time tortuous. But as the smaller pores that combine the large pores is drained are the intra porosity contributing to the total Dp/Do in a great extent. This theory is illustrated in the figure below.

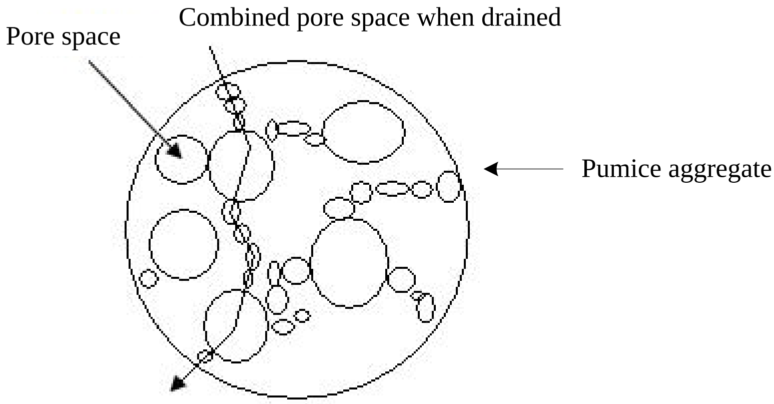


Figure 46 The inhomogeneous pore size distribution that result in Dp/Do, ε plot for the Pumice intra pore space.

The four media in the above figure 46, differs in chemical composition, and physical parameters such as bulk density, surface area etc. To get a more precise picture of the influence of the effect of aggregate size the Dp/Do, ε relationship for the three similar media, Profile, Turface (1-2mm) and Turface (2-5mm) are therefore plotted in the figure below. The samples are packed at the same bulk density and they have the same porosity and as the distribution between inter and intra porosity is the same is this therefore also similar (see section 6.2). The effect of aggregate size can thereby be evaluated. The Dp/Do Vs ε plot of the three medias can be seen in figure 47below.

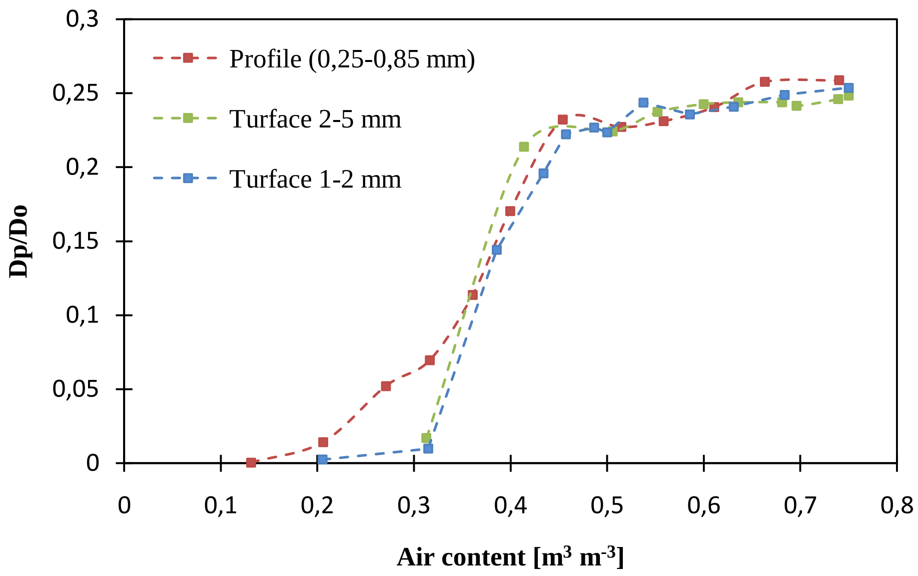


Figure 47 the Dp/Do Vs ε plot for the aggregated media Profile, Turface (1-2mm) and Turface (2-5mm).

Again it is seen that the hypothesis based on Currie (1983) is in accordance with the measurements. The relationship between Dp/Do and ε is in two parts, corresponding to inter and intra porosity. The Dp/Do ε plot in the wet outer space is, as expected, like as for single grained particles, effected by the water induced disconnectivity and the water blockage where it is for large aggregates that the largest effect is seen.

The intra porosity seems to be similar and for all three media does the curve follow each other and the total Dp/Do results in the same. For these three aggregated media it is only if the outer space is occupied by water that the Dp/Do differs from each other and thereby seen as an effect of aggregate size. But depending on the compaction of the aggregates and the structure can the Dp/Do, ε relationship differ as e.g. is seen for the Pumice inner space.

Whether the WLR model can predict the Dp/Do in aggregated soil or it has limitation regarding this can be seen in figure 48 where both total porosity and macro porosity has been used. Only Profile and Turface (2-5 mm) have been used for this purpose. They are chosen as they represent a small aggregated soil and large aggregated soil and as there are measurements when both inter and intra pores are occupied with water.

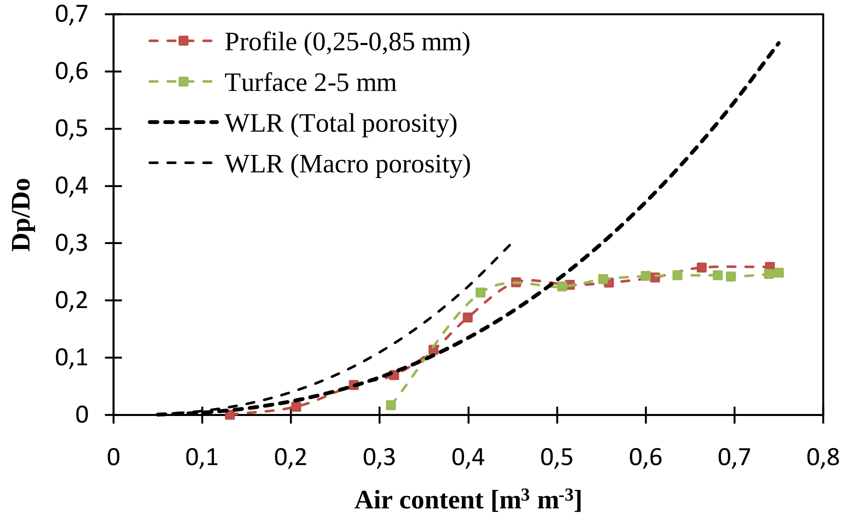


Figure 48 (Dp/Do,ε)-plot for Profile and Turface (2-5 mm) and the WLR model where macro porosity and total porosity has been used.

As seen in figure 48 is neither of the two WLR model using ϕ_T or $\phi_{macro\ pores}$ in accordance with the measured data. In the part of the curve that show the relationship of Dp/Do and ε in the outer pores are the WLR model using macro porosity over predicting and the WLR model using total porosity is under predicting – however not in such great extend. On the other hand it is over predicting the total Dp/Do in a great extent. Depending on the intra pore network and the hydraulic conditions (pF) at a given site will it therefore be okay to use the WLR model with macro porosity to predict the diffusivity. If the WLR model should fit perfectly in the outer space, as it is assumed that the intra pores will not be drained at "normal" hydraulic site conditions, could the parameters T and C be changed. In figure 49 below has T been changed to 1,9.

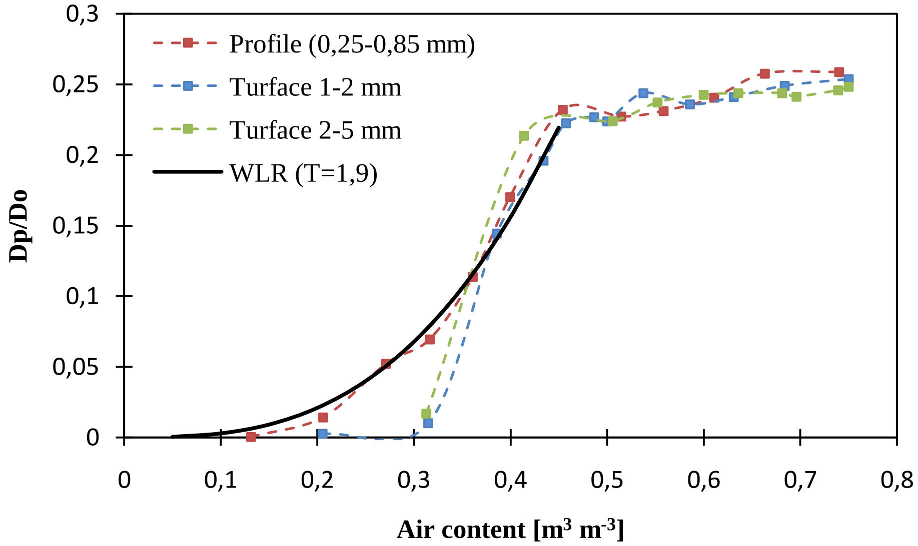


Figure 49 The (Dp/Do,ε)-plot for Profile, Turface (1-2 mm) and Turface (2-5 mm) and the WLR model where macro porosity is used and the tortuosity factor is 1,9 instead of 1,5

As seen on figure 49 will the WLR model using macro porosity and T equal to 1,9 fit the measurements very good. But as the Dp/Do Vs ε plot is very depended on aggregate size, inter and intra pore network and the degree of aggregation it is not assumed as a good solution to change the parameters T and C, as no uniform model for aggregated soil will fit all situations and many preliminary examination of the soil site must be done before having a well argument for suggestion for the T and C parameters. It is therefore evaluated that the WLR model using the macro porosity will work fine regarding risk assessment for aggregated soil – maybe using a little higher porosity than the macro porosity to be on the safe site.

Summary

- The Dp/Do, ε relationship is expressed by to different curve behaviour. One for the inter pores that follows the curve behaviour for one region soils and a curve behaviour for the intra pores according to Currie (1983).

- Having different aggregate size, the effect is seen most clearly in the Dp/Do, ε relationship for the inter pore space as this can result in high water blockage in the inter pore space.

8.4 The effect of structure - fractures

In figure 50 is shown (Dp/Do, ε)-plot for the fractured soil from the Nærum site and the Gug site (Thorbjørn, 2008b). The soil from Nærum is a fine texture soil and the soil from Gug is limestone with a very fine micro pore structure.

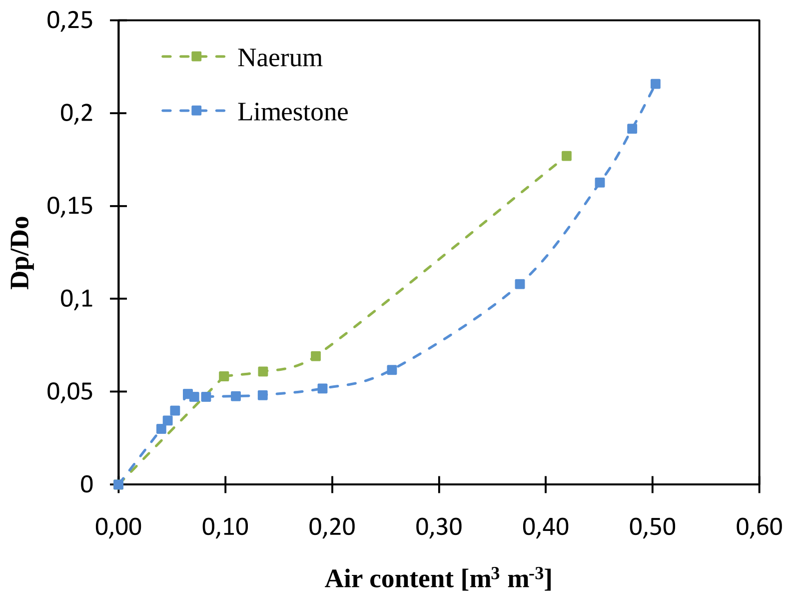


Figure 50 The (Dp/Do,ε)-plot the fractured Nærum soil and the fractured Gug limestone

It is seen in figure 50 that the measurements is in good accordance with the hypothesis for fractured soil. In the beginning of the plot where the soil samples are wet is there a high gradient in Dp/Do because the fractures is drained quickly and as this pore space is well connected and almost straight tubes will the diffusion be optimal in these fractures. As the surrounding pore space is started draining in this case around 0,1 m^3 m^{-3} is it seen that it follows a curve for a soil that is un-fractured as this pore space is tortuous and disconnected in higher or less degree. As it is seen it is not having a so large influence on Dp/Do values compared to an un-fractured soil sample. But at sites where the soil is highly fractured this will a significant effect on the total diffusion in the soil. Whether the WLR model can predict the Dp/Do in fractured soil or it has limitation regarding this can be seen in figure 51.

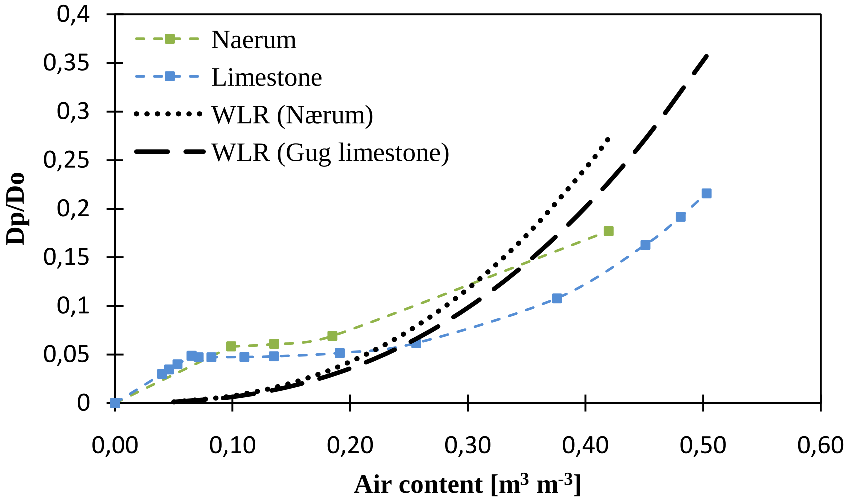


Figure 51 The (Dp/Do,ε)-plot the fractured Nærum soil and the fractured Gug limestone and the Corresponding WLR curves.

As seen on figure 51 is the WLR model for both the Nærum soil and the Gug limestone under predicting the Dp/Do in the first part of the curve whereas it in the last part of the curve is over predicting the Dp/Do. This over-prediction in the last part of the curve cannot be ascribed to the fractures but probably more to the fine texture that the WLR model in general cannot predict. But in the part of the curve – the wet area is it seen that the fractures as expected results in high Dp/do due to the relative straight well-connected pore space – the fractures. Depending on the degree of fractures can cause some underestimates of the diffusion in the wet soil. An idea could therefore be, to adjust the curve as seen on figure 52 below.

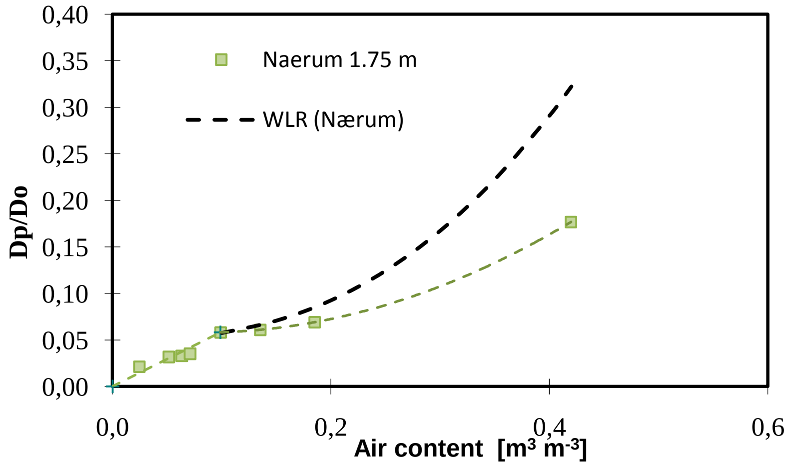


Figure 52 The WLR curve is adjusted to fit a cracked soil where the first part of the curve is linear

What is done is that depending on the degree of fraction, will the curve for the first part of the air filled porosity follow a straight line as suggested by Penman, 1940 where Dp/Do = h·ε. Depending on the soil type, compaction and maybe aggregation will the following curve after the fractured part has been drained follow a normal WLR curve. In this figure it is seen that the WLR model does not fit the measurements which is probably because of greater tortuosity that will have to be adjusted further to fit exactly these measurements due to the fine texture.

Summary

- Having fractured soil the Dp/Do values in the wet area of the Dp/Do Vs ε plot will be high due to the well connected pore space that is occupied with air and low tortuosity due to the fractures.

- The WLR model will not could predict the Dp/Do values in fractured soils and an additional term must be added to the WLR model as seen in the figure above.

8.5 T-C analysis

Another way to compare the different effects of texture and compaction is on the basis of the WLR model to see the difference in Tortuosity, T and pore connectivity, C. A so-called T-C-analysis. This is firstly done for texture study where the result can be seen in table 12 and following for the compaction study where the result can be seen in table 13 an 14. The result of T is based on Log(Dp/Do)/Log(ε) = T for a measurement on a completely dry soil. The result of C is based on solver where all measurements have been attaching importance to equally.

Table 12 the tortuosity parameter, T and the pore connectivity parameter, C as a function of texture. The Dune sand is measured by Yoshikawa, 2009

Texture	**Air content $m^3\ m^{-3}$**	**Tortuosity, T**	**Pore Connectivity, C**
Hokkaido (Coarse sand)	0,47	1,7	1,7
Nærum (fine sand)	0,47	1,8	0,9
Dune (Coarse sand	0,44	1,6	1,3
Currie 1961 (Coarse sand)	0,38	1,6	1,5

As seen in table 12 is the tortuosity factor highest for the fine textured soil where it for the coarse textured soil is lowest. However the difference is not so great and neither if compared to the 1,5 which is the T factor in WLR model. Regarding the pore connectivity factor, C is there also a difference between the coarse and fine textured soil. For the fine texture is it lower than for the coarse texture. Compared to value of 1 which is the C factor in the WLR model is it not so different for the fine texture but for the coarse texture is it somewhat higher. In the table is furthermore seen two other coarse textured soils, the Dune sand and the Currie 1961 sand, it is also here seen that the T factor is higher than the 1,5, thereby indicating a higher tortuosity which was not expected for the coarse sand. The C factor is higher than 1 which was expected. The T and C factors are not the same for the three coarse textured soils which could be due to the fact that the texture is not completely the same but as seen is the bulk density neither the same which can also be the reason. In table 13 and 14 below is the result for the T-C analysis shown for the compaction study.

Table 13 The tortuosity parameter, T and the pore connectivity parameter, C as a function of compaction (bulk density) for the Lyøvej samples. Three measurements have been performed for each bulk density and the deviation is listed on the right of the result for T and C. Only one measurement has been performed for the bulk density of 1,72 Mg/m^{3}and (-)refers to no deviation

Bulk density Mg m^{-3}	**Air content m^3 m^{-3}**	**Tortuosity, T**	**Pore connectivity, C**
1,52	0,42	1,95 (±0,05)	1,35(±0,35)
1,65	0,38	1,75 (±0,05)	1,30(±0,2)
1,72	0,35	1,85(-)	0,7(-)

Table 14 The tortuosity parameter, T and the pore connectivity parameter, C as a function of compaction (bulk density) for the Hjørring samples. Three measurement has been performed for each bulk density and the deviation is listed on the right of the result for T and C.

Bulk density Mg m^{-3}	**Air content m^3 m^{-3}**	**Tortuosity, T**	**Pore connectivity, C**
1,52	0,42	1,85(±0,01)	1,1(±0,2)
1,65	0,38	1,70(±0,01)	0,95(±0,25)
1,72	0,35	1,68(±0,01)	0,65(±0,05)

As seen in table 13 and 14 is the tortuosity factor highest for the samples with a bulk density of 1,52 Mg m^{-3} and lowest for the sample with a bulk density of 1,72 Mg m^{-3}. This is with the exception of the Lyøvej samples. But for the compaction of 1,72 Mg m^{-3} is only on measurement performed, and the tendency that is seen for the Hjørring samples is therefore considered correct as three measurements has been performed. This tendency can also explain the difference between the two coarse textured soils (Hokkaido and Currie, 1961) where the T factor is lower for the Currie 1961 measurement that also has a higher bulk density. It is furthermore seen that the T factor is the same for the Hjørring and Lyøvej samples except for the bulk density at 1,72 Mg m^{-3}. Looking at the C factor is the same tendency seen for both the Lyøvej samples and the Hjørring samples, where the samples with the lowest bulk density has the highest C factor and the samples with the highest bulk density has the lowest C factor. The values is however not the same when looking at the C factor, which can be due to texture which is not completely the same and thereby possible differences in surface area. If looked at the deviations for the T and C factor for each measurement is it seen that the deviation is not so high for the T factor but the deviation is on the other hand rather high for the C factor which could indicate the water distributes very differently and thereby might is a factor that is difficult to predict in general. The T factors are al greater than the 1,5 which is the T factor in the WLR model indicating that the T factor in the WLR model is to high in general. It is also seen that the C factor is either higher or lower than 1 which is the C factor in the WLR model.

9 The combined effect of texture, compaction and structure

The effect of texture compaction and structure has in the previous section been examined for samples that have been packed and where it is assumed that only one of the parameters has an effect on the diffusion in each sample. In the field the parameters are often varying simultaneously, for which reason the combined effect of texture, compaction and structure has been examined by a study on 15 intact soil samples from the Lyøvej site. The samples have been collected by Rambøll using a GeoProbe® that collects samples in PE-tubes (d_i=50 mm) that subsequently is cut in minor parts of about 100 cm^3 (H5xB5,1 cm). The 15 intact soil samples is all from borehole B316 and can be seen on figure 53 below.

Figure 53 The Lyøvej intact soil samples. The samples has been placed after which depth they have been collected starting from the left.

A roughly texture analysis has been made based on sieving. The result can be seen in table 8 section 6.3.1. The texture analysis based on sieving in section 6.3.1 for the intact soil samples, is very roughly and it only separates the fraction in coarse, medium and fine sand and does not differentiate between silt and clay particles. This means e.g. that for the L3 loam sample and the L15 sandy sample that visually, clearly are not the same, but has the same amount of particles < 200 um, can the texture difference and difference in properties still be very great. For the L15 sample can this be fine sand particles and for the L3 can this be clay particles. A further screening of the samples where therefore made and the texture determination is therefore also based on visual appearance, feeling of the soil, visual sedimentation properties (hydrometer) and water retension properties.

Overall is it clearly to see that three different textures are represented by the 15 intact soil samples; Limestone, sandy texture and a loam texture. A more detailed determination will be made in the following where the samples can be seen as well. The samples will not be presented after which depth they have been collected but instead after textural groups. The limestone sample will be described first, than the loam soil samples and finally the sandy soil samples.

Limestone samples

Figure 54 The L4-L6 soil samples seen from the top and from the side. L4 (left) L5 (middle) L6 (right)

The limestone samples are represented by sample L4-L6 and the texture determination is only based on visual appearance. The samples are the only samples that are semi intact samples as they have been packed by pouring wet limestone into the samples. No visible fractures were seen in the samples, both when looked from the top of the sample and down through the sides of the sample. However when the samples are dry are some fractures appearing.

The loam soil samples

The loam soil samples is represented by sample L1-L3 (3,6-4,1 m b.g.s) and L10-L12 (13-13.4 m b.g.s). Sample L1-L3 will be described in the following and afterwards L10-L12.

The soil samples L-L3 is pictured on the figure below where they can be seen from the top as well as from the side. The soil samples are pictured under dry conditions.

Figure 55 The L1-L3 soil samples seen from the top and from the side . L1 (left) L2 (middle) L3 (right)

Sample L1-L3 is considered as being a **stony coarse loam soil**. This is based on sieving, visual appearance, visual sedimentation properties (hydrometer) and water retention properties. The soil samples had a high content of stones and it was also seen from the visual sedimentation (hydrometer) that it had a content of coarse fine particles < 200 µm which can be seen in figure 56 below.

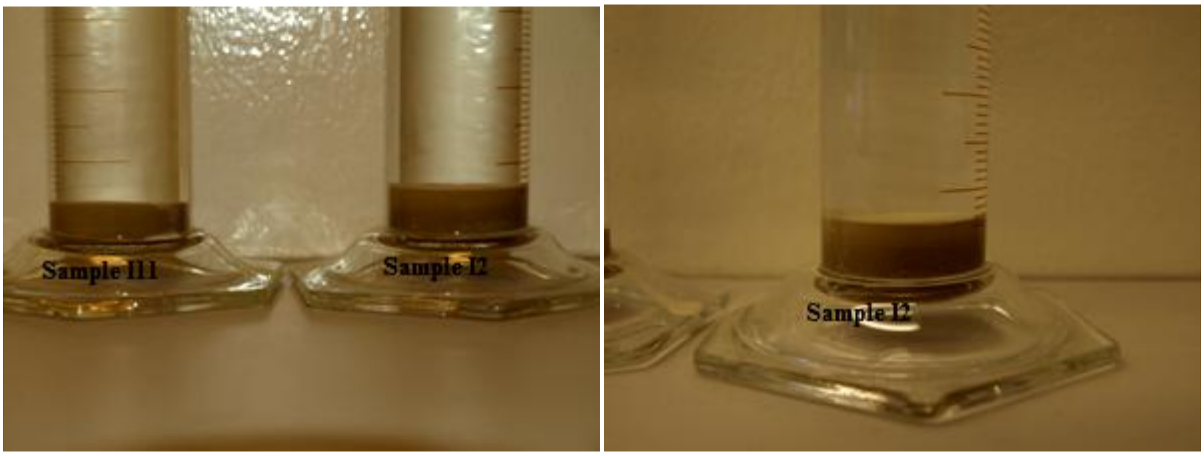


Figure 56 the visual sedimentation experiment, where it is seen that there is a content of coarse fine particles in the fraction of the sample that is < 200 µm (right). It is clearly seen that there are two different layers with different particle size. The left picture compares the texture with a texture consisting of only fine particles (sample I11, fine loam).

The soil in the hydrometer is a part of the soil content from sample I2 where the particles is < 200 µm. And it is seen that there is two layers of particles where the bottom layer has more coarse fine particles. The I2 sample is compared to the I11 sample that only has fine particles. Furthermore was it seen that the samples had a high water content at pF 2 and pF 2,7 which also support the texture determination as being loamy. As seen on figure 55 some cracks are occurring on the side of the very dry samples. Furthermore, is it seen that on sample L2 is there a little cracking down through the sample which is seen in sample L1 and L3. In addition, a number of bryozoans (i.e. tiny colonial animals that generally build stony skeletons of calcium carbonate) were observed in the samples. Most species of Bryozoans live in marine environments, and those found in the Lyøvej samples are probably marine deposits (WEB 1)

Figure 57 The bryzoan skeleton scaled up. The average length of the skeletons are 2 mm and the diameter around 0,5 mm . On the right picture has one of the skeletons been pictured from above where the porous inner structure can be seen.

As seen on the figure is the bryozoans skeleton porous and it is assumed that they can have an influence on the diffusion like e.g. aggregates resulting dual porosity behaviour regarding Dp/Do in the sample.

In the following will the loam soil samples L10-L12 (13-13,4 m b.g.s) be described. They are pictured in the figure below. The samples are also pictured under dry conditions.

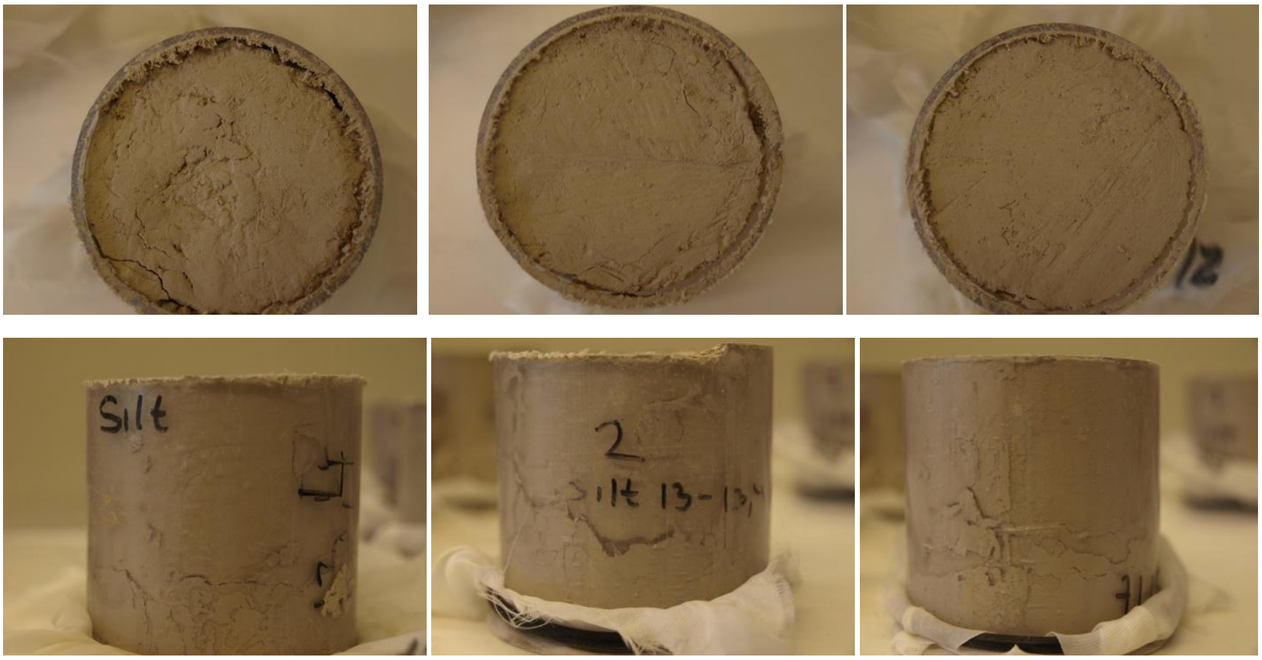


Figure 58 The L10-L12 soil samples seen from the top and from the side. L10 (left) L11 (middle) L12 (right)

Sample L10-L12 is considered to be a **fine loam soil**. This is based on sieving, visual appearance, the visual sedimentation properties (hydrometer) and the water retention properties. Compared to samples L1-L3, sample L10-L12 seems more fine and homogeneous. See figure 58 above. They also showed swelling and shrinking properties which is characteristic for the smectite minerals which is clay mineral group (Singer, 2006) As seen on figure 58 is there a tendency of space between the soil sample and the sample cylinder and there is also seen a little tendency of crack down the side on the samples.

<u>The sandy soil samples</u>

The sandy soil samples is represented by sample L7-L9 (11,7-12,2 m b.g.s) and L13-L15(15,2 m b.g.s). Sample L7-L9 will be described in the following and afterwards L13-L15.

The soil samples L7-L9 is pictured on the figure below where they can be seen from the top as well as from the side. Also under dry conditions.

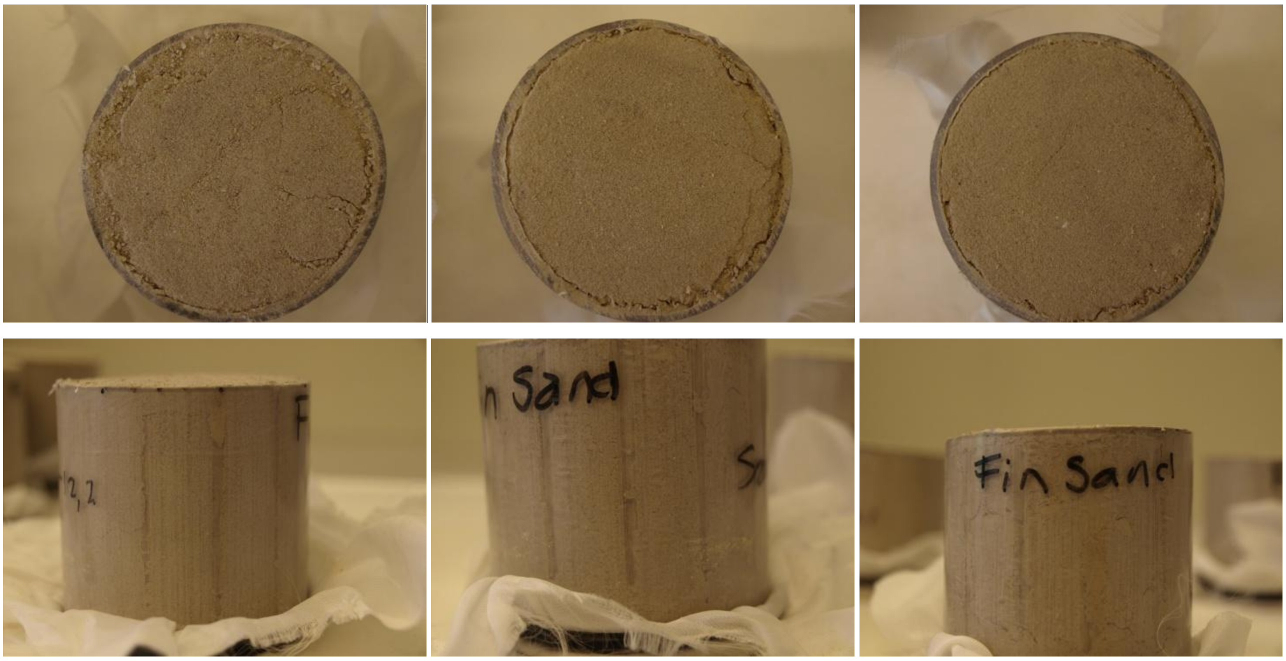


Figure 59 The L7-L9 soil samples seen from the top and from the side. L7 (left) L8 (middle) L9 (right)

Sample L7-L9 is considered a **fine sandy soil**. This is based on sieving, visual appearance and the water retention abilities. Compared to sample L1-L3 and L10-L12 can the individual grains be seen and felt when squeezed moist which is characteristic for a sandy soil (singer, 2006). Furthermore does the samples have a somewhat lower water content than the loam soil samples at pF 2 and pF 2,7. The samples have little fractures when dry as seen on figure 59. On figure 59 is it seen that down the side of the sample are there small long straight cracks that probably is due to the sampling method. Otherwise the sample texture does look fairly homogeneous however with a small degree of aggregation.

In the following sample L13-L15 will be described. They are pictured on the figure below. Under dry conditions also.

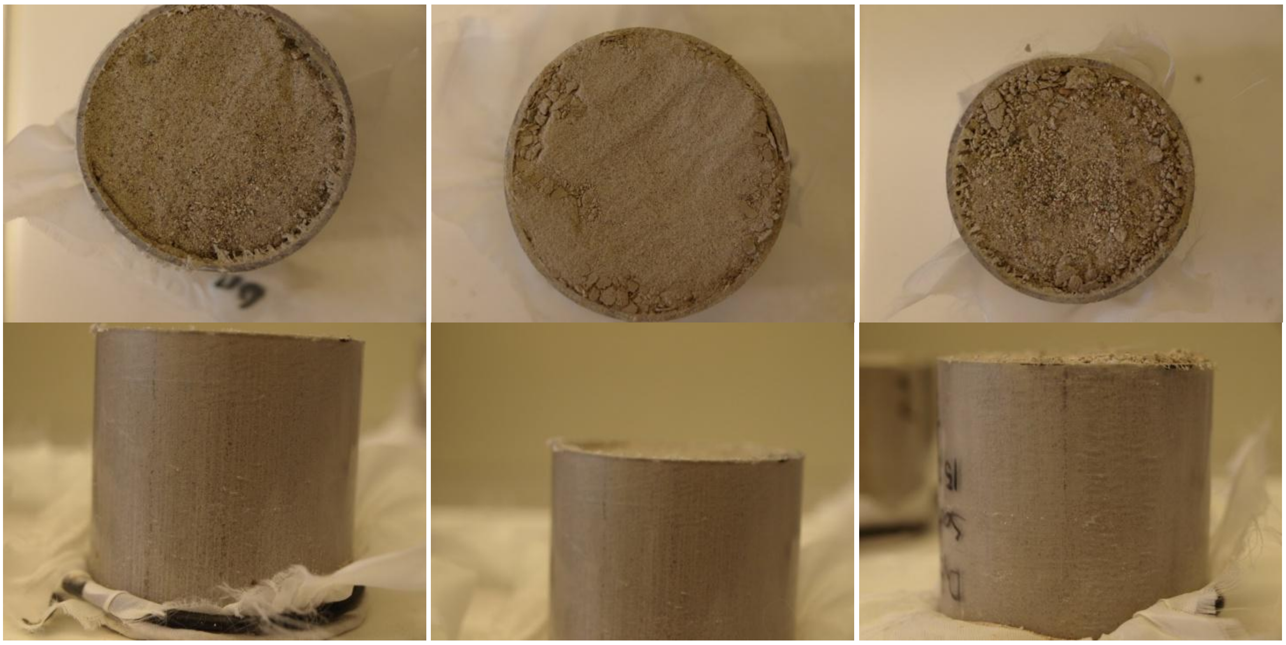


Figure 60 The L13-L15 soil samples seen from the top and from the side. L30 (left) L14 (middle) L15 (right.)

Based on sieving, visual appearance and the water retention properties is sample L13-L15 considered as a **coarse sandy soil** where it is seen that sample L14 is probably more a fine sand soil. This is especially based on visual appearance but also water content af pF 2 and pF 2,7 that was more like sample L7-L9. In sample L13 and L15 are there a high fraction of particles between 200 and 500 μm which make them coarser. Again are the individual grains seen and felt when squeezed moist. The samples do not have fractures when dry as seen on figure.

9.1 Dp/Do vs. ε for the intact Lyøvej samples

In the following the results of the Dp/Do vs. ε will be shown and analysed for the Lyøvej intact samples. Figure 61 below shows Dp/Do related to ε for the limestone samples and fitted with the WLR model.

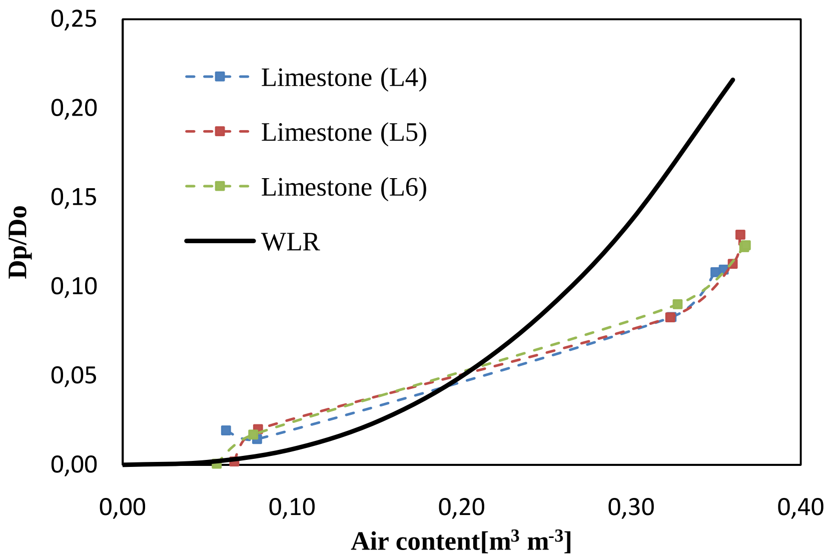


Figure 61 The Dp/Do Vs ε plot for the semi intact limestone samples.

The three curves seem to be very similar indicating that the samples are very homogeneous. For all three samples are there not any indication of fractures in the sample if one compare the curve to the characteristic curve trend with the steep slope of the first part of the curve that was seen in section 8.4 for fractured soil. In the part of the curve where the samples are dry is there however a steep slope for the curve. As it was seen that the samples cracked a little when dry could this indicate that there is some fracturing in the sample when it is dried out. The WLR model seems to under predict the Dp/Do values when the samples are wet, but it is not much. When the samples are dry is the WLR model on the other hand over predicting the Dp/Do values, which was also expected as it was expected for the limestone samples to have a high tortuosity. Compared to measurements of Dp/Do for limestone samples taken in Storvorde in Denmark, does the result seem very realistic as they are very similar, see figure 62.

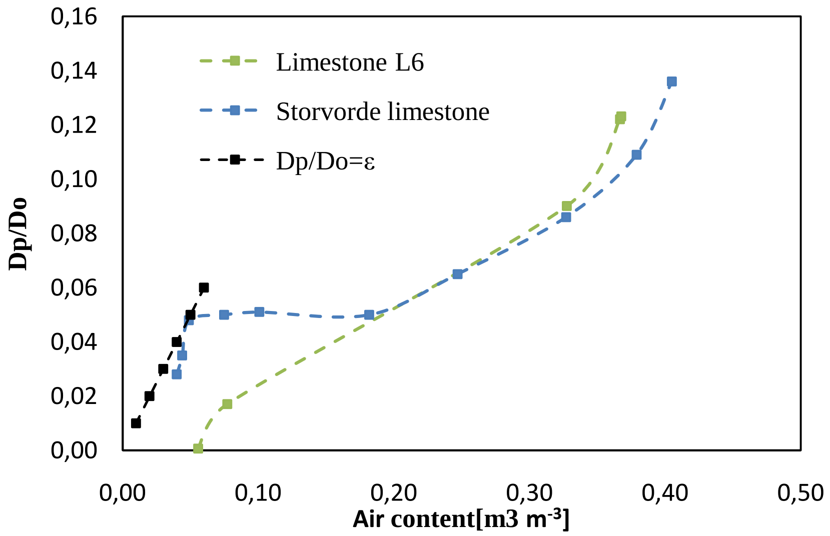


Figure 62 The Dp/Do Vs ε plot for the semi intact limestone sample L6 compared to measurements for Storvorde limestone where the Dp/Do = ε can be seen

The Storvorde limestone sample and the L6 Lyøvej limestone sample do not have the same porosity. It is 0,43 m^3 m^{-3} for the Storvorde limestone sample and 0,39 m^3 m^{-3} for the Lyøvej limestone sample. It is seen on the figure that in the wet area of the curve are the measurements not similar but at a air content of 0,2 m^3 m^{-3} or more are the measurements very similar. It is also seen that for both curves are there last part of the curve steeper than the rest. For the Storvorde limestone it is also seen that Dp/Do measurements are highly influenced by fractures as the cure follow the Dp/Do = ε plot.

In the following, will the Dp/Do, ε relationship for the loam soil samples be described and analysed. The Dp/Do Vs ε plot for the stony coarse loam soil samples can be seen in the figure below.

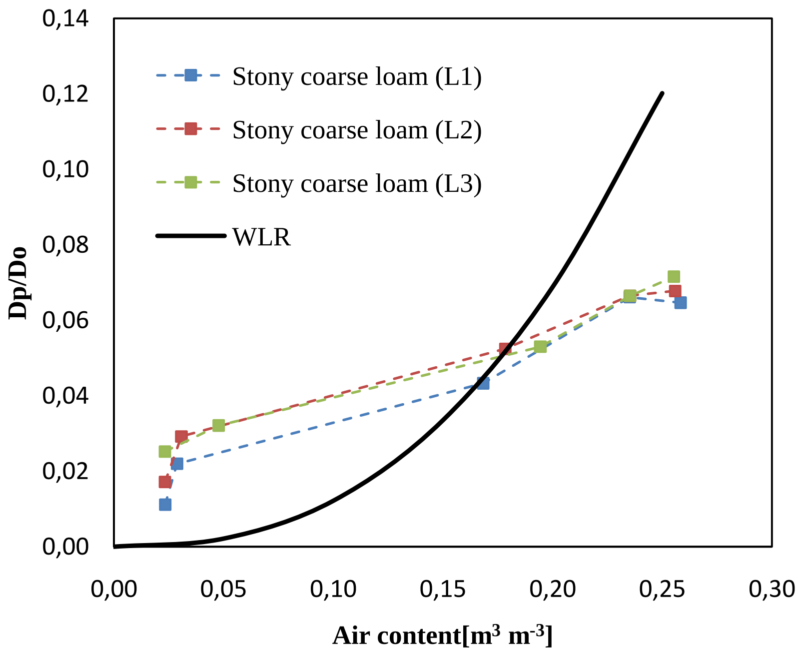


Figure 63 The Dp/Do Vs ε plot for the intact stony coarse loam samples.

The three curves seem to be very similar indicating that the samples are very homogeneous and the measurements also support the texture determination as being a loam soil with a high content of clay and silt in the samples, as the Dp/Do values are low, which is characteristic. Generally the curve look as expected for a very fine textured soil where the water induced disconnectivity is low which is seen in the wet area and the solid induced tortuosity is high which is seen in the dry part of the curve. This also results in that the WLR model under predicts and over predict in the wet and dry area respectively. In the first part of the curve is there a bend indicating some fractures in the soil sample. Based on the visual appearance were no cracks seen in the sample from the side or the top, when the sample was wet. An explanation to this could maybe be the stones that create macro pores that "act" like fractures and result in the characteristic curve trend – a steep slope- in the first part of the curve. The three samples all had a content of bryozoans skeletons which was expected to have an influence on the Dp/Do like for aggregated soil, but it does not seem to have an effect. The samples are however highly compacted, and based on the analysis in the previous section should this result in higher Dp/Do, but the Dp/Do values seems rather low and this effect does not seem to have an influence in these samples. But as the samples has a high content of stones that contribute to the high bulk density it is therefore difficult to evaluate anything for the compaction effect on Dp/Do for these samples.

In figure 64below is shown the Dp/Do Vs ε plot for the fine loam samples, L7-L9.

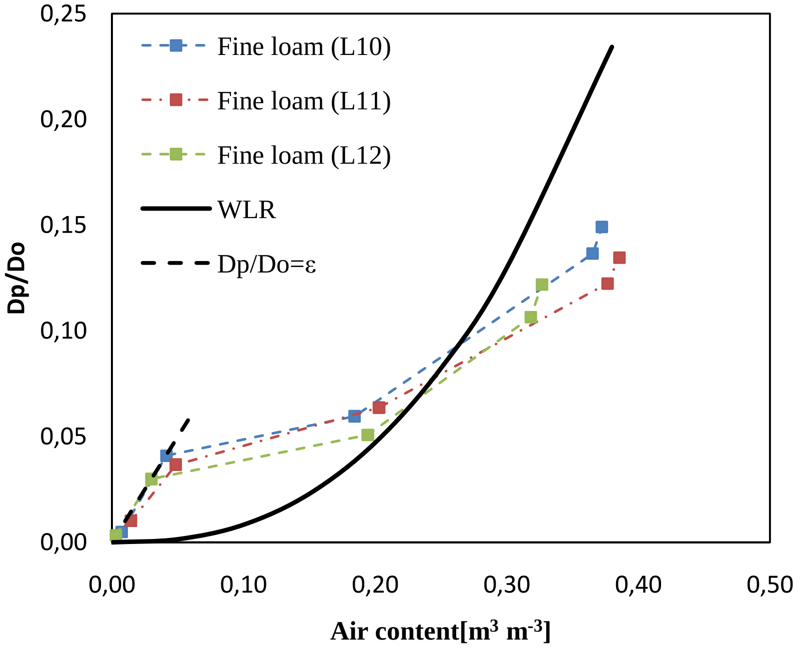


Figure 64 The Dp/Do Vs ε plot for the intact fine loam samples.

Also these three curves seem to be very similar indicating that the samples are very homogeneous and the measurements also support the texture determination as being a loam soil with a high content of clay and silt in the samples as the Dp/Do values are low, which is characteristic. Generally the curve look as expected for a very fine textured soil where the water induced connectivity is low and the solid induced tortuosity is high. This also results in that the WLR model under predicts and over predict in the wet and dry area respectively. The first part of the curve follows the curve Dp/Do= ε indicating some fractures in the soil sample. This was also expected as fractures were seen in the sample both from the top and from the side, when the sample was both wet and dry.

If the Dp/Do Vs ε plot is compared for the fine loam sample and the stony coarse loam samples are the same trend seen in the curves which was also expected, but the slope of the curve is steeper for the stony coarse loam than for the fine loam. See figure 65 below

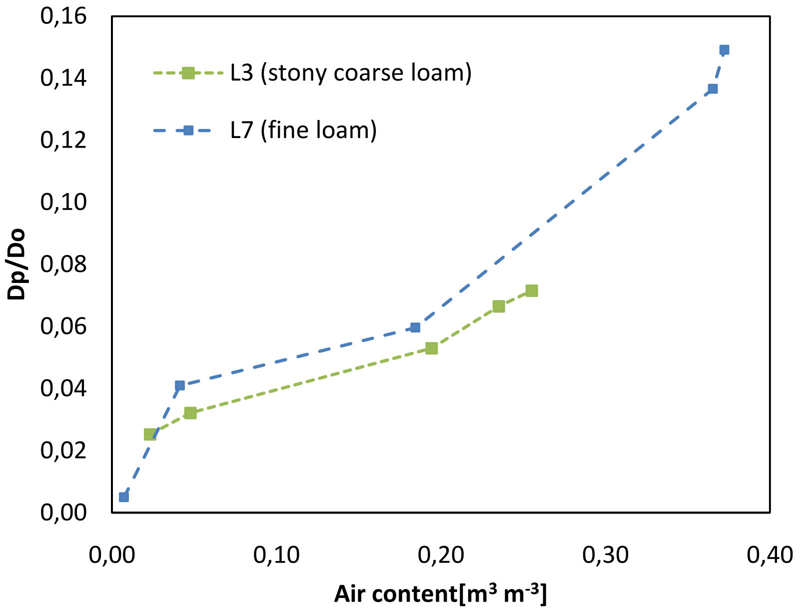


Figure 65 The Dp/Do Vs ε plot for the intact fine loam sample and stony coarse loam sample.

From the figure it is seen that the fine loam has higher Dp/Do value than the stony coarse loam at a given specific air content. This was not expected. From the soil texture study and the compaction study was it seen that more fine particles resulted in lower Dp/Do values and furthermore was it seen that the high compacted soil resulted in higher Dp/Do values. As the stony coarse loam soil samples are higher compacted than the fine loam samples should this result in higher Dp/Do values as well as the fine loam samples has a higher content of fine particles and should therefore result in lower Dp/Do values than for the stony coarse soil samples. This is not the case and the only other difference on the samples is the stones and bryozoans that therefore must be the explanation for this. It should however be added that study of compaction is for intermediate texture and this is a fine loam and it can be the case that the effect of compaction is not the same for fine textures.

In the following, will the Dp/Do, ε relationship for the sandy soil samples be described and analysed. The Dp/Do Vs ε plot for the fine sandy soil samples can be seen in the figure below.

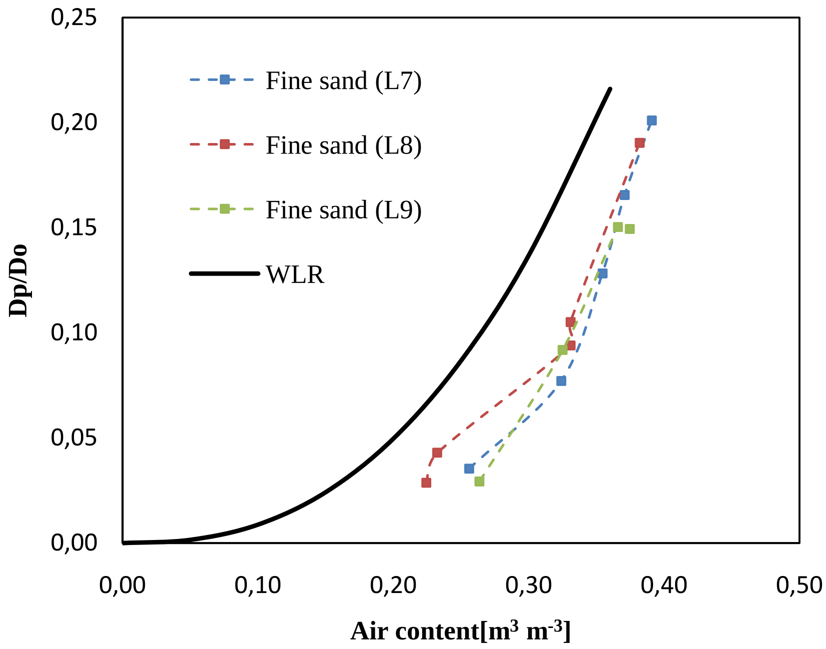


Figure 66 The Dp/Do Vs ε plot for the intact fine sandy samples

Again is it seen that the three curves are pretty similar, which was also expected as the samples seemed homogeneous based on both the sieving and visual appearance and also the water content at pF 2. All three curves follow the WLR curve well but the WLR model is for all the measurements over predicting Dp/Do. So as for the tortuosity does the measurements seem to match the 1,5 that is the T factor in the WLR model. For the water induced disconnectivity it is uncertain as measurement has not been made in the wet are of the curve, as the first measurement was made at pF 2. From the curve trend it does not look like cracks or aggregation is affection the diffusion, there were however a little tendency of aggregation in the sample but it does not seem to effect the Dp/Do measurements. To be able to clarify this are measurements in the dry area needed as the structure effects would be seen in the wet area both for fractures and aggregation that results in high water blockage.

In figure 67 below are the Dp/Do Vs ε plot for the coarse sandy soil shown.

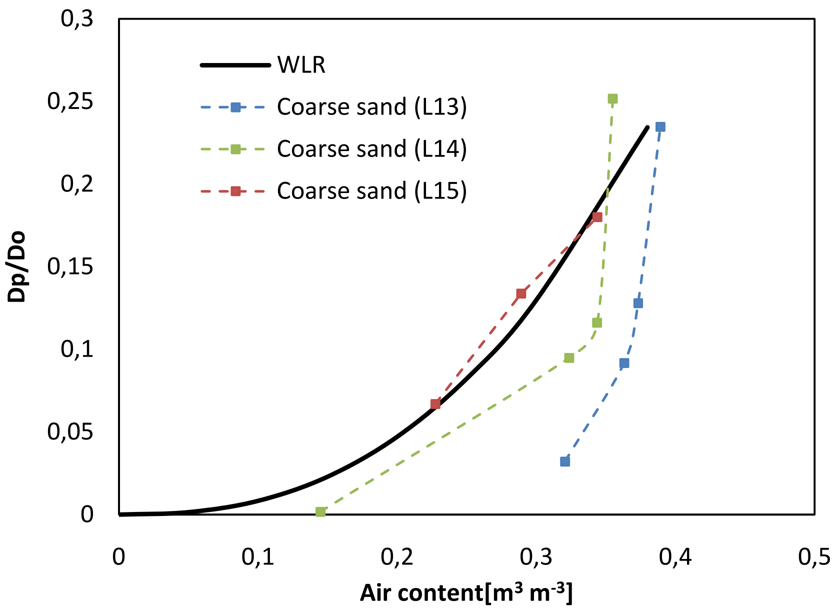


Figure 67 The Dp/Do Vs ε plot for the intact coarse sandy samples

Where the curves so far have been very similar is it for the three coarse textured soils seen that they differ. Sample L13 and L15 seems to be rather similar, where sample L14 differs from the two other curves. This is also in accordance with the sieving and the visual appearance where L13 and L15 where similar in texture. It is furthermore seen that sample L14 follows the WLR curve where the WLR model over predicts the Dp/Do values for sample L13 and L15. It is for these two samples seen that there is high water induced disconnectivity as the samples has a rather high air content before an actually diffusion in the pore space is seen. This is also what was seen in section 8.1 for the coarse soil samples. On the other hand is it seen that the tortuosity is in accordance with the tortuosity factor of 1,5 in the WLR model. The last measurements for L13 and L14 is however uncertain as the samples collapsed a bit.

In figure 68 below are the Dp/Do Vs ε plot shown for all the textures.

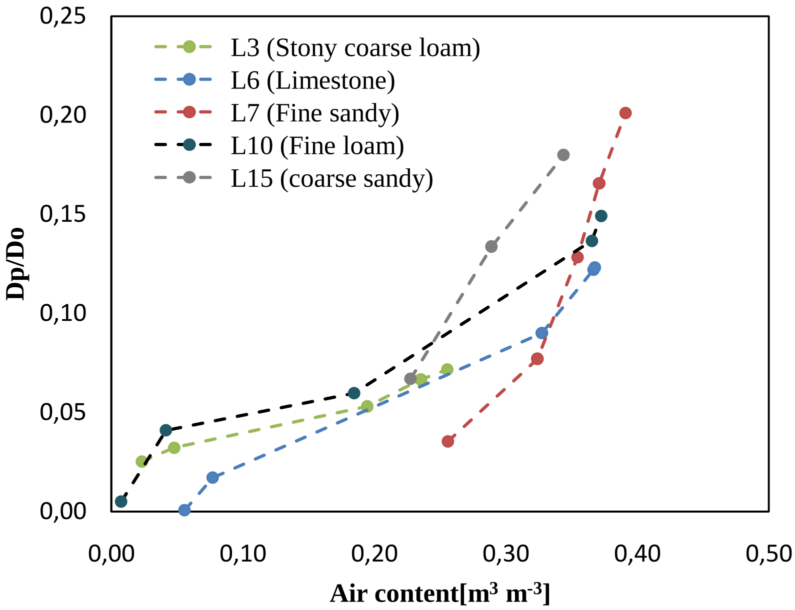


Figure 68 The Dp/Do Vs ε plot for the five textures represented.

As it is seen on the figure are the Dp/Do Vs ε plot for the loam samples and limestone samples close to each other, whereas the sandy soil samples is more similar. It is also seen that the loam and limestone samples – very fine textured soils samples - has higher solid induced tortuosity than the sandy soil which are coarser. The water induced disconnectivity is difficult to compare, but for the loam and limestone is it seen that it is low, but as no measurements has been performed in the very wet sandy soil samples is it difficult to say. All this is in accordance with the hypothesis and also what was seen in the section 8.1 “the effect of soil texture”. Regarding compaction it was seen for the stony coarse loam soil but the expected effect of higher Dp/Do was not occurring, but these samples was also the most inhomogeneous samples with stones and bryozoans skeleton and it is therefore difficult to evaluate the effect of compaction. Aggregation was also seen in the samples but for neither of the results has this effect been seen as expected according to section 4.3. This could indicate that a certain degree of aggregation must be appearing in the sample before the single grained effect on Dp/Do can be “suppressed”. As a last thing was structure also seen in some of the samples, and especially for the fine loam samples with a content of clay was this effect seen as expected. Having a clay soil is it therefore important to be aware of fractures in the soil e.g. risk assessment. Overall based on this study it is seen that the texture, especially the fine texture and structure are the parameters that results in differences in Dp/Do compared to the WLR model for this study. Additionally where the effects as compaction and aggregation not really seen or did not show the expected which is probably due to fact that other effects besides those examined in this project where influencing the Dp/Do measurements.

The samples does not have the same porosity and if the result should be compared regarding risk assessment is more correct to compare them at a given pF value. These plots can be seen in the figures below.

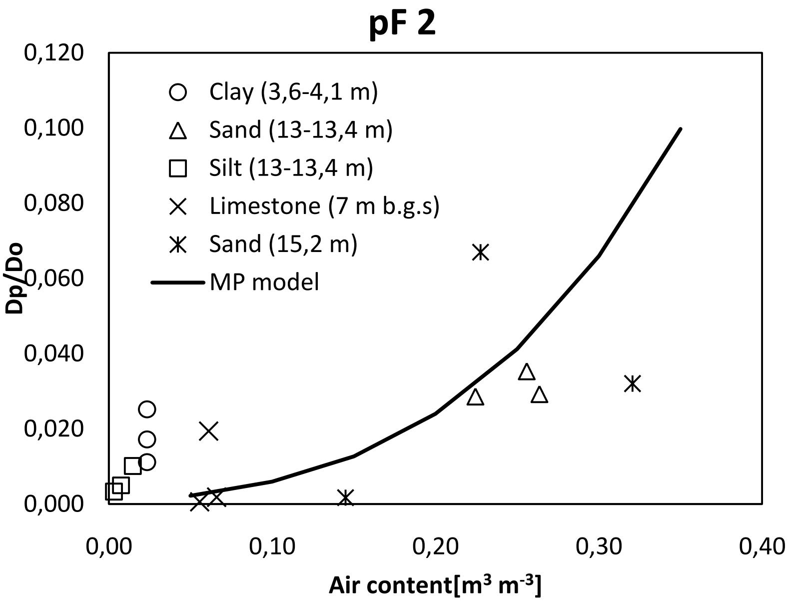


Figure 69 The Dp/Do Vs ε_{100} plot for the five textures together with the MP model..

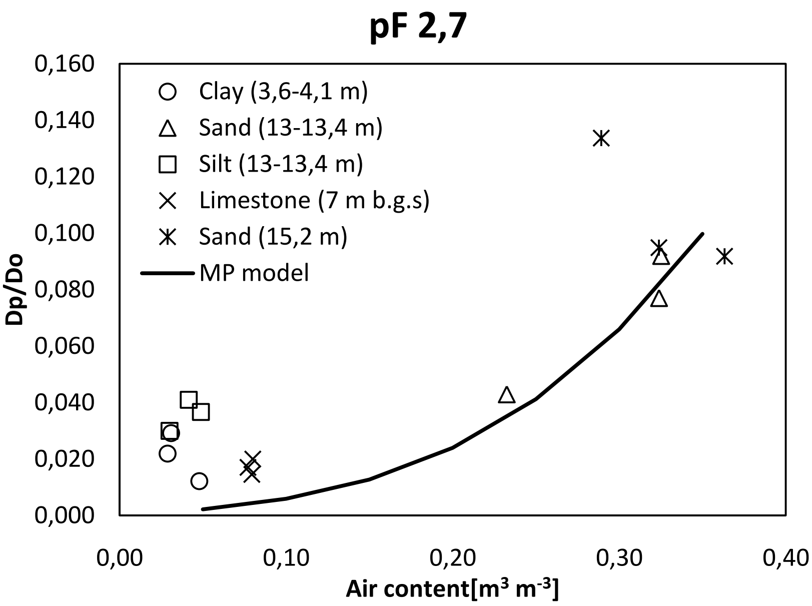


Figure 70 The Dp/Do Vs ε_{500} plot for the five textures together with the MP model..

First of all is it seen in both figure 69 and 70 that the samples have a different air content which was also expected due to the different textures. But it is also seen that the Dp/Do values are different. The macro porosity model (MP model) is also shown on the figure to see how the measurements is, compared to a model that is based on the air content at pF 2 for figure 69 and pF 2,7 for figure 70. The model can be seen in eq. 9.1 below

$$\frac{D_{p,100}}{D_0} = 2 \cdot \varepsilon_{100}^{3} + 0{,}04 \cdot \varepsilon_{100} \qquad (9.1)$$

(Moldrup et al., 2000a)

Where ε_{100} is ε_{500} in figure 69 and 70. Generally is it seen that all Dp/Do values is under 0,04 except for one measurement when the soil samples has been drained to pF 2. It is only fine sandy soil samples that fit the model and two of the Dp/Do values measured on two of limestone samples.

The MP model is also seen on the figures 69 and 70 where it again is the fine sandy soil samples that fit the best. Especially is it seen that the sandy soil samples has higher Dp/Do values than for pF 2 compared to the loam soil samples and limestone samples. The Dp/Do values are higher for the fine loam samples than the stony coarse loam samples at the same air content which was the opposite at pF 2 which could indicate that the water is better distributed in the fine loam soil samples than the stony coarse loam samples.

10 The use of the WLR model in risk assessment

Risk assessment is an evaluation of the environmental and health related consequences of soil pollution. As mentioned in the introduction risk assessment in Denmark makes use of a PC-based spreadsheet JAGG (Soil, Volatilization, Gas, Groundwater) which is a calculation tool made in accordance with guidelines issued by the Danish Environmental Protection Agency. In the following a risk assessment scenario will be set up based on the Lyøvej site. The focus here is only on the diffusive transport of gases through the soil until the zone of influence demarcated with a dotted line in the Figure 71. The migration of gases thereafter will be predominantly convective and hence will not be discussed. In the figure below, the scenario 1 is illustrated where soil texture and layer thickness is shown.

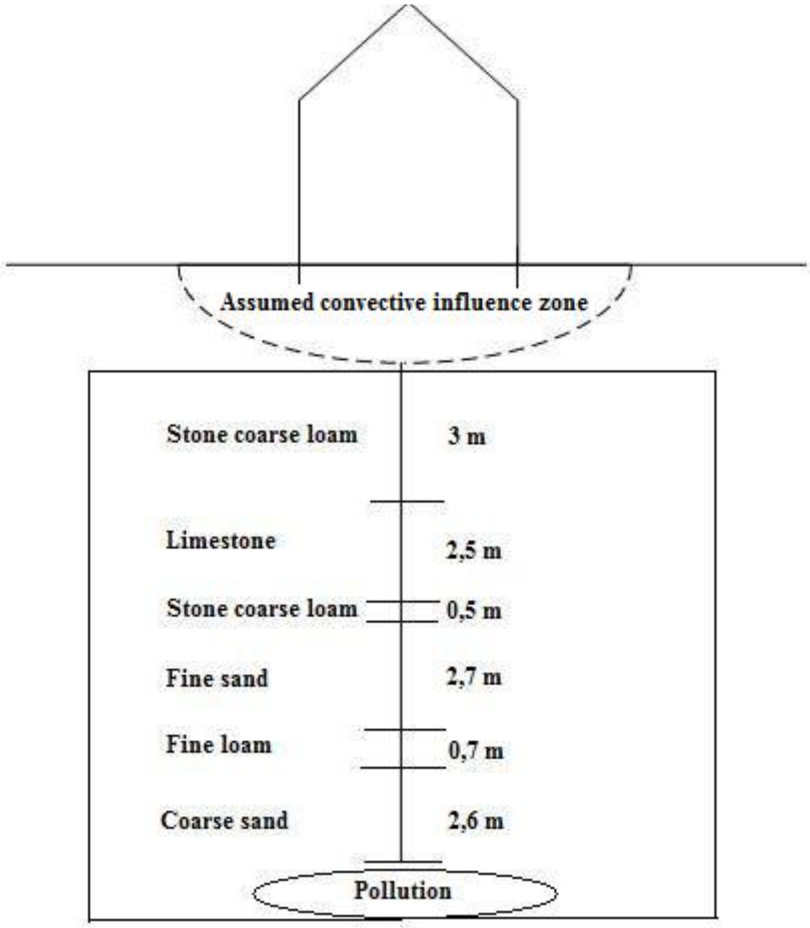


Figure 71 Risk assessment scenario 1 for the Lyøvej site, where the texture and layer thickness is shown for the soil profile

Under stationary conditions the diffuse gas transport through the pore air can be described by Fick's law as also given in eq 2.1 section 2.1. Using the issued guidelines by the Danish Environmental Protection Agency a possible background concentration should also be included and the eq. is given as.

$$J = -N \cdot Do \cdot \frac{C_0 - C_l}{z} \qquad (10.1)$$

Where N is denoted a material constant but more correctly is Dp/Do

C_o is the background concentration mg/m^3

C_l is the concentration due to the pollution mg/m^3

In the so far used JAGG 1 model N is suggested to be found according to Millington and Quirk, 1961

$$N = \frac{\varepsilon^{3,33}}{\phi^2} \qquad (10.2)$$

In the suggested JAGG 2 N is suggested to be found according to the WLR model (Moldrup et al., 2000a)

$$N = \frac{\varepsilon^{2,5}}{\phi^1} \qquad (10.3)$$

As seen in equation 10.1 N is just a proportionality factor and as Do for a given compound is just a constant, Dp will be the controlling parameter for the diffusive flux through the soil and up to the bottom of the foundation - typically the cellar. Dp is not essentially the same through the whole soil profile and depending on texture, porosity, air content and structure each layer has a different Dp. The integrated Dp for the whole soil profile, denoted as the effective Dp (Dpeff), is therefore the controlling parameter for diffusive gas transport through the soil profile. Dpeff can be calculated as the harmonic mean of the different Dp values for each layer as follows (Turcu et al., 2005);

$$D_{peff} = \frac{\sum_{k=1}^{n} \Delta Z_k}{\sum_{k=1}^{n} \frac{\Delta Z_k}{Dp}} \qquad (10.4)$$

(Turcu et al., 2005)

Where Z is the depth of each layer hereby assuming the same texture, porosity, air content and structure within the layer , and n is the total number of layers.

Hence, equation 10.1 and thereby the flux can be rewritten as

$$J = -Dp_{eff} \cdot \frac{C_0 - C_l}{z} \qquad (10.5)$$

From the equation 10.5 , it can be seen that the flux is proportional to Dpeff and hence it controls the magnitude of the flux. In the following calculations for Dpeff will be made for the Lyøvej site based on (i) measurements, (ii) the WLR model and (iii) Millington and Quirk, 1961 model. In figure 72 and 73 the change in air content, porosity as well as Dp through the soil profile can be seen. The porosity, air content and Dp for each layer is based on the average of triplicate measurements representing each layer and therefore a minor mean error in measurements. Air content and porosity and hence Dp may differ within each layer, but in this analysis we assume each layer has homogeneous properties.

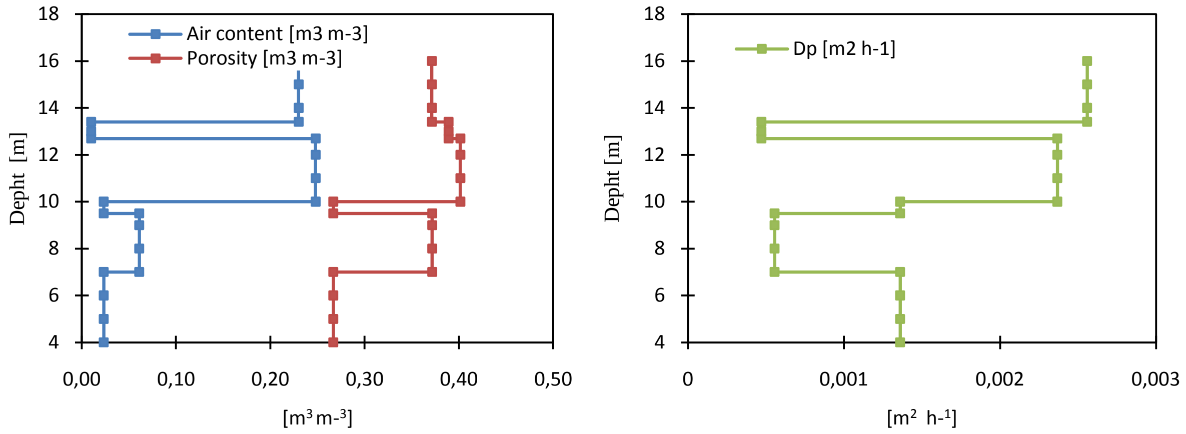


Figure 72 The porosity, air content and Dp at pF 2 for the soil profile at Lyøvej

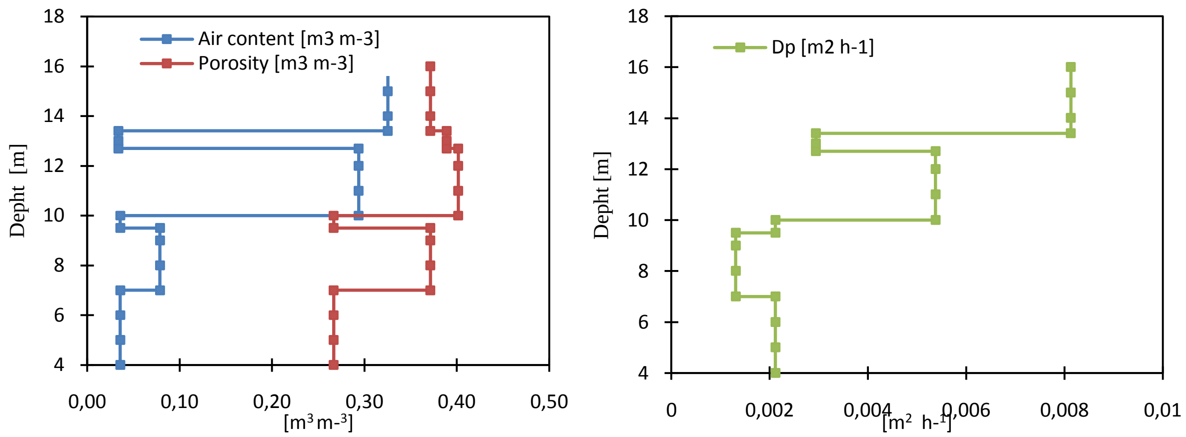


Figure 73 The porosity, air content and Dp at pF 2,7 for the soil profile at Lyøvej

As it is seen in the figures porosity, air content and Dp vary along the depth.

The table 15 lists the Dp_{eff} values based on measurements and on the predictions of WLR (Marshall) model and MQ 1961 model at pF 2.0 and pF 2.7.

Table 15 The Dp_{eff} for the Lyøvej site at pF 2 and 2,7 (scenario 1)The numbers in the parentheses should not be seen as standard deviation but as minimum and maximum values for the Dpeff. They are based on the standard deviation for the Dp for the three samples in each layer for the measurements. And for the WLR model and the MQ 1961 are they based on the standard deviation for the air content for the samples in each layer.

	Measurements	**WLR**	**MQ 1961**
Dp(eff.) at pF 2 [m^2 h^{-1}]	0,0011 (±0,0008)	1,4 *10^{-5} (±1,1*10^{-5})	7,2 *10^{-7} (±1,8*10^{-6})
Dp(eff.) at pF 2,7 [m^2 h^{-1}]	0,0026 (±0,0005)	0,00016 (±6,6*10^{-5})	3,5 * 10^{-5} (±3,5*10^{-5})

As seen in table 15 , both the WLR model and MQ 1961 model could not accurately predict the Dp_{eff} and underestimate measured Dp. This is due to the fractures in the loamy samples that result in higher Dp values than the models predict. It can be said that the measurements are performed on a partly open system due to the cracks even though the air content is very low. The models, on the other hand, predict a Dp in a closed system due to the low air content, as they do not take the cracks into account. It should be noted that there is a certain uncertainty for the difference between the measurements and the models predictions as the air content is low in samples and measuring on these samples using the measuring equipment described in section 5 is associated with a little uncertainty. Based on this analysis, however, is it concluded that in fractured soil with high water content both WLR and MQ 1961 models are not applicable for predicting Dp and therefore for the use of risk assessment.

10.2 Scenario 2 – Risk assessment for non fractured soil

In the following the above fractured loam layers (stony coarse loam, fine loam) will be replaced with none fractured sandy textures (fine sand and coarse sand), meaning that the profile only consist of fine sand and coarse sand. In scenario 2a the layers will be replaced with fine sand wehreas in scenario 2b they will be replaced with coarse sand. The soil profiles for scenario 2a and 2b can be seen in figure 74 and 76 respectively and the corresponding porosity, air content and Dp are shown in figure 75and 77, respectively.

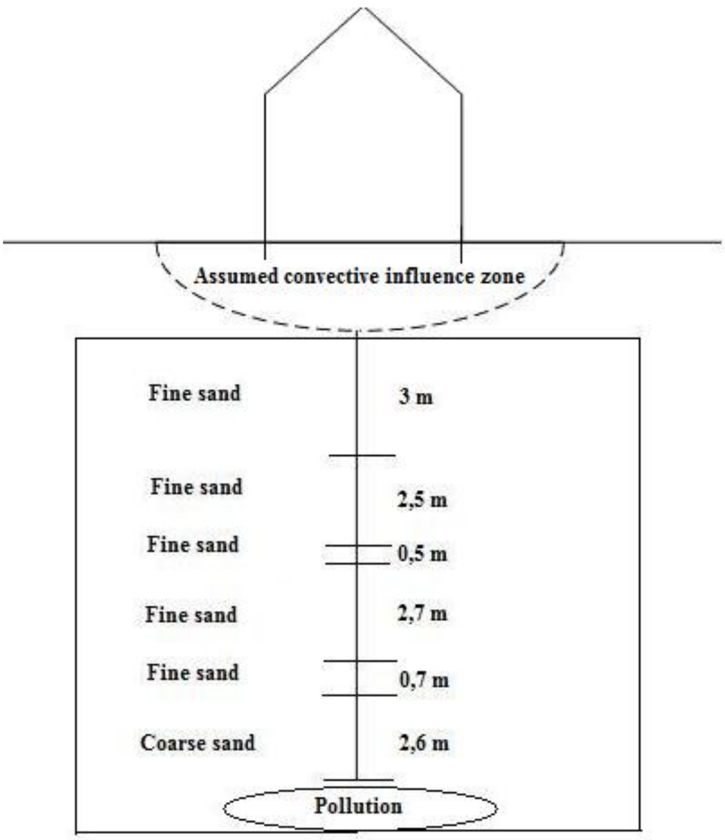
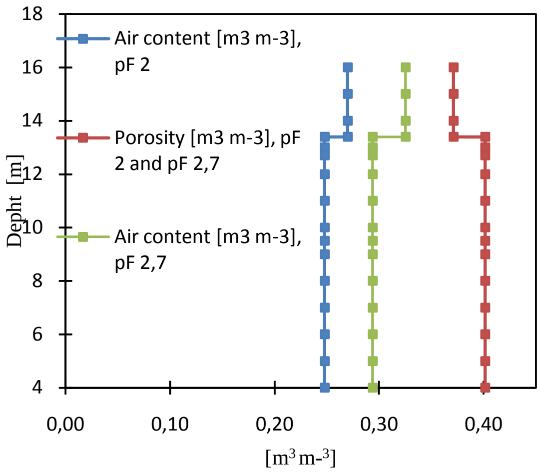


Figure 74 Risk assessment scenario 2a for the Lyøvej site, where the texture and layer thickness is shown for the soil profile



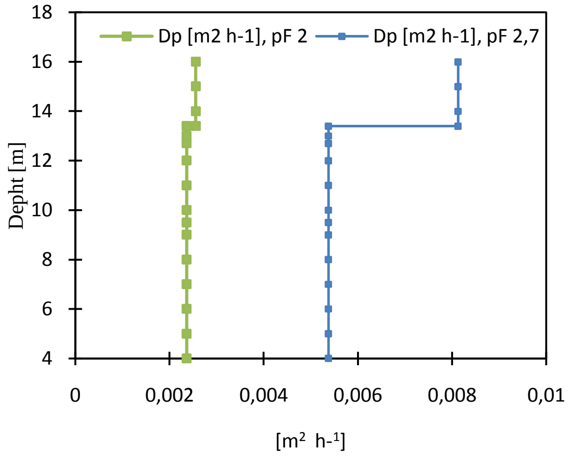


Figure 75 The porosity, air content and Dp at pF 2 and pF 2,7 for the soil profile at Lyøvej (scenario 2a)

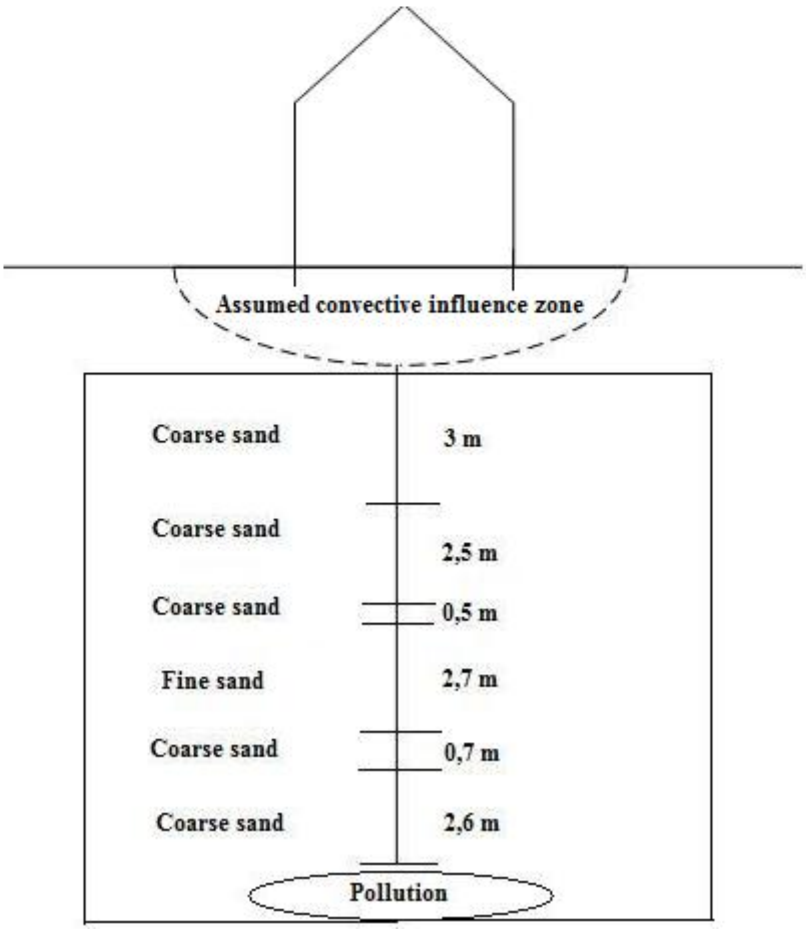


Figure 76 Risk assessment scenario 2b for the Lyøvej site, where the texture and layer thickness is shown for the soil profile

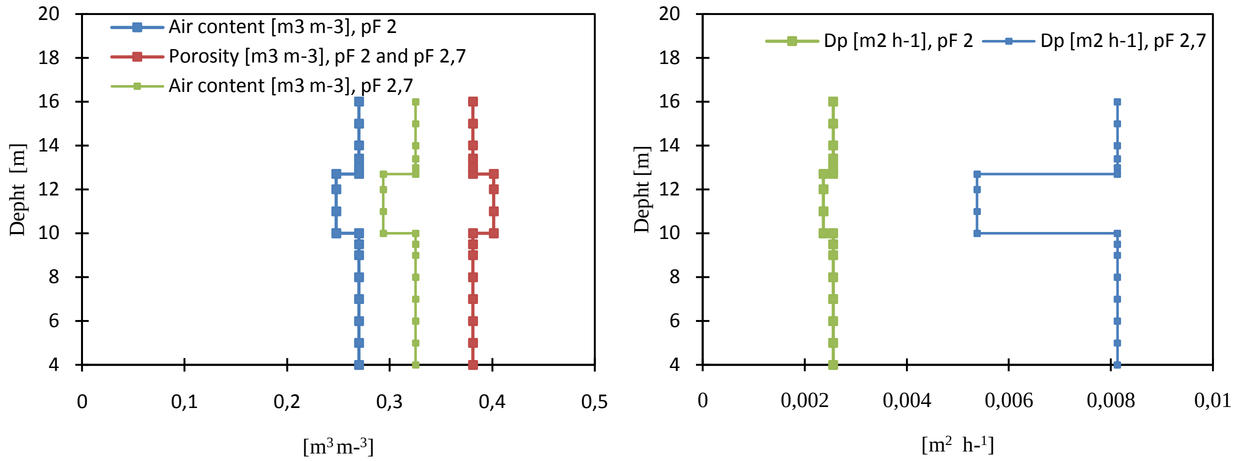


Figure 77 The porosity, air content and Dp at pF 2 and pF 2,7 for the soil profile at Lyøvej (scenario 2a)

The Dp_{eff} for scenario 2a and 2b based on measurements, the WLR (Marshall) model and MQ 1961 model for pF 2 and pF 2,7 can be seen in table 16.

Table 16 the Dp_{eff} for scenario 2a at pF 2 and 2,7

Scenario 2a	**Measurements**	**WLR**	**MQ 1961**
Dp(eff.) at pF 2 [m^2 h^{-1}]	0,0024(±0,002)	0,006(±0,0009)	0,005(±0,0016)
Dp(eff.) at pF 2,7 [m^2 h^{-1}]	0,0058(±0,0018)	0,0094(±0,0019)	0,0087(±0,004)

Table 17 the Dp_{eff} for scenario 2b at pF 2 and 2,7

Scenario 2b	**Measurements**	**WLR**	**MQ 1961**
Dp(eff.) at pF 2 [m^2 h^{-1}]	0,0025(±0,002)	0,005(±0,002)	0,0065(±0,004)
Dp(eff.) at pF 2,7 [m^2 h^{-1}]	0,007(±0,0018)	0,0114(±0,0018)	0,0115(±0,004)

As seen in table 16 and 17 , the models will predict higher Dp_{eff} when the fractured loam and limestone layers are replaced with non fractured sandy layers. This will result in a conservative risk assessment where the calculations for scenario 2a and 2b at pF 2 for both scenarios, will be most conservative. It should be noted here that, whether the fractured layers are replaced with fine sand or coarse sand does not result in significant differences in model predictions using WLR model or MQ 1961 model.

10.3 Scenario 3 – Risk assessment for fractured soil

As suggested in section 8.4, the Dp could be calculated for fractured soils in two steps using the WLR model or MQ 1961 model with an additional fracture term. The first part of the Dp/Do, ε relationship is expressed as a linear function given by Dp/Do= h·ε, where h is the proportionality constant between Dp/Do and ε. The rest of the curve should be calculated according to WLR or the MQ 1961 (See figure 78)

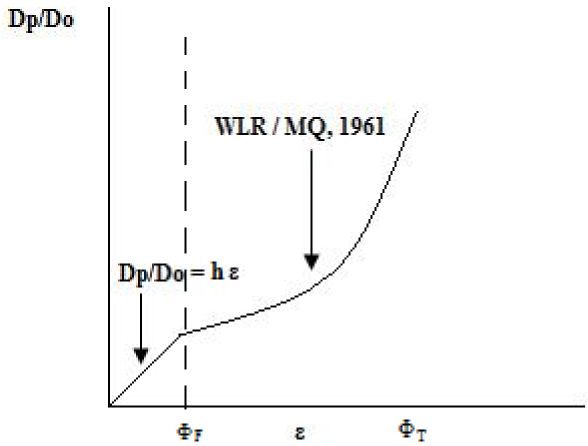


Figure 78 The Dp/Do, ε relationship for cracked soil

A scenario 3 has therefore based on the calculation procedure of Dp as in shown in figure 78 to explain the difference between the model predictions and the measurements. The equations will be as given in eq. 10.6 and 10.7 where the WLR model is used for the last part of the curve.

$$\frac{D_p}{D_0} = h \cdot \phi_{\mathrm{F}} + \frac{(\varepsilon_{\mathrm{pF}\,2} - \phi_{\mathrm{F}})^{2,5}}{(\phi_{\mathrm{T}} - \phi_{\mathrm{F}})^{1}} \qquad (10.6)$$

$$\frac{D_p}{D_0} = h \cdot \phi_{\mathrm{F}} + \frac{(\varepsilon_{\mathrm{pF}\,2,7} - \phi_{\mathrm{F}})^{2,5}}{(\phi_{\mathrm{T}} - \phi_{\mathrm{F}})^{1}} \qquad (10.7)$$

The soil profile is the same as for scenario 1 as well as the porosity, air content and Dp for the different layers (see figure 71, 72 and 73). For the stony coarse loam soil samples the fractures constitute 2 % pore vol. at pF 2 and 4% pore vol. at pF 2,7. For the fine loam 1 % pore vol. at pF 2 and 3% pore vol. at pF 2,7. The Dp_{eff} for scenario 3 can be seen in table 18 below.

Table 18 the Dp_{eff} for scenario 4 at pF 2 and 2,7

Scenario 3	**Measurements**	**WLR**	**MQ 1961**
Dp(eff.) at pF 2 [$cm^2\ s^{-1}$]	0,0003 (±0,00025)	0,0015 (±6,6*10^{-5})	0,0016(±0,0002)
Dp(eff.) at pF 2,7 [$cm^2\ s^{-1}$]	0,0025(±0,0002)	0,0038(±5,2*10^{-5})	0,0031(±0,0005)

As can be seen in table 18 the new approach improves the predictions of Dp_{eff}. Both models slightly overpredict the Dp_{eff} hence conservative and important in risk assessment standpoint. It is however seen that the WLR model prediction of the Dp_{eff} is the most conservative model at pF 2 and also pF 2, 7 as it is closer to the measurements.

11 Discussion of main findings

Gas diffusion in the vadose zone is a complicated process influenced by many factors. Among these are texture, compaction and structure of the soil combined with the water content and the water distribution. Some of the main findings of this research explain how these parameters affected Dp/Do and how these should be related to risk assessment. Below, the main findings of this study will be discussed in detail.

11.1 The new measuring equipment

In this project new equipment that was set up in this project period was used for most of the measurements. Measuring equipment was tested against leaks and proved well functioning for measuring Dp/Do as they could reproduce the same results for the soils tested with different measuring equipment at UCD. It is considered that the new equipment is easier to use as all controlling units have been assembled together for each chamber. One of the units that are new on the equipment is the sample holder mechanism which is considered to be a very good and effective renewal as it is easier to use and at the same time establishes a good connection to the sample that keeps the system tight. Also, it opens the opportunity for using samples that are not exactly 5 cm in diameter, as the packings used for the sample holder, should be blown up and thereby can adjust to the sample if it is little smaller or little larger than the traditional 100 cm^3 samples (5x5,1 cm), see figure 79. In fact, this was the case for the Lyøvej intact samples that were a little smaller than the standard size.

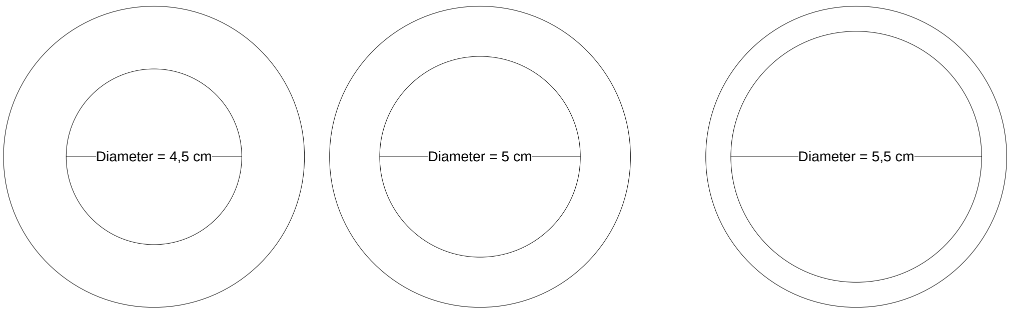


Figure 79 The hallow packings; fitting different sample diameter.

In a greater perspective this unit is also considered useful for larger samples (20x20 cm) and thereby measuring equipment in larger dimensions. The large samples might be even more difficult to be kept tight in a rigid sample holder and therefore the new unit will make it easier to place the large sample within the flexible packings. The new feature for the sample holder is, however, combined with some new reservations. As the packings are filled with nitrogen is it important to check that the packings are not leaking as this will affect the measurements. For the equipment used at UCD, it was only necessary to ensure an airtight joint so that the atmospheric air could not enter. A unit that is still the same is the oxygen sensor, and it was experienced in this project period that this unit and the calibration was very important and could result in great errors if this was not correct. It is therefore considered that as a next improvement for this measuring equipment would be to find another solution for this as this still combines the system with uncertainties if this is not carried out precisely and cautiously.

11.2 Measuring the Dp/Do on urban soils and "space" media

Measurements on urban soil and space media have been performed in this project to study the effect of texture, compaction and structure on the diffusion coefficient. These measurements resulted in some overall curve behaviours going from wet to dry which can be seen in the figure below.

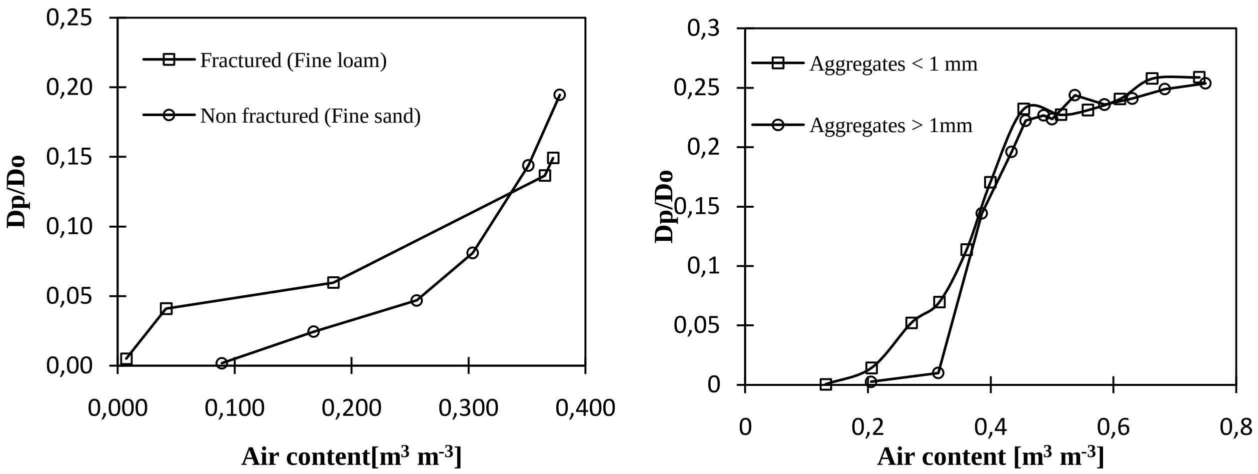


Figure 80 The Dp/Do Vs ε plot for some urban soils and space media showing some characteristic curve behaviours.

As seen on the figure was it for both urban soils and space media structural effects that resulted in some "new" characteristic curve behaviours. For the urban soil it was structure in the form of fractures that was seen for samples with a high clay content, limestone samples and samples with a high content of stones. This resulted in high Dp/Do values compared to non fractured soil as the water induced disconnectivity and the tortuosity becomes smaller. In figure 79 is it can also be seen that the fine loam sample has higher Dp/Do values than the fine sand, which should be the opposite, due to the presence of fractures. For the space media it was the structure in the form of aggregates that resulted in high water blockage effects even in samples with high air content. Aggregates of 1 mm were seen to have a great effect on water blockage.

11.3 The effect of texture, compaction and aggregation

The study of the effect of texture, compaction and structure was performed on both repacked and intact samples. The study on the repacked samples showed that regarding water induced disconnectivity and solid induced tortuosity which was the parameters focused on, an effect could be seen especially for the disconnectivity when looking at the effect of texture. The effect was higher for coarse textured soils and lower for fine textured due to the difference in surface area. The tortuosity, on the other hand, did not seem to be so different for the different textures which were also seen from the T-C analysis. This was when comparing the textures at the same air content. But comparing the effect of texture at the same pF showed that the texture have a great effect on the difference in Dp. This is due to the difference in water retension capacity, where fine textured soils will have a higher water content than coarse textured soils that results in the difference in Dp which was seen for the intact Lyøvej samples. The texture study on the repacked samples was only done for one compaction degree and this effect is assumed to influence these mentioned effects on T and C due to texture, in another way. It was seen that compaction did have an effect on the Dp in that sense that higher compaction resulted in higher Dp values at the same air content. Again this study was only made for one kind of texture and the effect may differ for different textures. It could therefore be interesting to make further measurements to study the compaction effect on different textures but also to study the effect of texture at different compaction. Looking at the Currie 1961 results of Dp/Do and the Dp/Do results for the Hokkaido sand, both of which are coarse textures but different compaction, different curve trends could be observed indicating that texture and compaction may have an influence on each other when combined, that could not be seen when just one of them is studied. Further studies must be made in order to clarify this. Another thing to be considered here is the method of compaction. In this project the compaction study was performed on repacked samples that have been packed in the laboratory, but it is considered that there might be a difference in natural compaction of the soil and manual compaction in the laboratory which also could have an influence on the result. Regarding the structure, it was seen that aggregation had an influence on Dp/Do for the packed soil samples where it was seen that it especially resulted in high water blockage and thereby low Dp/Do values up to rather high air content. It was seen that aggregates of only 1 mm resulted in a really high water blockage effect. The intra porosity also had an effect on Dp/Do if the porosity was high and pores are well connected. Soil samples with fractures were also seen to have a great effect that resulted in high Dp/Do values particularly in wet soil samples. This was an effect that was seen both in the repacked and the intact Lyøvej samples. Depending on the degree of fractures and tortuosity of the fractures this effect will have great influence on Dp/Do.

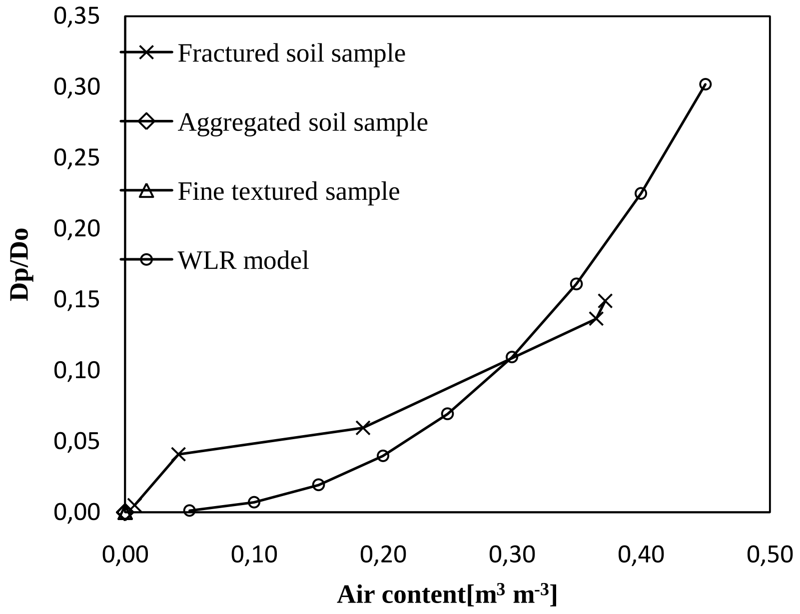


Figure 81 The Dp/Do Vs ε plot for the most characteristic curve behaviours found in this project.

11.4 The WLR model as a descriptive model

The WLR model is suggested to predict the diffuse transport of volatile polluted compounds in the vadose zone and also intended to be a descriptive model that can predict the diffusion in the vadose zone for e.g. soil aeration, design of cleanup of contaminated sites and quantify emission of methane flux. Regarding risk assessment it is important that the calculations of the Dp/Do are conservative and not necessarily completely precise which however is the case using the WLR model for the other mentioned purposes. Regarding the validation limits of the WLR model, this means that the WLR model has some limitations where the WLR model will not be accurate to calculate the diffuse contribution in environmental health and risk assessment. Regarding texture, there are not so great differences in the measurements of Dp/Do for the different textures and the predictions of the WLR model. It is, however, seen that it fits the intermediate texture the best and the least for fine textured soils. In the dry area, the WLR model over predicts the Dp/Do for all textures but close to the coarse and intermediate textures. In the wet soils, the WLR model over predicts Dp/Do for coarse textures and under predicts Dp/Do for fine textures, but the differences are not so great. Regarding compaction, the WLR model does not predict the Dp/Do values exactly but over predicts the values instead. This is for all compactions levels and mostly for the loose packed samples, but again is the difference not so great. Structured soils also get wrong estimates of Dp/Do from the WLR model. It is seen for aggregated soil that the difference is not so great when looking in the inter pore space and it fits Dp/Do pretty well only with a little over prediction, but if the porosity is high in the intra pores and the pores are well connected, it may result in a great difference, which was seen for the Pumice samples where the intra pores resulted in back channelling. Using only the WLR model will therefore in some cases not be enough to predict Dp/Do for aggregated soil. Regarding cracked soils, the WLR model was unable to predict the Dp/Do in wet soils but depending on the texture, the compaction and degree of fractures the model probably more or less fitted the Dp/Do values in more dry cracked soils. Considering all of this in the perspective of risk assessment, it is clear that all situations cannot be handled equally. But overall is it concluded that the WLR model is suitable as a predictive model for the Dp/Do and thereby deserves to be used in the risk assessment tool JAGG. It does not fit the measurements exactly but in most cases is it an over prediction which makes the estimations more conservative. However when dealing with highly structured soil will the WLR model as a uni-modal not be sufficient for the prediction of Dp/Do.

Based on the study of Dp/Do for the repacked and intact soil samples and the fingerprints and curve trends seen for the soil samples from wet to dry, this will lead to the set up of the following general conceptual model. This could be when dealing with risk assessment or one of the other mentioned purposes.

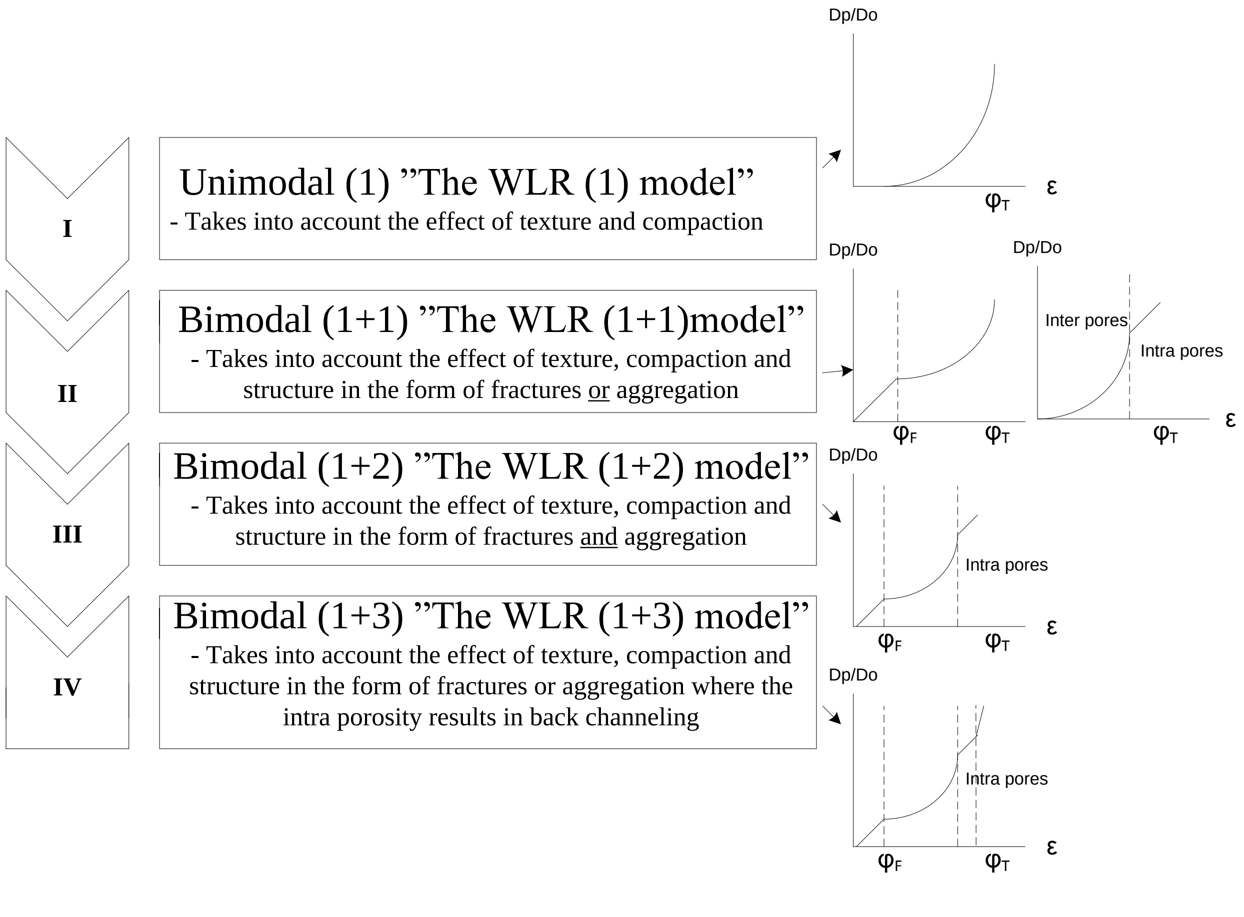


Figure 82 The conceptual model for predicting the diffusion in the vadose zone. The numbers in the parentheses represents the number of terms that besides the WLR model should be used to predict the Dp/Do in the vadose zone.

The conceptual model should be seen in the way that:

I) Having a soil profile without any influence of structure can the WLR model be used to predict the Dp in the different layers. From the T-C analysis was it seen that T and C should be changed regarding texture and compaction to fit the measurements precisely. But regarding risk assessment this is considered not necessary as the WLR model over predicted the Dp/Do values in a degree that was expectable. For wet fine textured soil the WLR model did however under predict the Dp/Do values. The WLR (1) model can therefore be used for predict Dp/Do with an effect due to texture and compaction.

II) Having some structural effects in the soil in the form of fractures or aggregation should "WLR (1+1) model" be used. Where fractures or aggregation will be taken into account by an additional term besides the WLR model.

III) If both fractures and aggregation is occurring a step further more must be taken in the model and one should use the "WLR (1+2) model" where both aggregation and fractures will be taken into account by adding two additional terms besides the WLR model.

IV) And finally if the soil is highly fractured and aggregated and where the intra porosity of the aggregates results in back channelling like the pumice media should the last step be taken and the "WLR (1+3) model" should be used. Which level in the module one should use also depends on the water content of the soil as e.g. for the "WLR (1+3) model" should the soil be really dry before the back channelling effect will have an influence on Dp/Do.

In the study on the intact samples from the Lyøvej site some of the effects were however not seen in such a great extent as expected. This was e.g. seen for the effect of aggregation where aggregation was seen in the samples but the expected effect was not seen in the results of Dp/Do. This indicates that there might be some kind of threshold line for the degree of aggregation before an effect can be seen. And based on the TC analysis for texture and compaction could this also indicate some kind of thresholds. This therefore contributes to further considerations regarding the conceptual model shown above. Meaning that for each of the modules should a threshold line by incorporated for e.g. the degree of structure, and for adjustment on T and C in the WLR model regarding texture and compaction to get more precise predictions of Dp/Do. This is illustrated in the figure below.

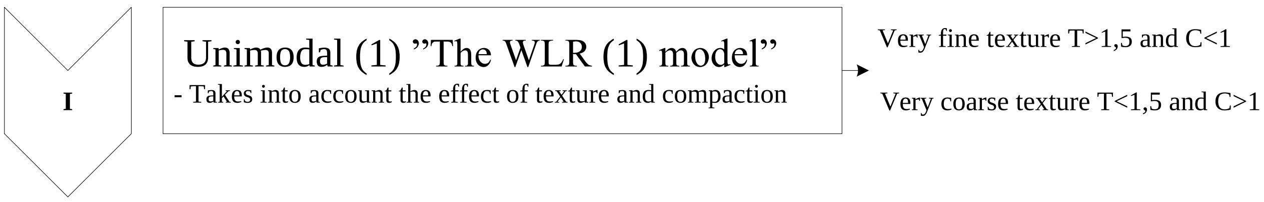


Figure 83 An example of a threshold in texture for the conceptual model

11.5 The use of WLR in risk assessment

Regarding the WLR (1+2) model and the WLR (1+3) model do they not seem as likely to be used in a risk assessment tool for environmental consulting companies as they are too detailed and will demand a lot of knowledge o the soil profile. But it is considered that the two first steps in the model could be useful as it was seen that especially cracks had a great effect, even though the degree of crack where not that high. This is shown in the figure below where only the first two steps of the conceptual model are taken into account.

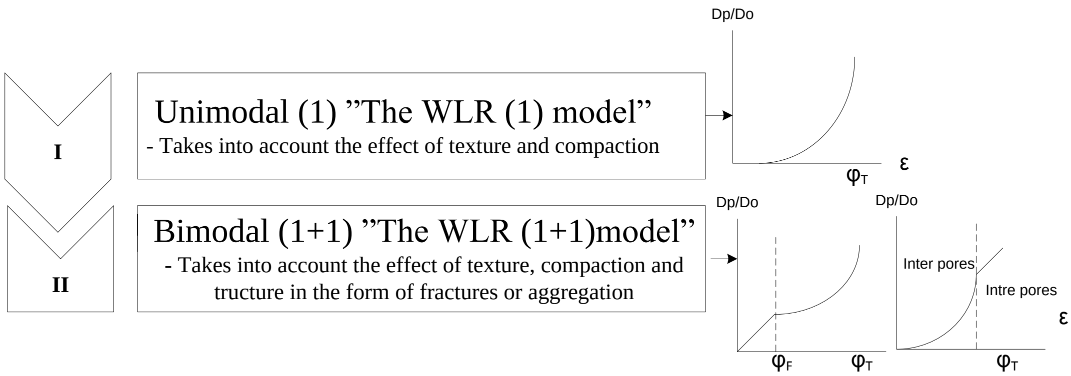


Figure 84 the reviewed conceptual model for predicting the diffusion in the vadose zone in connection with risk assessment.

The reviewed conceptual model has only the two first steps included, but it has then been expanded with some threshold lines for the texture and compaction module regarding the T and C factor in the WLR model and for the structure regarding the degree of structure. As mentioned earlier, only few experiments has been made for the texture and the compaction and it is therefore considered that more experiments need to be done before determination of the threshold lines for texture and compaction is made. In this study there is however a general tendency of the T factor being too high for all textures so it is considered that this may have to adjusted for the general WLR model .

The intact Lyøvej loam samples had different compactions where the high compacted samples (stony coarse loam) had a lower Dp/Do than the low compacted samples (fine sand), which was not the result found for the repacked soil samples. But as the high compacted soil samples (L1-L3) had a high content of stone is it difficult to compare these results and conclude anything from this. This therefore also contributes to some considerations regarding risk assessment and the conceptual model shown above. As step number one before using JAGG and the suggested conceptual model should be to obtain more detailed insight of the geology and texture. Having a high stone content resulted in, that the model cannot really be used as it was seen in this study that the expected effect was not in accordance with what was seen in these samples. Having the wrong layer depth will also result in wrong predictions of the effective Dp for the soil profile if the layers are very controlling, So as a final remark is considered, that knowing the polluted site regarding geology, texture and layer depth is very important and is considered should be improved in the Danish environmental consulting companies as this has a great influence on the results of the Dp/Do at a specific site.

12 Conclusions

- The new measuring equipment
  - The system is air tight
  - The system is flexible regarding size of soil sample
  - The system is applicable for equipment in larger dimensions.

- Dp/Do measurements on urban soils and "space media"
  - Two important curve behaviours was identified as a result of structure and aggregation

- The effects of texture, compaction and structure
  - The amount of fine particles can affect the Dp/Do in the vadose zone
  - High compaction can result in higher Dp/Do values than low compaction
  - Structure in the form of fractures resulted in higher Dp/Do values in wet soil
  - Structure in the form of aggregation can result in water blockage

- The WLR model as a descriptive model
  - The WLR model is considered a reasonable model for the prediction of Dp/Do for most soils. However with some limitations when:
    - The texture is very fine or very coarse
    - The soil is extreme high or low compacted depending on texture
    - The soil is highly structured

- The use of WLR model in risk assessment
  - The WLR model is considered useful in risk assessment regarding the diffusivity in urban vadose zone
  - However when the soil is fractured, highly aggregated or has a high content of stones is which was seen for urban Lyøvej site the WLR model is not sufficient as a uni-mode lfor predicting the diffusivity.

The study of the diffusion in the vadose zone has in this project been regarding risk assessment. But diffusivity in the vadose zone is also important to study regarding many other perspectives. As mentioned in the introduction has the use of soil been intensified due to agricultural and urban use and regarding the preservation of the soil is knowledge of diffusion important. But also regarding climate changes is the diffusion in the vadose zone important as it controls the emission of greenhouse gasses, but also the aeration of the soil that secure oxygen for the bacteria in the soil that can decompose methane. And as something new within the last ten years, also plant growth in outer space as diffusion also here is important to be able to predict for being able to compose optimal media.

13 Reference list

Allaire et al., 2008, Measurement of gas diffusion through soils: comparison of laboratory methods, Journal of Environmental Monitoring, 10, pp. 1326-1336

Augustus, C., Moldrup, P., Kawamoto, K., Yoshikawa, S., Rolston, D. E., and Komatsu, T., 2008, Variable Pore Connectivity Factor Model for Gas Diffusivity in Unsaturated, Aggregated Soil, Vadose Zone Journal, vol. 7, No. 2.

AVJ; 2004; Amternes Videncenter for Jordforurening – Transport af gasformig forurening I umættet zone og i bygninger, Litteraturstudie; Teknik og Administration.

Blonquist, J. M., et al, 2006, Microstructural and phase configurational effects determining water content: Dielectric relationships of aggregated porous media, WATER RESOURCES RESEARCH, VOL. 42, W05424

Chamindu, K., 2009. Data on repacked Hjørring soil. Personal communication.

Currie, J. A., 1960 Gaseous diffusion in porous media, Part 1.- A non steady state method, British Journal of Applied Physics 11, 314-317

Currie J. A., 1983, Gas Diffusion through soil crumps: the effects of wetting and swelling, Journal of Soil Science, 34, pp. 217-232

DMR, 2003, Supplerende forureningsundersøgelse på ejendommen matr. Nr. 45, Hjørring Markjorder, Hjørring beliggende Frederikshavnsvej 9-11, 9800 Hjørring, Danish Environmental Consulting (2003)

Hamamoto, S., et al. 2009b. Paper accepted for Vadose Zone Journal.

Hamamoto, S., 2009a. Data on Hokkaido loam from Japan. Personal communication.

Loll, P.; Moldrup, P.; 2000; Soil characterization and polluted soil assessment; M.Sc. Course; Aalborg University.

Miljøstyrelsen; 1998; Oprydning på forurenede lokaliteter; Vejledning fra Miljøstyrelsen 6 og 7; Miljø- og Energiministeriet Miljøstyrelsen.

Moldrup, P.; Olesen, T.; Gamst, J.; Schjønning, P.; Yamaguchi, T.; Rolston, D. E.; 2000a; Predicting the gas diffusion coefficient in repacked soil:. Water induced linear reduction model; Soil Science Society of America Journal; 64; 5; pp 1588-1594.

Moldrup, P., Olesen, T., Yamaguchi, Y., Schønning, P. and Rolston, D. E., 2000b, Predicting the gas diffusion coefficient in undisturbed soil from soil water characteristic, Soil Science Society of America Journal, Vol. 64, pp. 94-100.

Moldrup, P., Olesen, T., Komatsu, T., Schønning, P., Rolston, D. E., 2001, Tortuosity, Diffusivity and permeability, Soil Science Society of America, 65., pp. 613-623

Moldrup, P., 2009, Dept. of Environ. Engineering, Aalborg University, Personal Communication

Nielsen, S. G. D.; 2004; Gasdiffusionskoefficienter i jord: Måleopstilling, prædiktionsmodellerog risikovurdering; Afgangsprojekt; Miljøteknologi; Aalborg Universitet.

Penman, H. L., 1940, Gas and vapour movement in the soil, I. The diffusion of vapours through porous solids, Journal of Agricultural Science (Cambridge) 30, pp 1113-1137

Papendick, R. P. and Runkles, J. R., 1965, Transient-state oxygen diffusion in soil: I. The case when rate of oxygen consumption is constant, Journal of Soil Science 100, pp. 251-261.

Partridge, G. P., Lehman, D. M. and Huebner, R. S., 1999, Modeling the reduction of vapour phase emission from surface soils due to soil matrix effect: Porosity/Tortuosity conceps, Journal of the Air and Waste Manegement, 49, pp. 412-423

Partridge, G. P. et al., 2002, Single and Multicomponent Gas Phase Diffusion in a Porous Media: Modeling and Laboratory Measurements, Soil and Sediment Contamination: An international Journal, Vol. 14 Issue 14, pp. 555-581

Rambøll, 2008, Supplerende undersøgelse af forureningsudbredelse på Lyøvej 2, Rambøll, Feruar 2008

Rolston, D. E.; Moldrup, P.; 2002; Gas Diffusivity; In J. H. Dane and G. C. Topp (ed.) Methodsof soil analysis. Part 4. SSSA Book Ser. 5, ASA and SSSA, Madison, WI; pp 1113-1139.

Shimamura, K.; 1992; Gas diffusion through compacted sands; Soil Science; 153; 4; pp 274-279.

Steinberg, S. L. et al., 2005, Physical and Hydraulic Properties of Baked Ceramic Aggregates Used for Plant Growt Medium, Journal of the American Society for Horticultural Science, 130(5), pp. 767-774.

Singer, M. J. And Munns, D. N., 2006, Soils an Introduction, Pearson Prentice Hall, New Jersey 07458.

Taylor, S. A., 1949: Oxygen diffusion as a measure of soil aeration, Proc. Soil Science Society of America, 14, 55-60

Thorbjørn, K A., Moldrup, P., Blenstrup, H., Komatsu, T., and Rolston, D. E., 2008a, A Gas Diffusivity Model Based on Air-, Solid-, and Water-Phase Resistance in Variable Saturated Soil, Vadose Zone Journal, Vol. 7 No. 4.

Thorbjørn K. A., 2008b. Preliminary GADIUS (gas diffusivity in intact, unsaturated soils) project reports on Danish and American soils.

Thorbjørn, A. K., 2005, Master thesis, Transport of PCE from Source to Indoor Air - System Understanding and Statistics Analysis, Environmental Engineering, Aalborg University

Tuller, M., and P.A. (Ty) Ferré. 2009. Merging measurements and modeling in soil physics. STAiR (soil technology and innovative research) PhD course and materials, Arizona, Aarhus and Aalborg Univ. **Turcu, V. E.,** Jones, S. B. and Or, D., 2005 Continuous Soil Carbon Dioxide and Oxygen Measurementsand Estimation of Gradient-Based Gaseous Flux, Vadose Zone Journal 4, pp.1161–1169.

Van Genuchten, M. Th.; 1980; A closed-form equation for predicting the hydraulic conductivityof unsaturated soils; Soil Science of America Journal; 44; pp 892-898.

Warrick, A. W. (ed), 2002, Soil Physics Companion, CRC Press, Boca Raton, Florida 33431.

Yoshikawa, S. 2009. Data on Dune sand from Japan. Personal communication.

Web pages

WEB 1, Available: (http://www.ucmp.berkeley.edu/bryozoa/bryozoa.html) [05-08-2009]

WEB 2, Available: http://www.mst.dk/Jord/Forurenede+og+muligt+forurende+grunde/ [06-03-2009]

WEB 3 Availeble:
http://www2.mst.dk/common/Udgivramme/Frame.asp?http://www2.mst.dk/Udgiv/publikationer/2000/87-7909-996-3/html/samfat_eng.htm [02-07-09]

Appendix

14 Appendix 1

“Methods used in this project”

Gas diffusion measurements have in this project been performed on both packed and intact soil samples. As it appears in the Main report the soil has gone through different procedures both before and after measurements. Procedures as packing, wetting, drying and texture analysis.

Measurement series 1 and 2 have been performed on repacked soil samples where all three procedures have been performed.

Measurements series 3 has been performed on intact soil samples where wetting, drying and texture analysis has been performed.

Measurement series 4 and 5 have been performed on packed samples and packing, wetting and drying has been performed on these samples.

Before packing the soil samples, the soil dried for two days. As for the Lyøvej soil, this was also crushed and sieved in a 2 mm sieve.

Packing soil samples

Before packing the Lyøvej soil samples and the cosmos media samples the water content has been determined in the loose soil/media for being able to determine the amount of soil needed for packing a sample at a given bulk density.

The water content, w is found as the weight loss of a little soil sample after 24 hours in a 105 ^{o} C oven according to the Danish standardization Method (DS) 204. W is given in %.

The amount of soil that should be used to packed the samples at the given bulk densities is given as

$$M_s = \rho_b \cdot V_T + w \cdot \rho_b \cdot V_T \quad (14.1)$$

Figure 85 The packing equipment

For the packing is used a stamper, that consist of a pole by a circle shaped foot that matches the sample cylinder diameter, whereupon there a weight sits, that can be moved freely cf. Figure 84 to the right. Before packing, the soil is divided in three parts that is packed individually, so they individually fill 1/3 from sample cylinder. The packing is done by help from the stamper, of which the circle shaped foot is placed on the soil in the sample and the weight is than raised and falls free a certain a number of times. Afterwards the soil surface is scratched with a wire to avoid a permeable layer. A new part of the soil is poured into the sample and the same procedure is carried out. The amount of times the weight falls freely is doubled for each new fragment packed. For packing the Lyøvej samples (C1-C7) where the number of times the soil was stamped 2-4-8 times respectively. But for the Cosmos soil was it 2-2-2. As the soil did not “act” as a “normal” soil.

Wetting and drying procedure

All samples both intact and packed samples have been water saturated initially before starting the measurements of Dp/Do. This was done by placing the samples on a tray with 2 mm of water. On the tray was placed a grid where the samples was placed. The samples were placed on the tray for two days, where the tray was supplied with water continuously. After two days on the tray the samples drained for about an hour. This was done so that the samples did not drain in the diffusion chambers. The first measurement of Dp/Do where therefore not performed on completely saturated soil samples.

Between each Dp/Do measurement were the samples dried by air/oven drying or drainage on the retensionbox.

For the measurement series 1,2, 4 and 5 and part of measurement series 3 were the samples dried by air/oven drying. Between each measurement the samples did lose about 4-5 g of water. For each time the samples had dried were they put in a closed box and wrapped in foil for about two days. This was done to achieve equilibrium in the samples. During these two days was it also important that the samples where turned continuously.

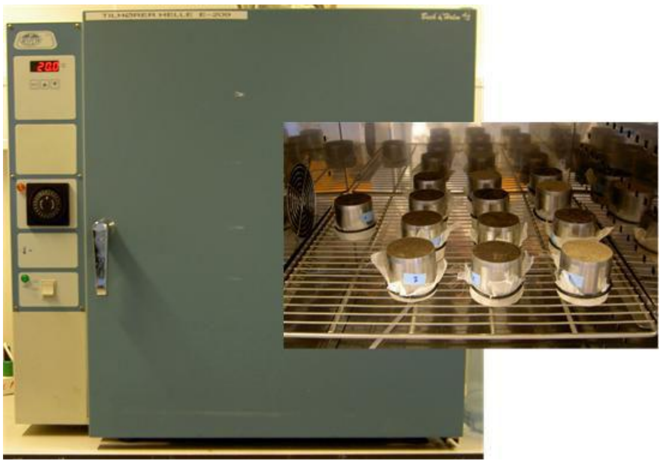


Figure 86 The incubator used to dry the samples in the end of the measuring series

In the end of the measuring series the samples where dried in an incubator at 30 ^{o} C for about one day to lose 4 g of water. For drying the samples completely were the samples also placed in the incubator but at 60 ^{o} C for four days. The incubator can be seen in figure 85.

In measurement series 3; in the experiment that where performed to check if the water was distributed equally independent of drying method (section 7) and in the experiment performed to check the validity of the retension curves made by Blonquist et al., 2005 regarding the packed cosmos samples in this project (section 7.1) where a so-called Eijkelkamp retention box used to drain the samples to a given pF value. The drainage level used in this project were pF 2, pF 2,7 and pF 2,9. In the figure below the retention box can be seen as well as a schematic drawing.

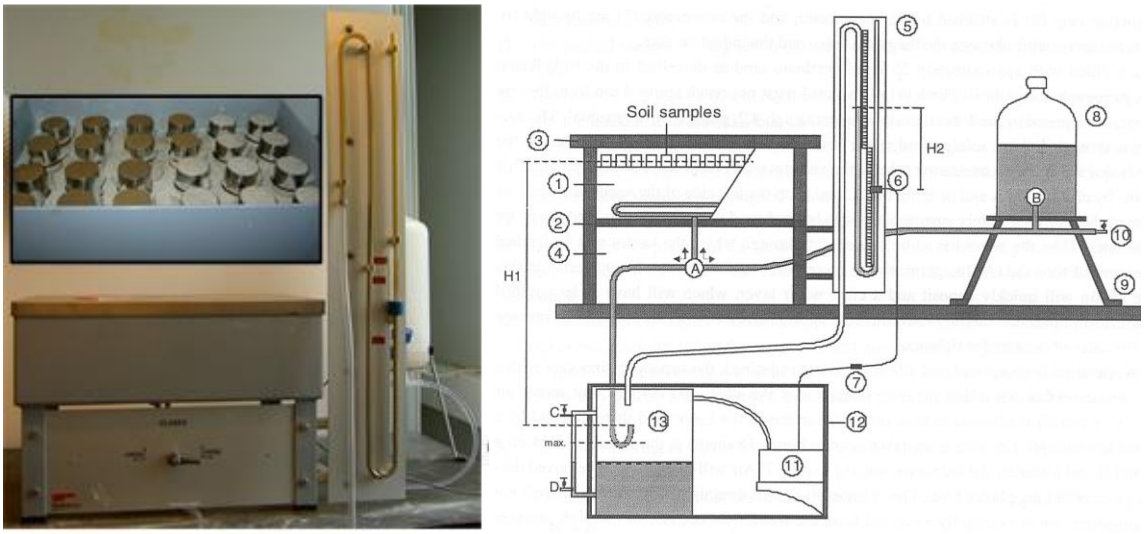


Figure 87 Retention box from Eijkelkamp used for draining intact and repacked soil samples to pF values at 2; 2,7 and 2,9. The sketch is from Loll and Moldrup, 2000 and the apparatus consist of following parts: 1, Rilsan-coated steel sample box, 2. Zink plated steel frame for sample box, 3. Aluminium cover with foam rubber lining, 4. Front panel with stopcock mounted on the samples, 5. Panel with U-tube mercury manometer, 6. Inducting ring, 7. Connectors, 8. Water supply bottle, 9. Zink plated steel standard for supply bottle, 10. Tab for connecting of sand box, 111. Vacuum pump, 12. Automatic inductive suction level control system, 13. Vacuum tank. (Loll and Moldrup, 2000)

The retention box is constructed as shown on the figure above. But consist mainly of a box covered with kaolin and a water supply bottle that keeps the kaolin layer wet, a vacuum pump for establishment of a suction and a manometer to adjust the wanted suction level. The soil samples are placed on the wet kaolin and are slightly pressed down to obtain an optimal contact with the kaolin surface. The manometer is set for the wanted suction level which is -100 cm, -500 cm and -800 cm. The samples will drain on the retention box for about two weeks. The samples can be taken of when the weight of the samples has been stabile for about three days. The loss of water that is accepted during the three days is of course depended on the amount of water in the sample (Relative water loss).

Determination air filled porosity for packed samples

For each Dp/Do measurement the air filled porosity in the sample has to be determined. Before and after each measurement has the sample therefore been weight. The air filled porosity has then been found as in eq. x below

$$\varepsilon = \frac{(W_{dry,total} - W_{wet,total})}{\rho_w} - \varphi \qquad (14.2)$$

Where,

$W_{dry,total}$ is the weight of the dry soil + sample

$W_{wet,total}$ is the weight of the wet soil + sample

P_w is the density of water 1 [g/cm^3 water]
Φ is the porosity of the sample (determination of this see this app)

Determination of porosity, bulk density and organic content on intact soil samples

The Dry bulk density, ρ_b in the 100 cm^3 intact Lyøvej soil samples is equal to the weight of the sample the sample have dried for 24 hours at 105°C, $W_{Dry,105°C}$. See eq. 14.3 below

$$\rho_b = \frac{(W_{Dry} - W_{Alu\ tray})}{100\ cm^3} \quad (14.3)$$

The weight of organic matter pr. 100 cm^3, M_{org} of soil is equal to the different in the weight of the sample before and after 2 hours at 550°C according to DS 204.

$$M_{org.} = (W_{Dry\ 105\ °C} - W_{Alu\ tray}) - (W_{oven,550\ °C} - W_{Alu\ tray}) \quad (14.4)$$

The porosity, ϕ is determined as given in eq. 14.5

$$\varphi = V_S - 100\ \text{cm}^3 \quad (14.5)$$

Where V_s is the volume of solids [m^3 soil m^{-3} soil vol.]

Vs can be calculated as given in eq. x

$$V_s = \frac{\rho_b}{\rho_s} \quad (14.6)$$

Where ρ_s can be calculated as given in eq. 14.7 below

$$\rho_s = W_{mineral\ \ part.,in\%} \cdot 2{,}65 Mg/m^3 + W_{organic\ \ cont.,in\ \%} \cdot 1 Mg/m^3 + W_{CaCO3,in\ \%} \cdot 2{,}7 Mg/m^3$$

(14.7)

Texture analysis

In this experiment, dry-sieving will be performed on the repacked and intact soil samples. Before sieving, the soil sample will be air dried at approximately 20 °C for 24 hours.The sieves applied have the following mesh sizes: 200 µm, 500 µm and 2000 µm. The sieves are placed on top of each other, ranging from the largest mesh size at the top to the smallest mesh size at the bottom, on a vibrating table. The experimental setup is shown in Figure 16 below. Beneath the 200 µm sieve, a bottom piece for collecting the soil particles less than 200 µm will be placed.

Figure 88 the experimental set up for determining the soil texture

Each soil sample is weighed and homogenized with a mortar, and then poured into the top sieve. Subsequently, the sample is sieved until the soil has stopped moving downwards through the sieves. When the sieving has finished, the sieves are removed according to the following procedure

1. For every sieve it will visually be evaluated if the soil has been homogenized enough. If this is not the case the remaining soil for each sieve will be homogenized again with the mortar, and then out back into the sieve. Then the sample is sieved again, until it is not possible to homogenize the soil sample further.
2. Then the individual sieve is removed and gently brushed in order to remove the fine dust sitting at the inner side of the sieve. The sieve is then emptied in a pre-weighed bowl by gently brushing the sieve’s mesh and, if necessary, easily knocking at the sides of the sieve.
3. The pre-weighed bowl containing the sieved soil sample is weighed. This procedure is done for every sample.

Measuring the gas diffusion coefficient, Dp/Do

In the following section is the analysis procedure described. There has been made some changes in the procedure that has been used so far. It is primarily in the calibration procedure and the in the calculation of the diffusion coefficient the changes has been made.

Measuring

As mentioned in section 5.4 the oxygen sensors should always be calibrated as the first thing and as the last thing in the calibration procedure the chambers are flushed with nitrogen. The chambers are therefore free of oxygen and ready for a measurement. The sample is therefore placed in the sample holder and the inner packing is filled with nitrogen keeping the sample airtight to the sample holder. Measurement of the diffusion through the soil sample can now start by pushing the slide back so contact between the soil sample and the chamber is established. To do this the nitrogen in the outer packing is discharged and the slide can be pushed back. After wards the outer packing should be filled with nitrogen again to keep the system airtight. During measurement the oxygen concentration is logged and monitored using a data logger and logger program.

The length of the measuring period depends very much on the soil sample for which the diffusion coefficient is wanted. In this project a measuring period of about ½-3 hours has been used depending on the soil type and the air content of the soil sample. But as a guideline the measurements have not been stopped until the oxygen concentration in the chamber has reached about 18 %. In Rolston and Moldrup 2002 is a method suggested for determination of measuring period based on parameters as dimensions of the equipment, volumetric air content and estimated diffusion coefficient. This method has been used to test if the measuring period was sufficient (see CD-rom ”New measuring equipment”).

Calculating the diffusion coefficient, Dp

The diffusion coefficient can be calculated based on Fick's low and an observation of the partly open system as seen in figure 88.

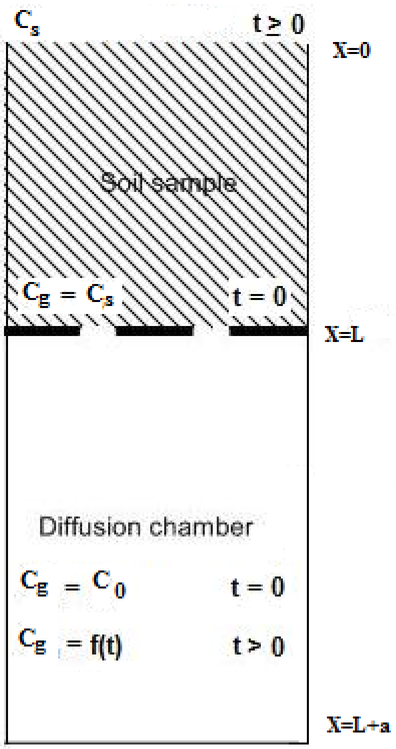


Figure 89 shows a diagram giving the initial and boundary conditions for the laboratory method for measuring the soil gas diffusion coefficient. Redrawn from Rolston and Moldrup 2002

As the system can be seen as a non steady state system cf. sectiont 5.1 the diffusion coefficient can be described by the combination of Fick's first and the continuity equation also known as Fick's second low.

$$\varepsilon \cdot \frac{\partial C_g}{\partial t} = D_p \cdot \frac{\partial^2 C_g}{\partial x^2} \qquad (14.8)$$

Where,

ε is the aircontent in the soil sample [m^3/m^3]

C_g is the concentration in the gas phase [g gas $\cdot$ m^{-3} soil air]

D_p is the diffusion coefficient [m3 soil air $\cdot$ m^{-1} soil $\cdot$ s^{-1}]

t is time [s]

x is height [m]

The height of the sample, L is 5,1 cm and the height of the chamber, a is 10,6 cm. The concentration in the atmosphere C_s, is constant during the measurement at 20,9 % oxygen corresponding to the concentration in the atmosphere, whereas the concentration of oxygen in the chamber C_g will be a function of time, and will only at t=0 equal C_0.

The concentration in the soil sample will only be 20,9 % at t=0 as N_2 will diffuse from the chamber an into the soil sample due to the N_2 concentration gradient.

When using Fick's second low it is assumed that the diffusion coefficient is the same everywhere in the sample and that the air content does not change in time or space. This is assumed to be the case, but as the soil samples are not completely homogeneous and evaporation occurs from the very wet samples during measurements, this is not completely fulfilled.

Equation (3.1) may be solved subject to the boundary and initial conditions given in figure 88. Carslew and jaeger (1959) has according to Rolston and Moldrup (2002) given a solution for the relative concentration as given in eq. 14.9 below

$$C_r = \frac{C_g - C_s}{C_0 - C_s} = \sum_{n=1}^{\infty} \frac{2 \cdot h\ e^{\left(-D_p\ \alpha_n^2 \cdot \frac{t}{\varepsilon}\right)}}{L \cdot (\alpha_n^2 + h^2) + h} \tag{14.9}$$

Where,

C_r is the relative concentration

C_g is the concentration of the diffusing gas in the chamber at time = t [g/m^3]

C_s is the concentration of the diffusing gas in the atmosphere [g/m^3]

C_0 is the concentration of the diffusing gas in the chamber at t=0 [g/m^3]

α_n is a constant

h is a constant

According to Rolston and Moldrup, will the terms n ≥ 2 be neglieble after some time and the equation is reduced to eq. 3.3 below.

$$C_r = \frac{2 \cdot h\ e^{\left(-D_p\ \alpha_1^2 \cdot \frac{t}{\varepsilon}\right)}}{L \cdot (\alpha_1^1 + h^2) + h} \tag{14.10}$$

As time and the relative concentration, C_r are the only variable parameters in eq. 14.11. The equation can be written as in eq. 3.4

$$\ln C_r = K \cdot t + konstant \qquad (14.11)$$

Where K is given as in eq 14.12

$$K = \frac{D_p \cdot \alpha_1^2}{\varepsilon} \qquad (14.12)$$

Plotting ln C_r against time will result in a linear curve after some time, with the slope, K. When estimating K by linear regression it is important that only the slope of the linear plot is used as eq. 14.12 is only valid in that area. In figure 89 is shown an example of a (t, ln $(C_g - C_s)/(C_0 - C_s)$) – plot.

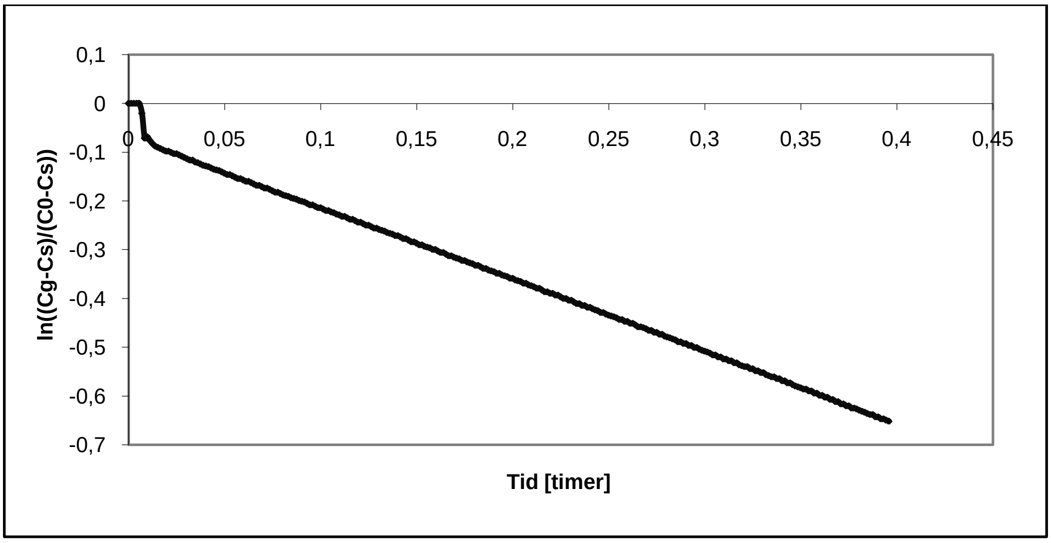


Figure 90 shows a (t, ln $(C_g - C_s)/(C_0 - C_s)$) – plot.

The linear ratio appears quickly in this plot but that is not the always the case so one has to be aware of that and find the data point where the best straight line appears and use those to estimate K.

When knowing K, the air content, ε and the constant α_1 the value of D_p can be determined. Indepedent determination of ε must be made from the soil bulk density and water content, θ and α_1 can be found as the smallest root in eq 14.13 below as this root equals α·L.

$$\alpha L \cdot \tan(\alpha L) = hL \qquad (14.13)$$

The root is determined using a table given in Rolston and Moldrup 2002 that lists sammenhængende values of hL and the first six roots in equation (14.13) (see CD-rom)

Firstly h is found from eq. 14.14 below

$$h = \frac{\varepsilon}{\alpha \cdot \varepsilon_c} \tag{14.14}$$

where,

a is the height of the chamber [m]

ε_c is the air content of the chamber [1 m^3/m^3 chamber]

15 Appendix 2

“Additional information on the Lyøvej soil and the Cosmos media”

In the following will additional information on the Lyøvej soil and the cosmos media be presented.

The Cosmos media

In connection with a project Blomquist et al., 2006 has observed the five cosmos media under field emission scanning electron microscope (SEM) to illustrate the size distribution and structure of the four media. These micrographs can be seen in figure 90 below.

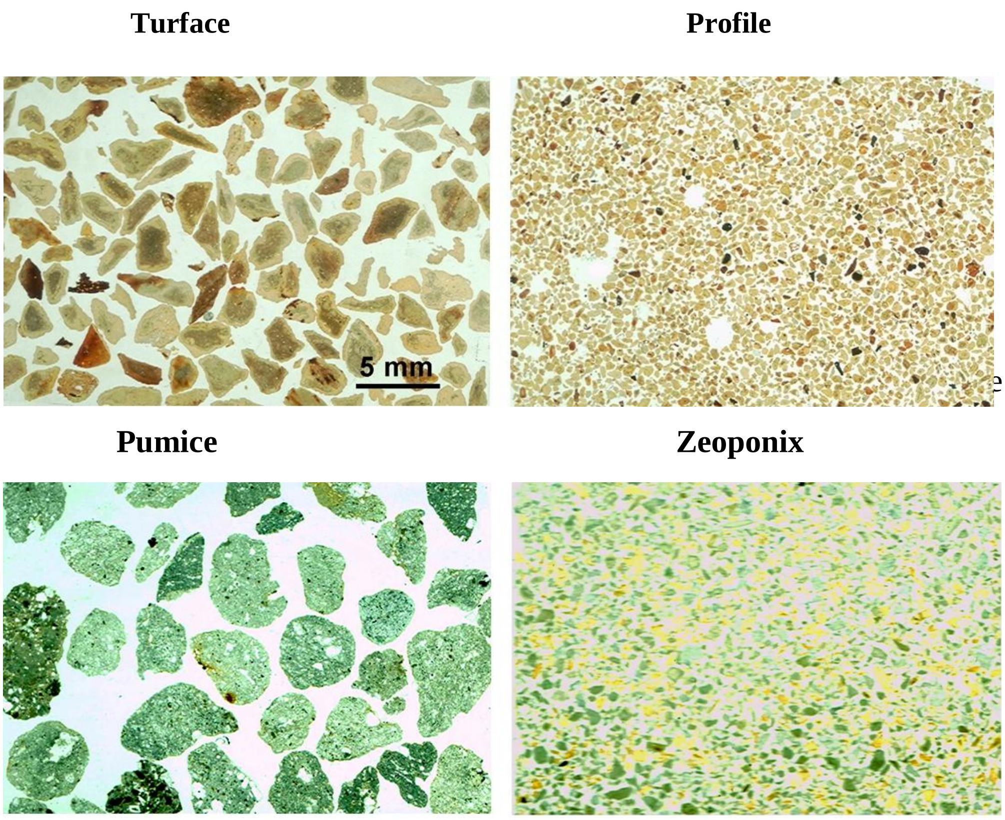
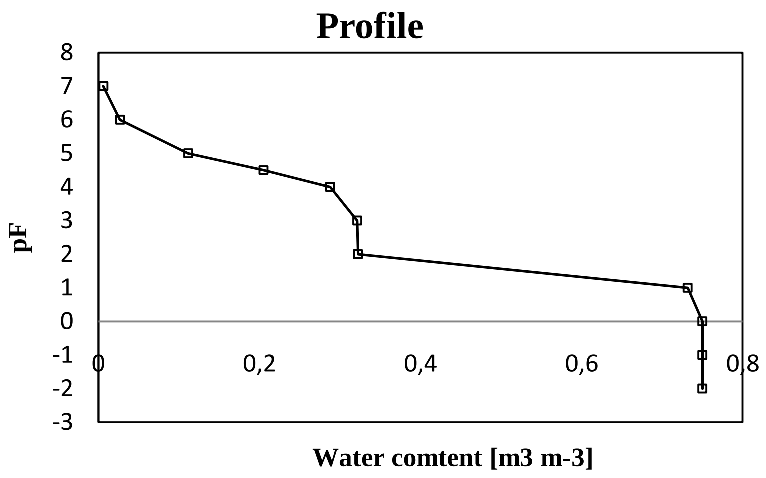
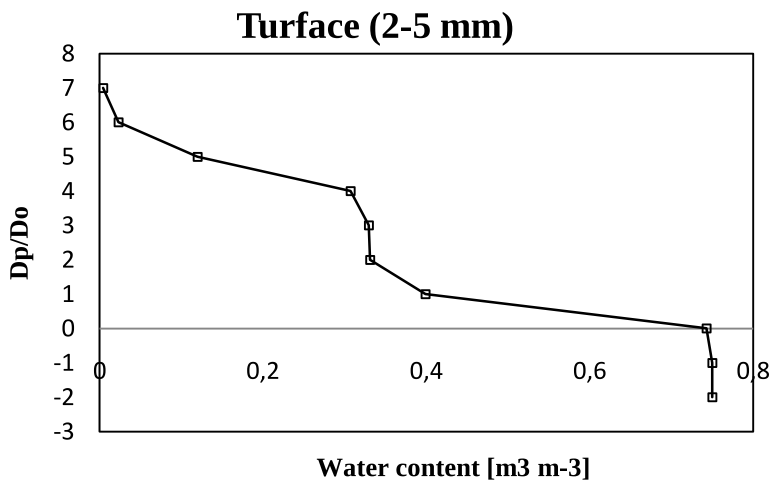


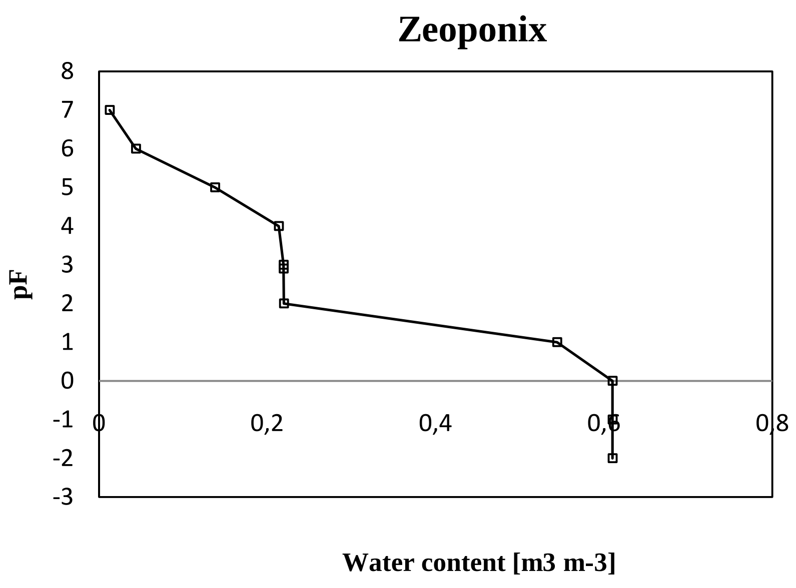
Figure 91 shows scanning electron micrographs of Turface, Profile, Pumice and Zeoponix. (Blonquist et al., 2006.)

Van Genuchten soil water retention characteristic

In the following are the van Genuchten soil water retention characteristic curves shown for Profile, Turface (2-5 mm) Zeoponic and Pumicee.


Profile
8
7
6
5
4
3
2
1
0
-1
-2
-3
pF
0
0,2
0,4
0,6
0,8
Water comtent [m3 m-3]


Turface (2-5 mm)
8
7
6
5
4
3
2
1
0
-1
-2
-3
Dp/Do
0
0,2
0,4
0,6
0,8
Water content [m3 m-3]


Zeoponix
8
7
6
5
4
3
2
1
0
-1
-2
-3
pF
0
0,2
0,4
0,6
0,8
Water content [m3 m-3]

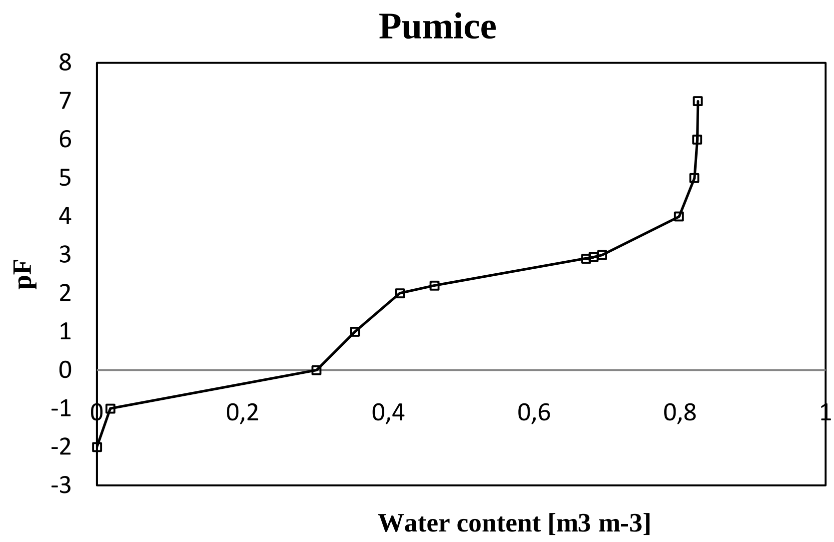


Figure 92 The van Genuchten soil water retention characteristic for Profile, Tyrface (2-5 mm), Zeoponix and Pumice.

The plots are made from the van Genuchten SWC model given as

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \sum w_i \left[\frac{1}{1+(\alpha|\psi_m|)^n}\right]^m \quad (14.15)$$

Where,

W_i weighting factor when modelling both inter and intra porosity

S_e is the residual volumetric water content

θ, is the water content [cm^3 cm^{-3}]

θ_s, is the water content at saturation [cm^3 cm^{-3}]

θ_r, is the residual water content [cm^3 cm^{-3}]

Ψ_m, is the matric potential [cm]

n, is a shape parameter

m, is a shape parameter (m=(1-(1/n)))

α, is a shape parameter [1/cm]

Table 19 The van Genuchten parameters for the inter pores

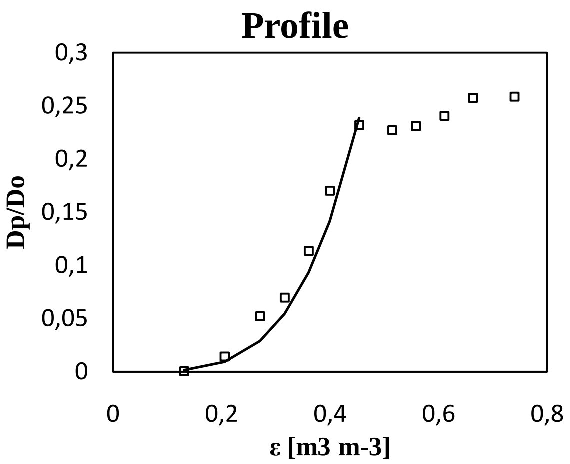
Parameter	Profile	Zeoponix	Turface(2-5 mm)	Pumice
residual water	0	0,027	0	0,005
α	6,56	8,14	27	377
n	7,01	6,92	2,78	2,41
saturated, θ	0,75	0,61	0,75	0,83
w1	0,57	0,64	0,56	0,43

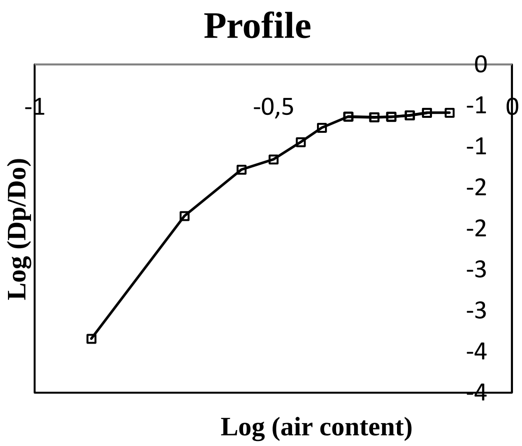
Table 20 The van Genuchten parameters for the intra pores

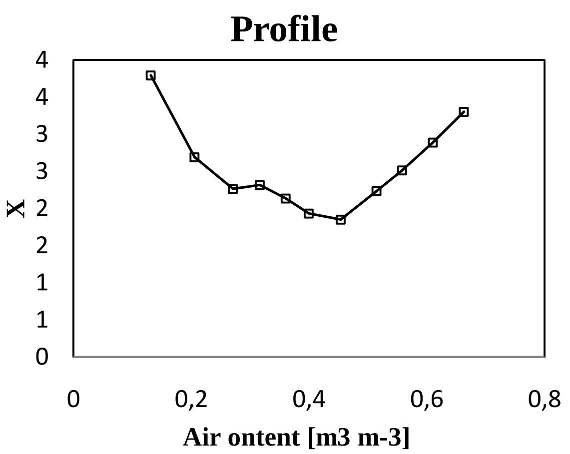
Parameter	Profile	Zeoponix	Turface(2-5 mm)	Pumice
α	0,00518	0,00194	0,00378	0,5843
Residual water	0	0,027	0	0,005
n	1,63	1,54	1,73	1,71
saturated, θ	0,75	0,61	0,75	0,83
w2	0,43	0,36	0,44	0,57

Determining inter and intra porosity of the cosmos media

For being able to analyse the Dp/Do Vs ε plot for the aggregated cosmos media was it important to have the precise determination of inter and intra porosity. They were given in Blonquist et al., 2006. But as for especially Zeopnix and Pumice did the packing result in some assumed differences according to the bulk density given in Blonquist et al., 2006. The inter and intra porosity were therefore determined for packed samples used in this project. The method is described in section x in the main report, but the plots can be seen below.







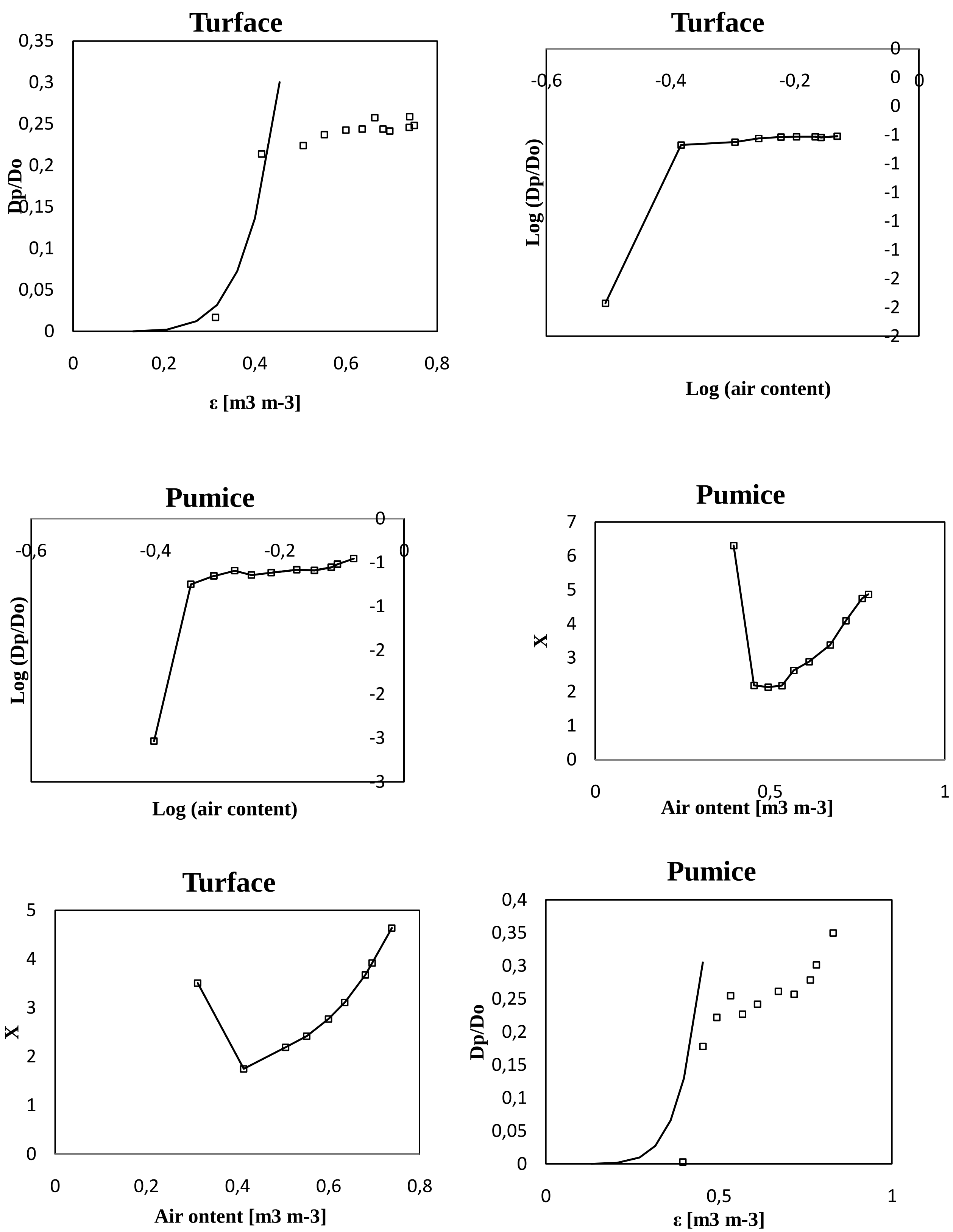
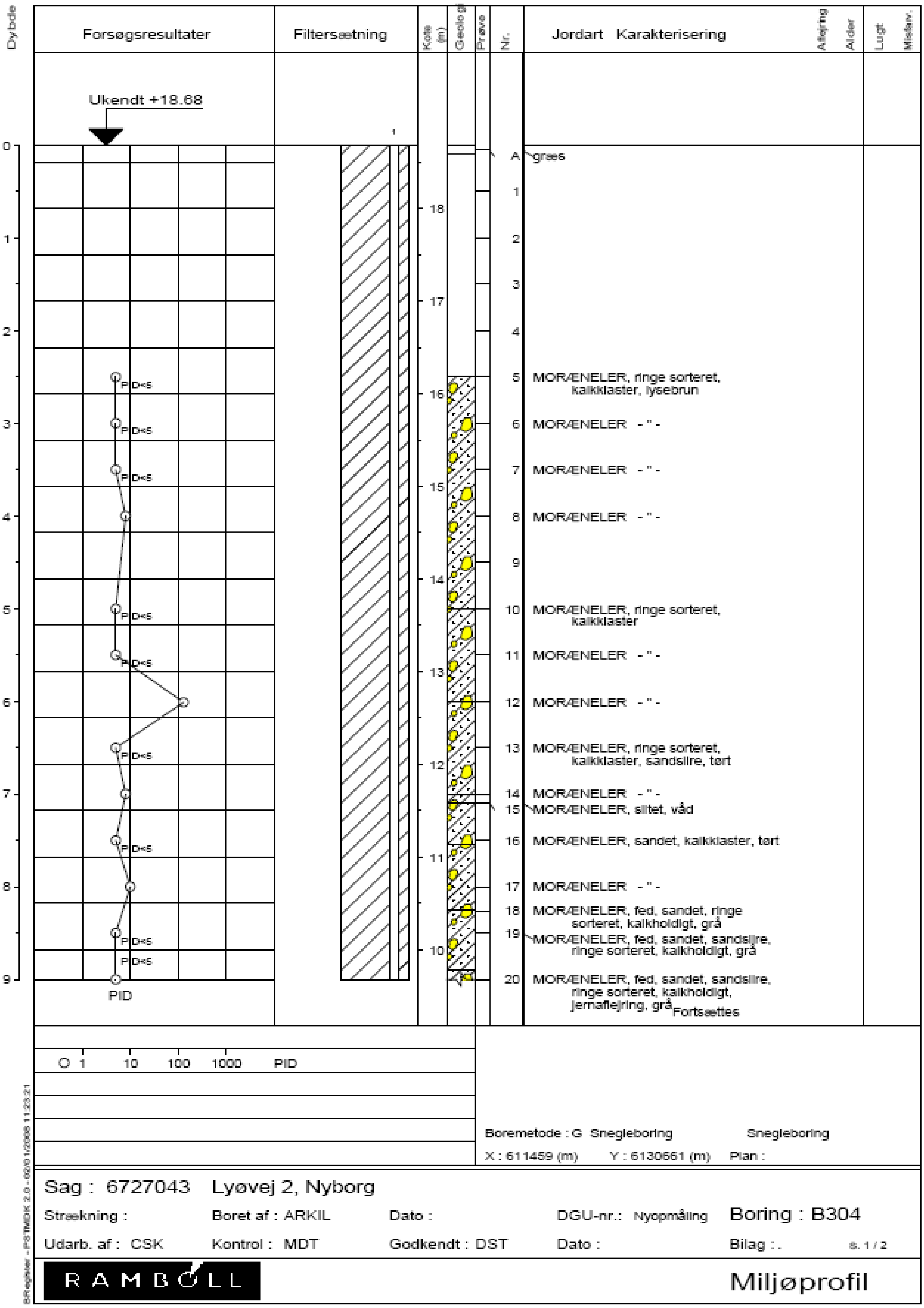
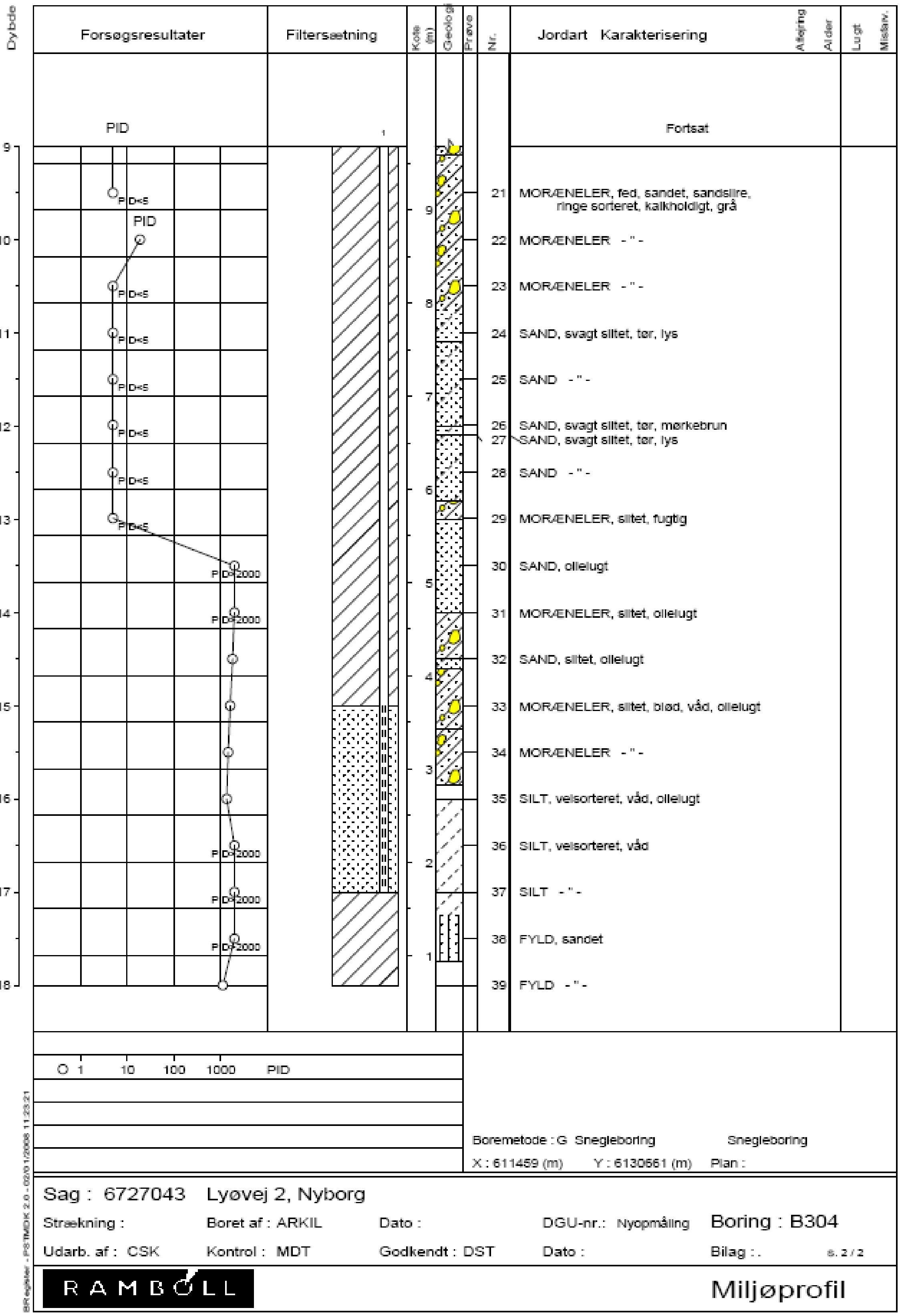


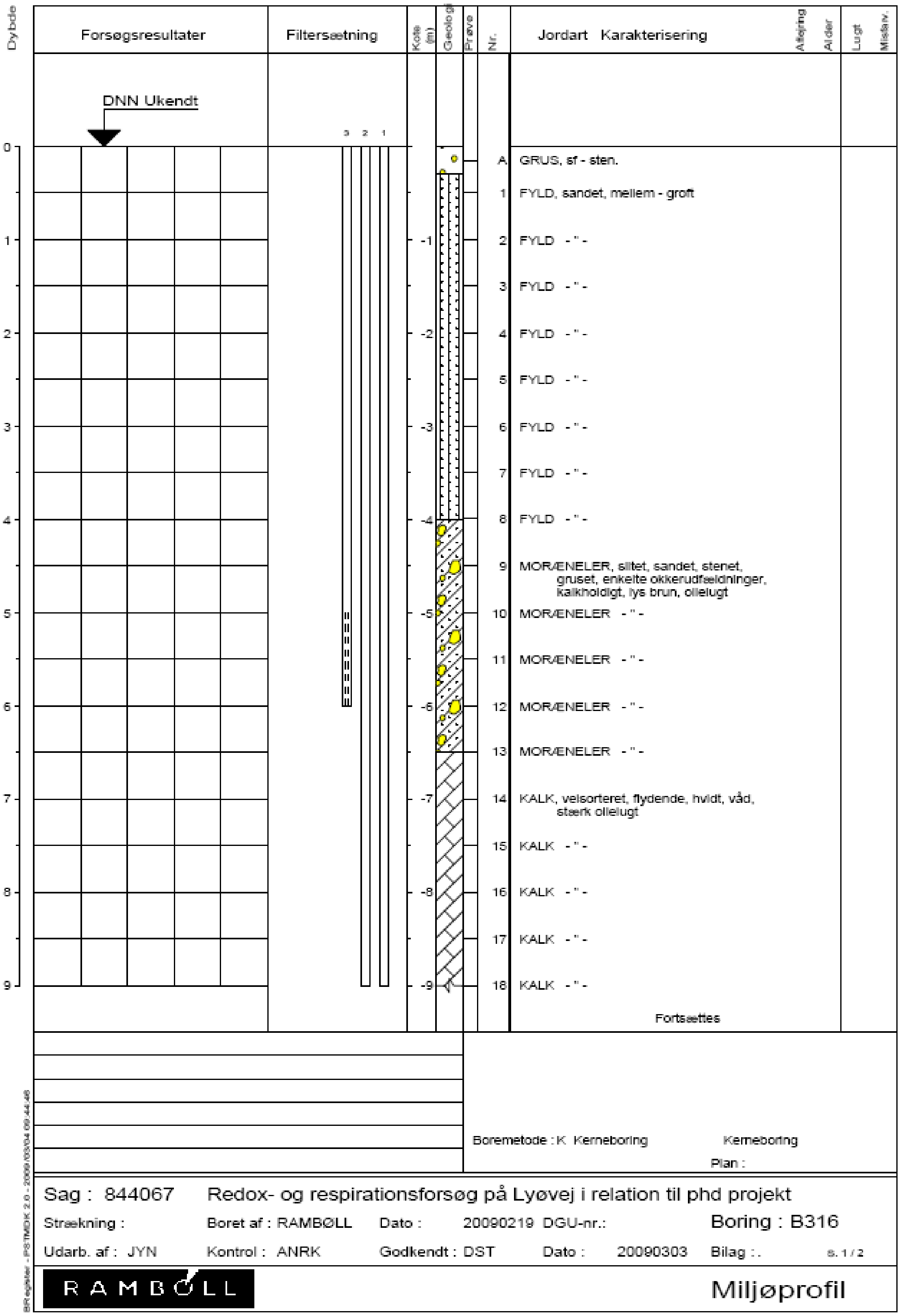
Figure 93 The Dp/Do Vs ε plot, Log (Dp/Do) Vs (ε) plot and the X Vs ε plot for Profile, Turface (2-5 mm) and Pumice

Borehole profile of borehole B304 at Lyøvej (Rambøll, 2008)




Dybde
Forsøgsresultater
Filtersætning
Kote (m)
Geologi
Prøve
Nr.
Jordart Karakterisering
Afsejring
Alder
Lugt
Misfarv.
PID
Fortsat
21 MORÆNELER, fed, sandet, sandslire, ringe sorteret, kalkholdigt, grå
22 MORÆNELER - " -
23 MORÆNELER - " -
24 SAND, svagt siltet, tør, lys
25 SAND - " -
26 SAND, svagt siltet, tør, mørkebrun
27 SAND, svagt siltet, tør, lys
28 SAND - " -
29 MORÆNELER, siltet, fugtig
30 SAND, olielugt
31 MORÆNELER, siltet, olielugt
32 SAND, siltet, olielugt
33 MORÆNELER, siltet, blød, våd, olielugt
34 MORÆNELER - " -
35 SILT, velsorteret, våd, olielugt
36 SILT, velsorteret, våd
37 SILT - " -
38 FYLD, sandet
39 FYLD - " -
PID<5
PID>2000
O 1 10 100 1000 PID
Boremetode : G Snegleboring Snegleboring
X : 611459 (m) Y : 6130661 (m) Plan :
Sag : 6727043 Lyøvej 2, Nyborg
Strækning :
Boret af : ARKIL
Dato :
DGU-nr.: Nyopmåling
Boring : B304
Udarb. af : CSK
Kontrol : MDT
Godkendt : DST
Dato :
Bilag : .
s. 2 / 2
RAMBØLL
Miljøprofil
BRegister - PSTMDK 2.0 - 02/01/2008 11:23:21

Borehole profile of borehole B316 at Lyøvej (Rambøll, 2008)



Dybde	Forsøgsresultater	Filtersætning	Kote (m)	Geologi	Prøve	Nr.	Jordart Karakterisering	Aflejring	Alder	Lugt	Misfarv.
		2 1					Fortsat				
9						19	KALK, velsorteret, flydende, hvidt, våd, stærk olielugt				
						20	MORÆNELER, siltet, sandet, stærkt gruset, enkelte flint, kalkholdigt, mørk grå				
10			-10			21	SAND, fint, velsorteret, svagt kalkholdigt, lys				
						22	SAND - " -				
11			-11			23	SAND - " -				
						24	SAND - " -				
12			-12			25	SAND - " -				
						26	SAND - " -				
13			-13			27	SILT, sorteret, stærkt leret, mørkebrun, fugtig, olielugt				
						28	SAND, fint, sorteret, svagt siltet, enkelte misfarvninger, mørk grå, svag olielugt				
14			-14			29	SAND - " -				
						30	SAND - " -				
15			-15			31	SAND - " -				
						32	SAND - " -				
16			-16			33	SAND - " -				
17			-17								
18			-18								

Boremetode : K Kerneboring Kerneboring

Plan :

Sag : 844067 Redox- og respirationsforsøg på Lyøvej i relation til phd projekt

Strækning : Boret af : RAMBØLL Dato : 20090219 DGU-nr.: Boring : B316

Udarb. af : JYN Kontrol : ANRK Godkendt : DST Dato : 20090303 Bilag : . s. 2 / 2

RAMBØLL Miljøprofil

Enclosure

16 Enclosure

In the following will Dp/Do measurements bee presented for the five measurements series. In the main report has only on measurement been showed but for each measurements series has triplicates been made. The yellow marks are uncertain measurements.

Measurements series 1

Drainage	C1		C2		C3	
	ε [m^3*m^{-3}]	**D_p/D_0**	**ε [m^3*m^{-3}]**	**D_p/D_0**	**ε [m^3*m^{-3}]**	**D_p/D_0**
Air	0,0987	0,000	0,089	0,001742	0,1105	0,000554
Air	0,1687	0,021	0,1675	0,024411	0,2229	0,013801
Air	0,2035	0,028	0,2556	0,046795	0,28535	0,08439
Air	0,27835	0,067	0,3035	0,08096	0,3367	0,144517
Oven	0,339	0,082	0,3513	0,143748	0,378	0,168158
oven	0,378	0,171	0,378	0,194442		
ρb	1,65 Mg/m^3		1,65 Mg/m^3		1,65 Mg/m^3	
φ						

Drainage	C4		C5		C6		L7	
	ε [m^3*m^{-3}]	**D_p/D_0**	**ε [m^3*m^{-3}]**	**D_p/D_0**	**ε [m^3*m^{-3}]**	**D_p/D_0**	**ε [m3*m-3]**	**Dp/D0**
Air	0,16	0,002	0,14	0,001961	0,16	0,047557	0,07	0,006433
Air	0,22	0,031	0,18	0,024369	0,22	0,029397	0,08	0,008533
Air	0,25	0,035	0,25	0,034721	0,25	0,035217	0,13	0,02149
Air	0,32	0,037	0,34	0,071952	0,31	0,061504	0,20	0,035577
Oven	0,38	0,061	0,39	0,107828	0,38	0,104657	0,25	0,051578
Oven	0,43	0,186	0,43	0,197985	0,43	0,178424	0,31	0,103592
Oven							0,35	0,14196
ρ_b	1,52 Mg/m3		1,52 Mg/m3		1,52 Mg/m3		1,72 Mg/m3	
φ								

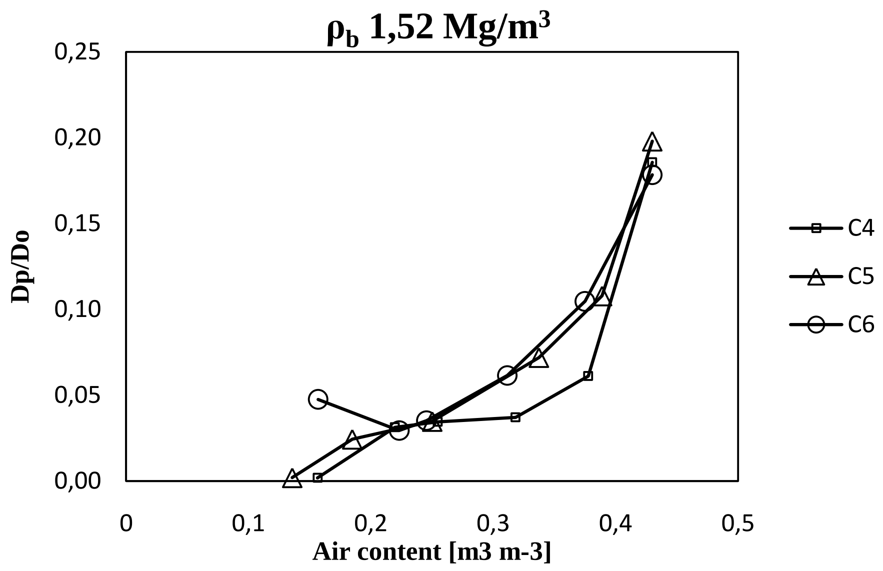


Figure 94 The Dp/Do Vs ε plot for the Lyøvej repacked soil samples, bulk density 1,52 Mg/m^3

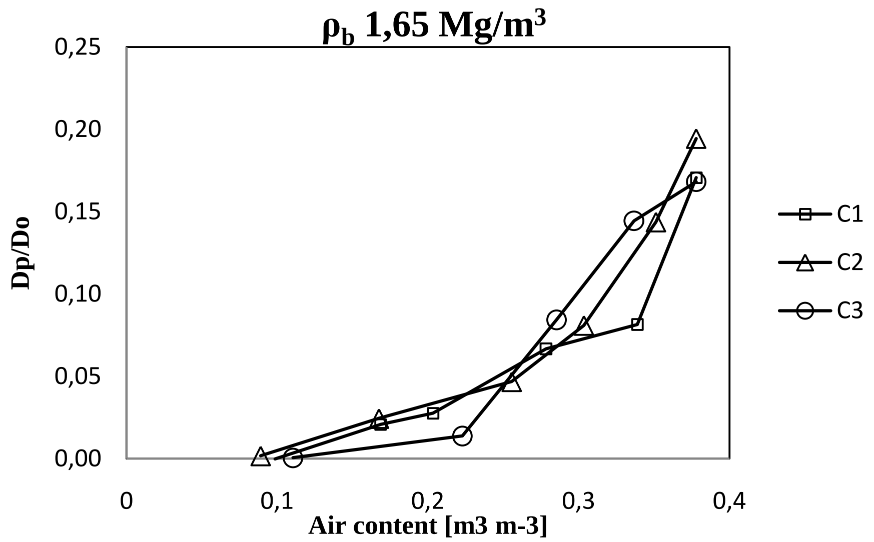


Figure 95 The Dp/Do Vs ε plot for the Lyøvej repacked soil samples, bulk density 1,65 Mg/m^3

Measurements series 3

Drainage level	Stony coarse loam (L1)		Stony coarse loam (L2)		Stony coarse loam (L3)	
	ε [m3*m-3]	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**
pF 2	0,023	0,011	0,023	0,017	0,023	0,022
pF2,7	0,029	0,022	0,031	0,029	0,048	0,032
Air dry 1	0,168	0,043	0,178	0,052	0,194	0,053
Air dty 2	0,235	0,066	0,235	0,067	0,235	0,067
Oven dry	0,258	0,065	0,256	0,068	0,255	0,072
P_b						
ϕ						

Drainage level	Limestone (L4)		Limestone (L5)		Limestone (L6)	
	ε [m3*m-3]	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**
pF 2	0,061	0,019	0,066	0,002	0,056	0,001
pF2,7	0,079	0,015	0,080	0,020	0,077	0,017
Air dry 1	0,324	0,083	0,323	0,083	0,327	0,090
Air dty 2	0,350	0,108	0,360	0,113	0,367	0,122
Oven dry	0,355	0,110	0,364	0,129	0,368	0,123
P_b						
ϕ						

Drainage level	Fine sand (L7)		Fine sand (L8)		Fine sand (L9)	
	ε [m3*m-3]	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**
pF 2	0,256	0,035	0,224	0,029	0,264	0,029
pF2,7	0,324	0,077	0,232	0,043	0,325	0,092
Air dry 1	0,354	0,128	0,331	0,094	0,366	0,150
Air dty 2	0,371	0,166	0,331	0,105	0,375	0,149
Oven dry	0,391	0,201	0,382	0,190		

Drainage level	Fine loam (L10)		Fine loam (L11)		Fine loam (L12)	
	ε [m3*m-3]	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**
pF 2	0,007	0,005	0,015	0,010	0,003	0,003
pF2,7	0,041	0,041	0,049	0,037	0,030	0,030
Air dry 1	0,184	0,060	0,203	0,064	0,194	0,051
Air dty 2	0,365	0,137	0,377	0,122	0,318	0,106
Oven dry	0,372	0,149	0,386	0,135	0,327	0,122
P_b						
ϕ						

Drainage level	Coarse sand (L13)		Coarse sand (L14)		Coarse sand (L15)	
	ε [m3*m-3]	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**
pF 2	0,321	0,032	0,145	0,002	0,227	0,067
pF2,7	0,363	0,092	0,324	0,095	0,289	0,134
Air dry 1	0,373	0,128	0,344	0,116	0,344	0,180
Oven dry	0,389	0,235	0,355	0,252		
P_b						
ϕ						

Measurement series 4 and 5

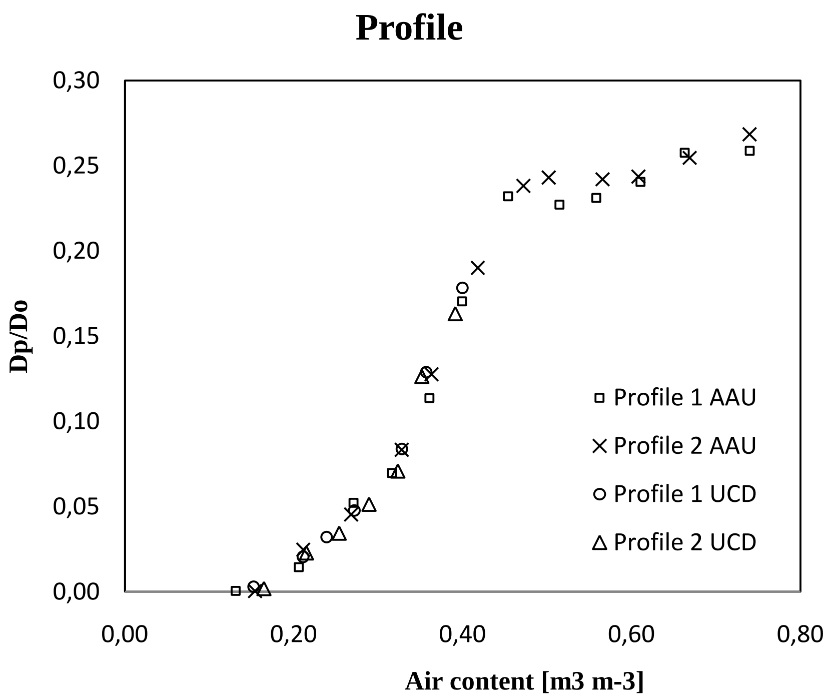
Profile 1 (AAU)

ε [m3*m-3]	**Dp/D0**	**(Dp/D0)/ε**	**X**	**h (m)**	**pF**	**θ/Vs**
0,13	0,000	0,003	3,79	0,14	1,14	2,474
0,21	0,014	0,069	2,69	0,16	1,19	2,176
0,27	0,052	0,193	2,26	0,17	1,23	1,916
0,32	0,070	0,220	2,32	0,18	1,27	1,734
0,36	0,114	0,315	2,13	0,20	1,31	1,557
0,40	0,170	0,426	1,93	0,24	1,38	1,402
0,45	0,232	0,511	1,85	81,88	3,91	1,184
0,51	0,227	0,441	2,23	220,72	4,34	0,941
0,56	0,231	0,414	2,51	366,43	4,56	0,766
0,61	0,241	0,394	2,89	678,36	4,83	0,557
0,66	0,258	0,389	3,30	1503,51	5,18	0,347
0,74	0,259	0,350	4,49	43896,38	6,64	0,040

Profile 2 (AAU)

ε [m3*m-3]	**Dp/D0**	**(Dp/D0)/ε**	**X**	h (m)	**pF**	**θ/Vs**
0,15	0,000	0,003	4,16	0,14	1,14	2,384
0,21	0,025	0,117	2,38	0,16	1,19	2,156
0,27	0,045	0,169	2,35	0,17	1,23	1,929
0,33	0,083	0,254	2,23	0,18	1,27	1,689
0,36	0,128	0,352	2,03	0,20	1,31	1,548
0,42	0,190	0,455	1,90	0,24	1,38	1,328
0,47	0,238	0,505	1,91	81,88	3,91	1,112
0,50	0,243	0,484	2,05	220,72	4,34	0,992
0,57	0,242	0,428	2,49	366,43	4,56	0,737
0,61	0,244	0,401	2,84	678,36	4,83	0,567
0,67	0,255	0,381	3,40	1503,51	5,18	0,325
0,74	0,268	0,363	4,37	43896,38	6,64	0,040

Profile 1 (UCD)		**Profile 2 (UCD)**	
ε [m3*m-3]	**Dp/D0**	**ε [m3*m-3]**	**Dp/D0**
0,15	0,003	0,16	0,002
0,21	0,020	0,22	0,023
0,24	0,032	0,25	0,034
0,27	0,048	0,29	0,051
0,33	0,084	0,32	0,071
0,36	0,129	0,35	0,126
0,40	0,178	0,39	0,163



Turface (1-2 mm)

Turface 1 AAU

ε [m3*m-3]	Dp/D0	(Dp/D0)/ε	X	h (m)	pF	θ/Vs
0,203	0,006	0,028	3,243	0,046	0,661	2,188
0,301	0,003	0,009	4,907	0,071	0,853	1,797
0,375	0,153	0,407	1,916	0,129	1,111	1,499
0,424	0,198	0,467	1,888	36,218	3,559	1,304
0,449	0,210	0,468	1,949	116,697	4,067	1,204
0,475	0,215	0,452	2,064	183,965	4,265	1,102
0,496	0,223	0,449	2,142	241,932	4,384	1,014
0,537	0,239	0,445	2,305	374,393	4,573	0,851
0,580	0,228	0,393	2,715	571,690	4,757	0,681
0,626	0,241	0,385	3,038	941,307	4,974	0,497
0,675	0,247	0,366	3,558	1984,111	5,298	0,299
0,750	0,251	0,335	4,804	1704446,328	8,232	0,000

Turface 2 AAU

ε [m3*m-3]	Dp/D0	(Dp/D0)/ε	X	h (m)	pF	θ/Vs
0,205	0,002	0,012	3,785	0,046	0,661	2,179
0,315	0,010	0,032	3,991	0,071	0,853	1,741
0,386	0,144	0,374	2,032	0,129	1,111	1,458
0,434	0,196	0,451	1,953	36,218	3,559	1,264
0,457	0,222	0,486	1,921	116,697	4,067	1,171
0,487	0,227	0,466	2,059	183,965	4,265	1,054
0,5001	0,224	0,447	2,161	241,932	4,384	1,000
0,538	0,244	0,453	2,274	374,393	4,573	0,850
0,58555	0,236	0,403	2,700	571,690	4,757	0,658
0,631	0,241	0,382	3,091	941,307	4,974	0,476
0,6837	0,249	0,364	3,657	1984,111	5,298	0,265
0,75	0,254	0,338	4,768	1704446,328	8,232	0,000

Turface 1 UCD / **Turface 2 UCD**

ε [m3*m-3]	Dp/D0	ε [m3*m-3]	Dp/D0
0,2096	0,012	0,2384	0,019
0,2755	0,018	0,28615	0,019
0,3177	0,018	0,326	0,031
0,37645	0,133	0,3901	0,145
0,4284	0,196	0,42865	0,209
0,46215	0,213	0,46275	0,221
0,49155	0,216	0,4894	0,211
0,5446	0,225	0,5427	0,234
0,57115	0,235	0,57115	0,230

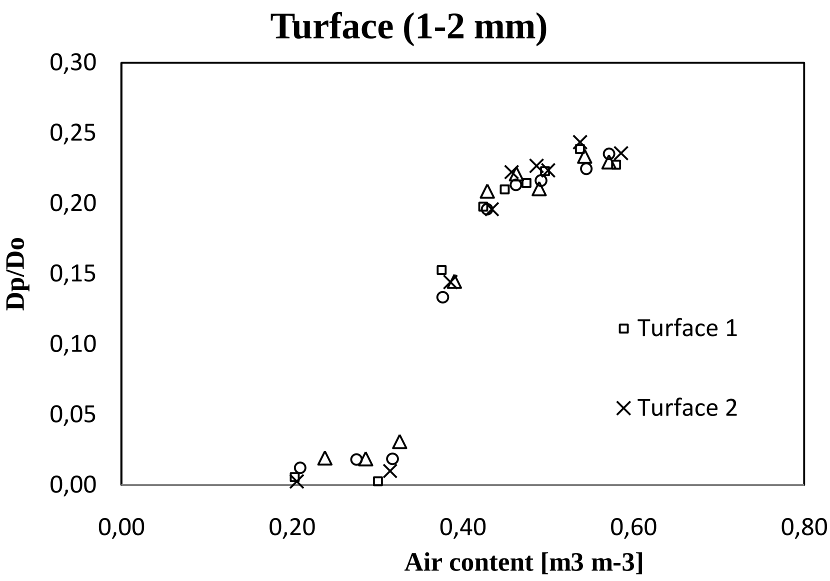


Figure 96

Turface (2-5 mm)

Turface 1 AAU **Turface 2 AAU**

ε [m^3*m^{-3}]	D_p/D_0	ε [m3*m-3]	Dp/D0
0,307	0,003	0,313	0,017
0,419	0,215	0,414	0,214
0,506	0,224	0,506	0,224
0,556	0,239	0,552	0,237
0,582	0,242	0,600	0,2425
0,619	0,2411	0,636	0,2438
0,681	0,2596	0,681	0,2438
0,717	0,24731	0,696	0,2414
0,750	0,2492	0,739	0,2459
		0,750	0,24832

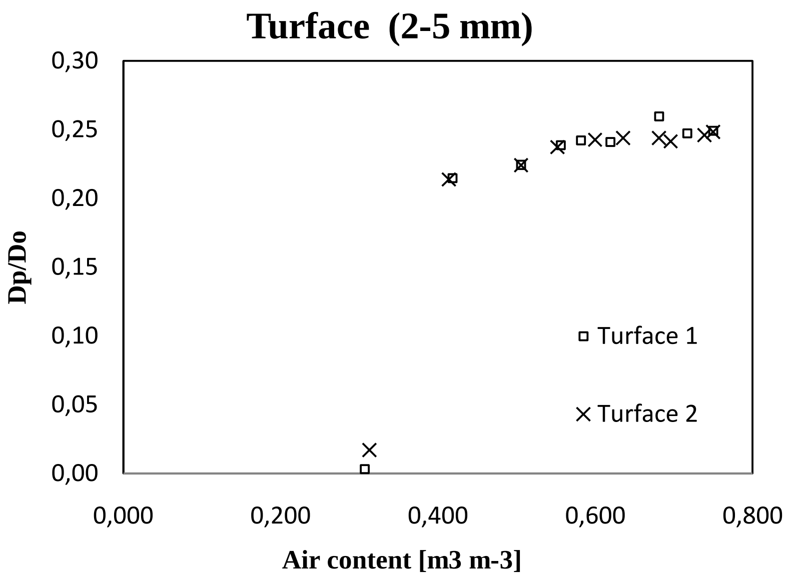


Figure 97

Zeoponix

Zeoponix 1

ε [m3*m-3]	Dp/D0	(Dp/D0)/ε	X	h (m)	pF	θ/Vs
0,149	0,00	0,009	3,50	**0,120944**	1,083	1,097
0,259	0,02	0,093	2,76	**0,148064**	1,170	0,837
0,332	0,07	0,210	2,42	**0,19529**	1,291	0,662
0,354	0,09	0,257	2,31	**0,447163**	1,650	0,609
0,392	0,13	0,327	2,19	**448,5628**	4,652	0,520
0,441	0,18	0,413	2,08	**1287,649**	5,110	0,403
0,495	0,23	0,457	2,11	**4921,906**	5,692	0,274
0,531	0,23	0,427	2,34	**29791,81**	6,474	0,188
0,572	0,23	0,406	2,61	**101020,4**	7,004	0,091
0,576	0,24	0,416	2,59	**253583,6**	7,404	0,081
0,610	0,24	0,400	2,86	**3,17E+29**	31,501	0,000

Zeoponix 2 AAU		Zeoponix 1 UCD		Zeoponix 2 UCD	
ε [m3*m-3]	Dp/D0	ε [m3*m-3]	Dp/D0	ε [m3*m-3]	Dp/D0
0,172	0,00	0,1821	0,00	0,19425	0,001
0,260	0,03	0,252	0,02	0,25755	0,020
0,318	0,06	0,2863	0,04	0,3269	0,055
0,347	0,08	0,3122	0,05	0,36575	0,089
0,391	0,12	0,3458	0,08	0,40165	0,137
0,439	0,20	0,37075	0,08	0,4359	0,175
0,49595	0,24	0,4008	0,14	0,46535	0,213
0,534	0,24	0,4342	0,18	0,4982	0,239
0,574	0,24	0,4744	0,24		
0,584	0,24				
0,610	0,24				

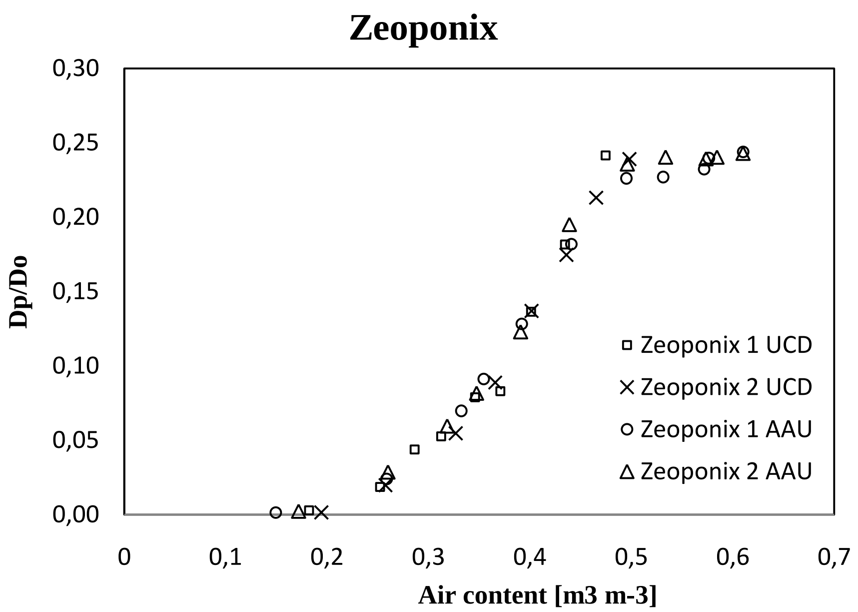


Figure 98

Pumice

Pumice 1 AAU

ε [m3*m-3]	Dp/D0	(Dp/D0)/ε	X	h (m)	pF	θ/Vs
0,396	0,003	0,007	6,302	0,878113	1,94355	2,411
0,454	0,178	0,392	2,186	1,589667	2,201306	2,089
0,494	0,222	0,449	2,136	2,181376	2,33873	1,865
0,494	0,221	0,448	2,139	2,168957	2,336251	1,865
0,534	0,255	0,477	2,179	2,891104	2,461064	1,644
0,568	0,2267629	0,399	2,626	3,677581	2,565562	1,454
0,612	0,241660822	0,395	2,888	5,117463	2,709055	1,214
0,672	0,261213696	0,389	3,375	8,81987	2,945462	0,879
0,717	0,25671181	0,358	4,094	15,45124	3,188963	0,626
0,764	0,278387588	0,364	4,747	29,69205	3,47264	0,368
0,782	0,301434016	0,386	4,869	48,61464	3,686767	0,268
0,830	0,349700804	0,421	5,639	1,23E+26	28,0916	0,000

Pumice 2 AAU		Pumice 1 UCD		Pumice 2 UCD	
ε [m3*m-3]	Dp/D0	ε [m^3*m^{-3}]	D_p/D_0	ε [m^3*m^{-3}]	D_p/D_0
0,387	0,074	0,441	0,003	0,417	0,007
0,444	0,200	0,486	0,146	0,466	0,158
0,482	0,231	0,519	0,252	0,507	0,242
0,513	0,238	0,548	0,267	0,531	0,247
0,520	0,2330	0,573	0,253	0,554	0,241
0,549	0,2288	0,630	0,263	0,6087	0,251
0,588	0,2371	0,658	0,286	0,6382	0,2742
0,647	0,26246				
0,694	0,26960