Norwegian University
of Life Sciences

Master's Thesis 2024 60 ECTS
Faculty of Environmental Sciences and Natural Resource Management

Could alteration of cemetery soil with artificial sand contribute to better bodily decomposition? A study of physical and hydraulic properties of machine crushed sand and their potential to facilitate microbial decomposition

Sigrid Esmeralda Arnestad
Environmental sciences

Acknowledgement

The work behind this assessment would never have been possible without the help from my main supervisor and Professor Attila Nemes, for his academic support and steady guidance into the world of soil physics, and not least for his availability and engagement concerning this topic. Inghild Økland for giving me the opportunity to work on this exiting project, and valuable feedback and editing help that carried me through the writing process. It has been a pleasure to work with both of you. I also want to thank Øyvind Peder Vartdal for his excellent help in the laboratory, and all the people that have provided me with valuable information.

I would also like to offer a special thanks to my family and friends for their encouragement and faith in me in times when I needed an extra push, and to my fellow classmates for late night advice, good vibes, and much time spent together. Finally, I want to thank my boyfriend Jonathan Linnerud for keeping up with me and motivating me through the process of finalizing this thesis.

Sammendrag

På norske gravplasser er plassmangel et problem grunnet svært treg nedbrytning av menneskekropper som fremdeles kan være intakte etter flere tiår i en kistegrav. Ved etablering av nye gravfelt har masseutskifting med blandinger av maskinelt knust sand blitt benyttet for å sikre god drenering. Det eksisterer derimot lite kunnskap om langtidseffekten av denne type kunstig jord på nedbrytning i kistegraver. Knust sand fra stein har troligere høy pH og skarpere overflater som sannsynligvis pakkes annerledes enn naturlig rundet sand, hvilket kan ha betydning for jordfysiske egenskaper og påvirke transport og innhold av vann og luft. De antatte egenskapene kan påvirke forhold som styrer den mikrobielle aktiviteten, som er avgjørende for god nedbrytning. Oppgaven har derfor som formål å bidra til økt kunnskap om egenskaper til knust sand gjennom å karakterisere fysiske, hydrauliske og kjemiske egenskaper, samt å undersøke jordmassenes påvirkning på organisk mikrobiell nedbrytning. Ulike tester ble gjennomført i et lysimeteranlegg på følgende utvalg av sand; to typer knust sand, to naturlige sand, og fire typer blandinger av disse. Teposer ble begravd i to dybder med kontrollert vannstand og standard fysiske og kjemiske analyser samt vannlagringskapasitet ble undersøkt på jordprøver i lab. I tillegg ble infiltrasjonshastighet målt på jordmassene i lysimetrene.

Resultatene fra studiet viste at massetap av te var signifikant mindre i knust enn naturlig sand, forholdsvis i det øvre jordlaget. Det antas at dette i hovedsak skyldes redusert mikrobiell nedbrytning, trolig som følge av høyere pH, lavt innhold av organisk materiale og for lite fuktighet i de knuste massene. Sistnevnte antakelig på grunn av lav vannlagringskapasitet. Nedbrytning av te var generelt lavere i det nedre jordlaget, trolig grunnet redusert oksygen som følge av mer fuktighet fra den nærliggende vannstanden. I de groveste kunstige og naturlige sandtypene ble det derimot ikke observert redusert nedbrytning i det nedre jordlaget, mulig som følge av fravær av kapillært vann fra den nærliggende vannstanden og antakelig fremdeles opprettholdelse av aerob mikrobiell aktivitet. Samtidig bør det bemerkes at forskjellene i nedbrytning stort sett ikke var signifikante mellom noen av jordtypene i dette jordlaget.

Sandpartiklene ser ut til å være betraktelig mer kantet enn de naturlige, men studien viste ingen overbevisende forskjell i total porøsitet og det er behov for mer forskning på langtidseffekten av konsolidering som følge av forskjeller i partikkelform. I alt indikerer resultatene at mikrobiell nedbrytning kan begrenses i knust sand sammenliknet med naturlig, noe som vil være ugunstig dersom massene benyttes på kirkegårder der det er ønske om høy mikrobiell aktivitet og nedbrytning.

Abstract

Decomposition is so slow in several Norwegian cemeteries that bodies have been found intact after decades in the soil, ultimately leading to a shortage of burial space. Soil alteration with mixes of artificial crushed sand from rock has been utilized in recent constructed cemeteries to improve drainage, but little is known about the impact of these materials on the microbial decomposition processes in soil. Artificial sand is suggested to have angular surface shape, possibly affecting physical and hydraulic behaviour, and higher pH, both of which could influence microbial decomposition rates. The aim of this thesis was therefore to characterize artificial sands in terms of their physical, hydraulic, and chemical properties and investigate their effect on microbial decomposition. To achieve this, several tests were performed in a lysimeter facility on a selection of four artificial and natural sands, and four mixes of these. To collect short term indicators of decomposition, teabags were buried in the soils at two depths with controlled water table. Standard physical and chemical analysis and the measurement of their water retention characteristics were performed on soil samples in the lab, while infiltration capacity was measured *in-situ* in the lysimeters.

The results from the decomposition experiment showed significant less mass loss of tea in the artificial sands compared to natural sands in the upper layer. It is assumed that this is likely due to microbial decomposition which may have been reduced by high pH, low organic matter content, and limited moisture. The latter probably as an effect of poor retention. The decomposition of tea decreased in most soils in the lowest layer closest to the water table, likely due to unfavourable air-water conditions. In contrast, decomposition did not decrease with depth in the coarsest artificial and natural sands. One suggestion could be the absence of upward capillary water movement still sustaining sufficient air-filled porosity for aerobic respiration. However, differences in decomposition between the soil types were mostly insignificant in this layer.

Physical particle characterisation support that crushed sands are more angular than natural sands, but further studies are needed to determine the long-term effect on physical shape after allowing longer time for consolidation. In all, results from this study indicates that microbial decomposition may be more limited in artificial sands compared to natural sands, which could have implications for bodily decomposition if utilized in cemeteries.

Table of Contents

List of figures

List of tables

1 Introduction

1.1 Background

Soil burials in coffin graves have a long tradition in Norway, and became the main burial practice with the Christianisation of Norway (NOU 2014:2, p. 26). The importance of a bodily return to soil is not only reserved for the belief in a spiritual resurrection, but is highly necessary for practical reasons such as space, particularly if the tradition of coffin burials is to continue, as the majority still prefers today (*Kremasjonsandelen*, 2024). In many Norwegian cemeteries, however, bodies are not undergoing complete decomposition (Økland et al., 2022). Even after 20 years, which is the required preservation time in Norway (Gravplassloven, 1997, § 8), the remains may still not have decomposed properly, and in some cases bodies have been found almost intact (Økland et al., 2022). In addition to the strain this puts on cemetery workers, incomplete decomposition leads to lack of burial space. Graves are by law not allowed to be reused if more than coffin or coarse bones remains (Gravplassforskriften, 1997, § 12). The reuse of graves is important to free up space, but where this is not possible due to problems with incomplete decomposition, shortage of space becomes a problem. Worse case, a lack of space may put people into unwanted situations where they must decide upon other burial practises, such as cremation. Although many choose cremation, statistics show that the practice of soil burial is the preferred ritual nationally (*Kremasjonsandelen*, 2024). Considering that the population is expected to grow (Leknes & Løkken, 2022), and the municipalities must provide sufficient burial space to 3 % of their citizens (Gravplassloven, 1997, § 2), the need for functional burial sites is inevitable. This is especially important for limiting the need to constantly expand into new areas, often at the expense of agricultural land (NOU 2014:2, p. 39).

The decomposition of soil buried corpses is mainly driven by microorganisms like fungi and bacteria (Carter et al., 2010; Klingberg, 2005). Their activity is controlled by various environmental factors, and importantly by temperature (Paul, 2014, p. 33). When the temperature reaches below 5°C, most microorganism are not active (Weil & Brady, 2017, p. 527). The nature of Norwegian climate, with long and cold winters (Dannevig & Harstveit, 2022), is therefore not favourable for rapid decomposition. Carter *et al.* (2008) demonstrated the relationship between temperature and decompositions of rats and found that the last stage of decomposition was not observed at 15°C, but at 22 and 29°C. In addition to temperature, other factors like moisture (Carter et al., 2010), burial depth (Schultz, 2007), type of cover (Teo et al., 2021), type of coffin (Klingberg, 2005), and individual characteristics (Pless et al., 1996) will influence the processes and rate of human decomposition.

In Norwegian cemeteries, unfavourable soil conditions may be the most important factor that prevents bodies from decomposing. A recent study of more than 70 graves in various Norwegian cemeteries suggested that stagnated water due to insufficient drainage was causing much of the incomplete decomposition (Økland et al., 2022). A soil that is saturated with water is depleted in oxygen, which aerobic microorganisms like fungi and bacteria depends on (Weil & Brady, 2017). Consequently, the microbial activity, which is suggested a major contributor to decomposition of soil buried cadavers (Carter et al., 2010), is limited, and may prevent decomposition. For this reason, cemeteries are strongly discouraged from being built on permanently waterlogged soils like wetlands or bogs (Klingberg, 2005). Adipocere, or "grave wax", may also be formed under anaerobic conditions in waterlogged or moist graves (Pless et al., 1996) and may inhibit further decomposition (Fiedler et al., 2015; Forbes et al., 2005). Consequently, conditions that slows the decomposition rate, and promote formation of adipocere, must be limited to ensure continued reuse of graves.

Problems with waterlogged graves can arise for a number of reasons, including incorrectly installed artificial drainage, location in the terrain, and/or unsuitable soil (Økland et al., 2022). In a cemetery in Trondheim, a case was reported were a woman was found completely intact after 70 years of burial in a heavy clay soil (Krüger, 2019). This example illustrates that the type of soil, and soil texture, may be of considerable importance for the decomposition rate, or in this case preservation of the body. Although the decomposition processes of human corpses within coffin graves is complex, and subject to various influencing factors, soil is the very habitat for microorganisms and its properties strongly influence key living conditions for microbiological life (Paul, 2014). The next chapter will therefore focus on soil properties that affect microbial activity and which are suggested to influence the rate of decomposition of corpses. Principles of soil physical and hydraulic properties will be presented, as they form the basis of today's recommendations for soils in cemeteries, as well as challenges that follows the current knowledge gap. This will lead to the final focus of this thesis.

1.2 The importance of soil

Texture

The distribution of different particle sizes in a soil, normally divided into clay (<0.002 mm), silt (0.06-0.002 mm), and sand (2-0.06 mm), forms the *texture* of the soil and controls key physical and hydraulic properties important for the air and moisture status in the soil (Weil & Brady, 2017, p.152). Texture influences the total pore space which accommodate the content of air and water, and importantly the *pore size distribution* which control the rate and movement of water (Weil & Brady, 2017, p. 189-92). In fine textured soil like clay, the pores are very small and water is strongly absorbed due to capillary forces, and both air and water movement is considerably slow (Weil & Brady, 2017, p. 153). This may cause poor soil aeration and exhausted oxygen levels (Weil & Brady, 2017, p. 303). In the example from Trondheim, where the body was preserved in a heavy clay soil, absence of decomposition may be due to low drainage capacity associated with clay, causing too high moisture content and poor soil aeration. Although certain microorganisms are anaerobic and can perform metabolism with other elements than oxygen, *aerobic* microbial activity is more efficient (Weil & Brady, 2017, pp. 552–553), and decomposition rate of corpses will increase in oxygen rich environments (Dent et al., 2004). The decomposition of adipocere may also be enhanced in oxygenated environment (Fründ & Schoenen, 2009). This illustrates the importance of a soil that accommodates a high air-filled porosity, particularly considering that oxygen diffusion is 10 000 slower in water than air (Weil & Brady, 2017, p. 305).

The importance of soil texture has been demonstrated in experimental studies and observations of human remains in cemetery graves. Experimental studies of pigs by Schultz (2007) found that cadavers decomposed slower in clay compared to sand. These findings are supported by soil characterisation in Norwegian graves, and associated degree of decomposition. Økland et al. (2022) found a strong relation between texture and decomposition of corpses, and that well-decomposed bodies, particularly the soft tissues, were associated with graves of sandy soils (Økland et al., 2022). Water in large pores of sandy soils is less affected by capillary forces, which only occur in the smaller pores, and will easily drain due to the influence gravity (Weil & Brady, 2017). Sandy soils may therefore better facilitate aeration than clay soil. This is supported by a study from Carter et al. (2010) who reported greater decomposition of cadaver rats in wet sandy soils than wet clay soils, and suggested that this was likely due to better gas exchange in the sandy soil.

Recommended grain size distribution

From the study by Økland et al. (2022) a recommended grain size distribution interval was compiled based on graves with good decomposition (Figure 1). According to this interval, soils with grain size distribution within this interval should facilitate good decomposition. The outer boundaries correspond to the texture class loam ("lettleire" in Norwegian), and coarse sand, but have in common to contain more than 50 % sand (<0,06 mm) (Økland et al., 2022).

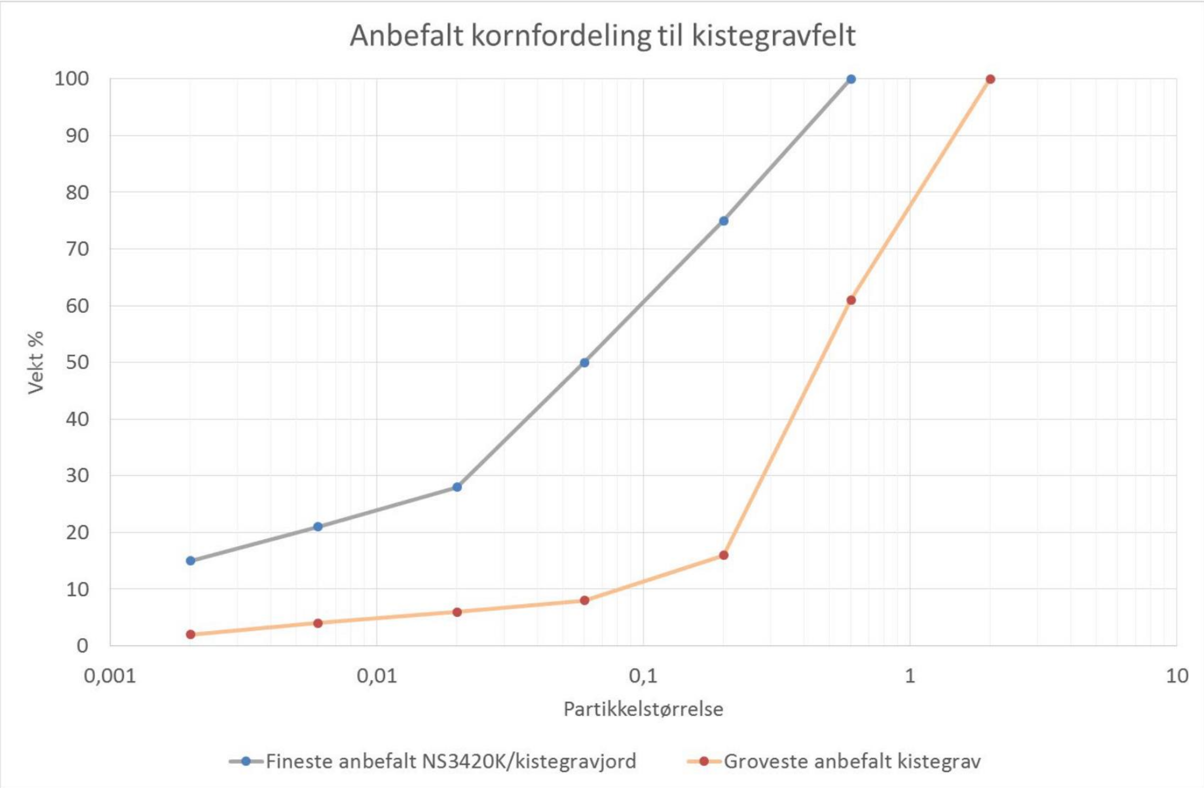


Figure 1: Recommended grain size distribution interval for grave soils, with maximum recommended fine particles (blue), corresponding to a "loam" and maximum recommended coarse particles (orange), corresponding to a «coarse sand". Based on this recommendation, the minimum recommended fraction of sand (>0,06 mm) is 50 % of the total volume of soil. The figure is taken from Økland et al. *(2022), p. 101.*

It must be considered, however, that poor decomposition also was observed in soils within this texture interval, indicating that other factors than soil texture must influence decomposition (Økland et al., 2022).

Organic matter and pH

For microorganisms to exist in the first place, there must be nutrients and sources of carbon and nitrogen available (Weil & Brady, 2017, p. 553). Schnürer et al. (1985) demonstrated a strong correlation between microbial biomass and organic matter in soil and reported that the abundance and activity of microorganisms increased with higher content of organic matter. Soils that are very low in organic matter may therefore be unfavourable in cemeteries as the decomposition depends on the existence and activity of microorganisms (Carter et al., 2008, 2010; Klingberg, 2005). Fründ & Schoenen (2009) also reported that a greater biological active soil may contribute to further degradation of adipocere in addition to an oxygenated environment. Klingberg (2005) suggested that incomplete decomposition of soil buried corpses in certain sandy soils likely was limited due to low content of organic material resulting in lack of microorganisms. This emphasise the importance of a soil with diverse microbial life.

Soil pH is also considered an important variable that control the diversity of microorganisms. Optimal condition for soil microbial decomposition is generally suggested around neutral pH (e.g. around 7) (Weil & Brady, 2017, p. 553). At the same time, fungi and bacteria comprise diverse groups and can develop in various soil environment from acid to alkaline soils (Weil & Brady, 2017, p. 513) However, some fungi are favoured by lower pH and dominant in acid soils, while the most diverse bacterial populations are associated with soils high in calcium and near neutral pH (Weil & Brady, 2017, p. 528).

As soil physical properties, organic matter, and pH influence the living conditions for microorganisms, the choice of soil type is of considerable importance when constructing or expanding new cemeteries, as emphasised in the report by Økland et al. (2022). However, there are many aspects to consider (placement, distance to church, topography technical operation etc), and an in many cases there is not always much of an option to choose regarding the type of soil (Klingberg, 2005). If the soil is dominated by silt and clay, and considered unsuitable with regard to drainage (e.g. according to existing recommendation in the report by Økland & Haraldsen (2020), the soil can be partly or fully replaced by soils with greater drainage properties, like that of sand.

1.3 Improving soil conditions in cemeteries

Sandy soils, with high macroporosity, may provide greater drainage and aeration than loamy and clayey soils. This may be particularly important in Norway, considering that much of the country is characterized by large amount of precipitation (Dannevig & Harstveit, 2022). The coastal areas have generally more precipitation than continental Norway, and it may rain more than 200 days per year with a quantity that exceeds 3000 mm/year (Dannevig & Harstveit, 2024). When expanding or constructing new cemeteries, the soil may be changed through mass replacement with e.g. sandy soils on the basis of their associated draining properties (Økland & Haraldsen, 2020). However, artificially made sand crushed from rock has been utilized as a substitute to natural derived sand, e.g. in parts of Alfaset and Klemetsrud in Oslo, and cemeteries in Sveio and Stavanger municipality, are examples were crushed sand has been utilized (H. A. Granøe, personal communication, 22 March 2024; S. K. Utengen, personal communication, 27 February 2024). Due to the graves being protected for minimum 20 years, however, it has not yet been possible to observe the effect of utilizing this type of soil components on the decomposition of corpses.

Crushed sand may have a higher pH than what is optimal for a diverse biological community. A study by Haraldsen & Pedersen (2003) utilized crushed sand from rock for a plant growth experiment, where chemical analysis indicated a pH higher than 8 in the artificial sands. In addition, considering that artificial sands are crushed from rock, they may also have more angular particle shape (sharp edged) than natural sand, which in contrast, through geological processes and transportation, are more rounded (Lutgens et al., 2015, p. 209). The report by Økland & Haraldsen (2020) proposed that sands from artificial crushed rock may contain fine particles (dust), which, in addition to the angular shape, may cause artificial sands to be packed more densely than natural sands. This may affect physical properties like the total pore space, pore size distribution, and pore connectivity, all of which regulate the soil moisture and oxygen.

1.4 Importance of physical properties

The total pore volume, which importantly accommodates the space for air and water, is largely determined by the sorting and packing of a soil (Weil & Brady, 2017, p. 182), which is why we are concerned about artificial sands as they may pack differently than natural sands. Figure 2 illustrates how sand grains may accommodate larger pore space if packed loose, and if the soil contains a variety of different pore sizes the bulk density may increase as smaller particles fit in between the larger pores decreasing the total porosity (Weil & brady, 2017, p 182-192) The figure also illustrates the possible packing of more angular particles, which could be the hypothetical case for artificial sand grains.

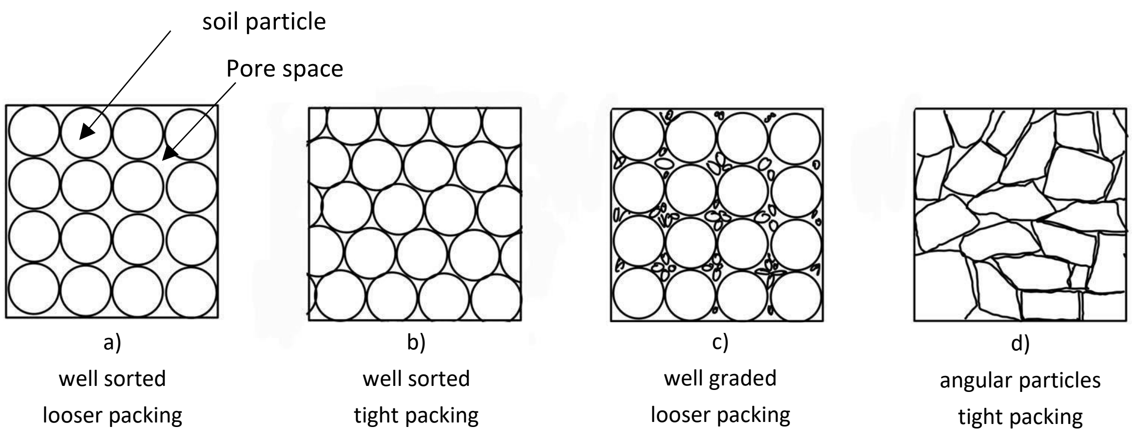


Figure 2: Simple illustration to demonstrate the effect of sorting and packing on total porosity and bulk density. a) illustrate a soil with uniform grains (well sorted) which accommodate a greater pore volume and lower bulk density than example b) which is more tightly packed. Example c) illustrate the effect of different pore sizes (poorly sorted/well graded) accommodating less pores space than uniform particle sizes. Example d) illustrate the possible effect and tighter packing of angular particle shapes. The figure is inspired by illustrations and theory in (Weil & Brady, (2017, pp. 182, 192) and Lutgens et al., (2015, p. 217).

The simple illustration in Figure 2 demonstrates the effect and importance of the physical properties accommodating the space for air and water. In addition, these physical properties (texture, sorting, packing, and particle shape etc) may affect the pore size distribution, which is highly important for the capacity to retain water.

Water retention

As earlier described, soil texture determine the pore size distribution which directly influence the potential to hold water (Weil & Brady, 2017). Although drainage has been emphasised as an important property to prevent water from filling too much of the pores, biological life in soil depends on moisture (Paul, 2014). Optimal conditions for microbial decomposition of soil organic components is in fact suggested when 60% of the total pore space is filled with water (Weil & Brady, 2017). Carter et al. (2010) studied the influence of soil moisture and found that cadaver decomposition was greater in wet conditions compared to dry conditions in the same sandy soil. This study concluded that lack of moisture likely limited microbial mobility and enzyme activity (Carter et al., 2010). The pore size plays an inevitable role in the potential to retain water (and thus sustain microbial activity), and this relation can be described by the simple capillary equation $r = 0.15/h$ which state that the smaller pore radius, the grater capillary force (Weil & Brady, 2017, p. 209; Danielson & Sutherland 1986, p. 450-451). This relation is the key behind the soils' capacity to retain water, and supply plants and microorganism with moisture.

The capillary equation demonstrates the influence of the pore size on the water status in soil but is at the same time a simplified expression of the soil pore relation to hydraulic properties considering that pores are not uniform, comes in a variety of size and shapes, and are connected differently within the soil matrix (Danielson & Sutherland 1986). The latter is also important for air and water movement. The importance of pore connectivity may be illustrated by an example from Økland et al. (2022), which regards the practical challenge of mixing soil components of different texture. In a grave with poor decomposition, they found separate layers of coarse and fine sand (natural) that was supposed to be mixed evenly, which resulted in uneven distribution of water, possibly caused by disconnection in the pore system/ capillary disruption (Økland et al., 2022). This illustrates the complexity of soil which must be considered in any interpretation of the soil and pore system.

Although the practical challenge of performing mass replacement is of considerable importance, as emphasised by the example above, and by Weil & Brady (2017, p. 158), this thesis, however, is primarily focusing on the properties of artificial sands that may influence the microbial activity.

1.5 Aim, objectives, and hypothesis

As we have not yet observed the long-term effect of using artificial sands on the decomposition of corpses in cemeteries, and at the same time it is planned to use such materials in future constructions e.g. Vorland in Bømlo municipality (H. A. Granøe, personal communication, 22 March 2024), there is need for knowledge regarding the possible impacts of utilizing artificial sand components. The overall aim of this thesis is therefore to gain knowledge about the soil hydraulic properties of artificial sand compared to natural sand, and to investigate their effect on microbial decomposition.

The objectives are as follows:

- To examine decomposition rate of a biological compound in artificial and natural sand as early indicators of decomposition capacity.
- To determine key physical, chemical, and hydrological properties of artificial and natural sand
- To evaluate effect of decomposition rate with associated soil properties

The objectives will be achieved through a short-term decomposition experiment with teabags, *in-situ* infiltration test, and laboratory measurement of soil physical, chemical, and hydrological properties.

The hypothesis to be tested in this study is as follows:

1. The decomposition of teabags is slower in artificial sands than in natural sands.
2. Given that they are formed differently, artificial sand has lower porosity and different pore-size distribution and thereby different hydraulic behavior.
3. Soil hydraulic properties affect decomposition of tea in sandy soils

2 Method

2.1 Site description

The decomposition experiment and infiltration tests were performed at a an outside lysimeter facility at the Norwegian University of Life Sciences (NMBU), situated in the municipality of Ås, southeast of Norway (Figure 3). The facility has 96 lysimeters of two sizes that were built into an elevated ground, each with individual outlet pipes connected to a cellar.

Figure 3: Experiment site at NMBU with 2x48 lysimeters on each side of a cellar that functioned as a control room for water drainage. Picture taken from the back (northeast). Photo: Sigrid E. Arnestad.

The roof protected the area from precipitation and direct sunlight, and planted trees shielded the north and north-east side. To prevent direct sunlight from the southwest, white sails were raised at the front opening (Figure 4). The facility had not been utilized the last 15 years, and some upgrades were considered necessary according to the needs of this experiment. This included replacement of outlet filters and mounting of new stopcocks/faucets on the outlet pipes.


Figure 4: Facility improvements included installation of white sails to prevent direct sunlight through the front opening (left), and mounting of stop cocks on the outlet pipes in the cellar for drainage management (right).

2.2 Experimental design

Soil types

Eight different combinations of artificial and natural sand were selected for the study. These included two types of natural soils, two types of crushed stone sand, and four mixes of these (Table 1). In addition, organic topsoil (T) was mixed into one of the soil mixes.

Table 1: List of the eight soil types selected for this study; crushed stone sands (C), naturally derived sands (N), topsoil (T), and mixes (C+N) or(C+N+T). Small letters are used to distinguish between the soils and indicate from where they originated. v=vinterbro, s=steinskogen, m=mysen, r=riis.

Soil type	Proportion crushed sand	Material	Texture [1]
Cv	100 %	0-2 mm Crushed gneiss from Vinterbro	Coarse sand
Cs	100 %	0-2 mm Crushed basalt from Steinskogen	Coarse sand
Nr	0 %	Natural forest soil from Riis	Loamy medium sand
Nm	0 %	85% 0-2 mm Natural sand from Mysen	Coarse sand
CvNm	50 %	Mix: 50 % Cv, 50 % Nm	Coarse sand
CsNm	50 %	Mix: 50 % Cs, 50 % Nm	Coarse sand
CvNr	50 %	Mix: 50 % Cv, 50 % Nr	Medium sand
CvNmT	40 %	Mix: 40 % Cv, 40 % Nm, 20 % T	Medium sand

The natural soils Nr and Nm originated from two different areas. Nr derived from a forest area from Riis Farm in Vinterbro, while Nm came from sandy deposits from Mysen. The topsoil (T) was ordered from *Drøbakveien Jord*. (n.d.) The crushed sands originated from two types of rock, respectively basalt

[1]Qantitative particle size presented in the results.

(Cs-Steinskogen) and gneiss (Cv-Vinterbro). Both artificial soils and Nm were coarse sands, while Nr was a loamy medium sand. The texture of the topsoil alone was not analysed.

Soil mixing

The soil mixes were blended with a cement mixer according to their ratio of artificial to natural sands. All but the CvNmT were mixed with 3 buckets (3x10 L) of each soil component at the time for 3 to 5 minutes. CvNmT was mixed with 2 buckets (2x10 L) of each Cv and Nm, and 1 bucket (10 L) of topsoil.

Implementation

The teabag experiment and infiltration tests were separated into two independent setups each containing 24 identical lysimeters (31x57-60 cm). In both setups each of the eight soil types were randomly distributed in three replicates according to the illustration in Figure 5.

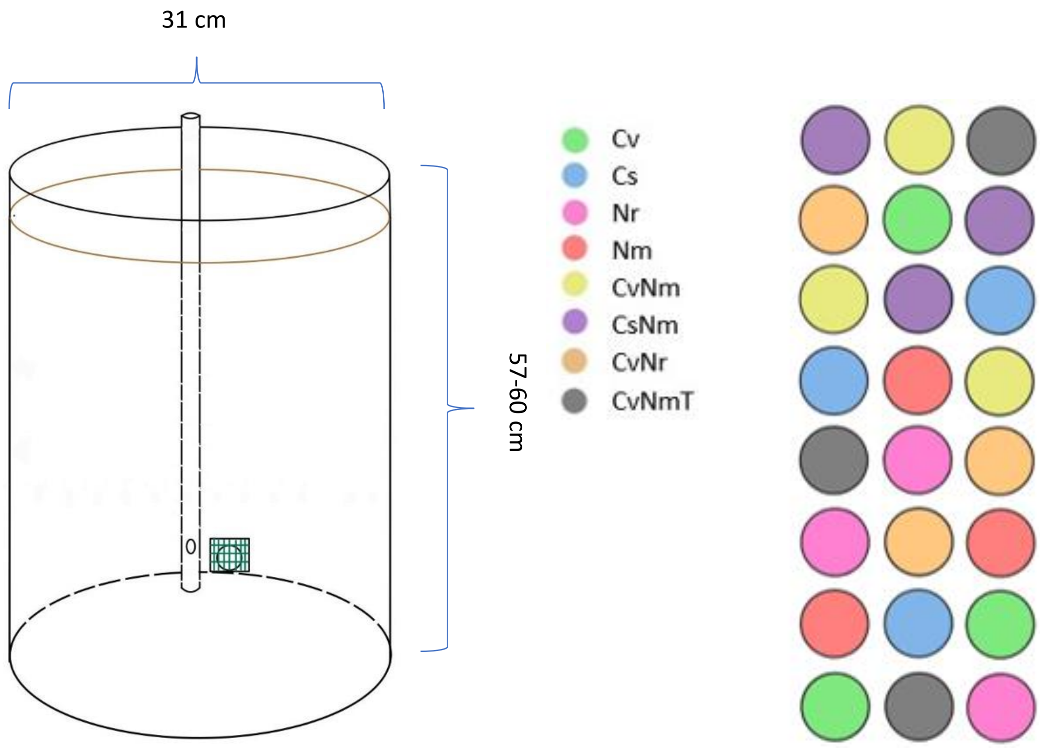


Figure 5: Setup of the lysimeters showing the randomization of the soil types in triplicates (right). Each replicate corresponded to an individual lysimeter (left) dimensioned to 31 x 60 cm and equipped with one water level pipe and an outlet hole leading the water through a pipe into the cellar. The bottom closest to the outlet measured 60 cm while on the opposite it was slightly raised to about 57cm. The lysimeter setup and design was equal for the teabag experiment and the infiltration test.

36 litres of soil were implemented in each lysimeter which previously had been equipped with a plastic pipe (66.6 x 3.2 cm) to control water level (Figure 5). To ensure water flowing from the soil into the pipe a 5 mm hole had been drilled into the pipe about 3 cm from the bottom.

Water level control

The water level in the lysimeters was intended to be established at 15 cm from the bottom and controlled twice a week by measuring the water level in the plastic pipe with an electric tape and adjusted by either adding water to the soil surface with watering cans or draining water from the outlet pipes in the cellar.

2.3 Field data collection

2.3.1 Decomposition experiment with teabags

To collect short term decomposition data as early indicators of decomposition potential, tea was used as the biological component. Teabags were buried for three months in each soil type followed by measurements of mass loss. The teabags were additionally buried in two depths, of which the lowest layer was close to the water level to test if differences in moisture content, depth, and/or oxygen would influence the decomposition. The methodological approach was inspired by the teabag index proposed by Keuskamp et al. (2013), but adjustments were made according to the purpose of this study.

Preparation

Two types of tea were used for the decomposition experiment, organic green tea (G) (*Sencha Ariake*), and organic rooibos (R) (*Rooibos Khoïsan*) – both from Palais de Thés, Oslo, Norway. Non-biodegradable, nylon, pyramid shaped, 5.5 x 7 cm sized teabags were obtained via the website www.frugo.no, (Frugo, n.d) and were manually filled with three grams of either of the tea types and sealed with five metal staples. The teabags were labelled on the paper attached to the thread covered with transparent tape to prevent it from decomposition.

Implementation

Two replicates of each tea type were buried in two layers, upper layer (T1) and lower layer (T2) (Figure 6). Considering that each soil type was triplicated, this would give six replicates (2x3) of both rooibos and green tea per layer. The implementation procedure included the following steps:

1. 18 litres of soil were added to the lysimeter.
2. Two replicates of each tea type were placed on top of a “smoothed” soil surface against the wall, with approximately 90° distance (Figure 6)
3. 9 litres of soil were added to the lysimeter.
4. Implementation of upper tea layer (T1). See step 2.
5. 9 litres of soil were added on top.

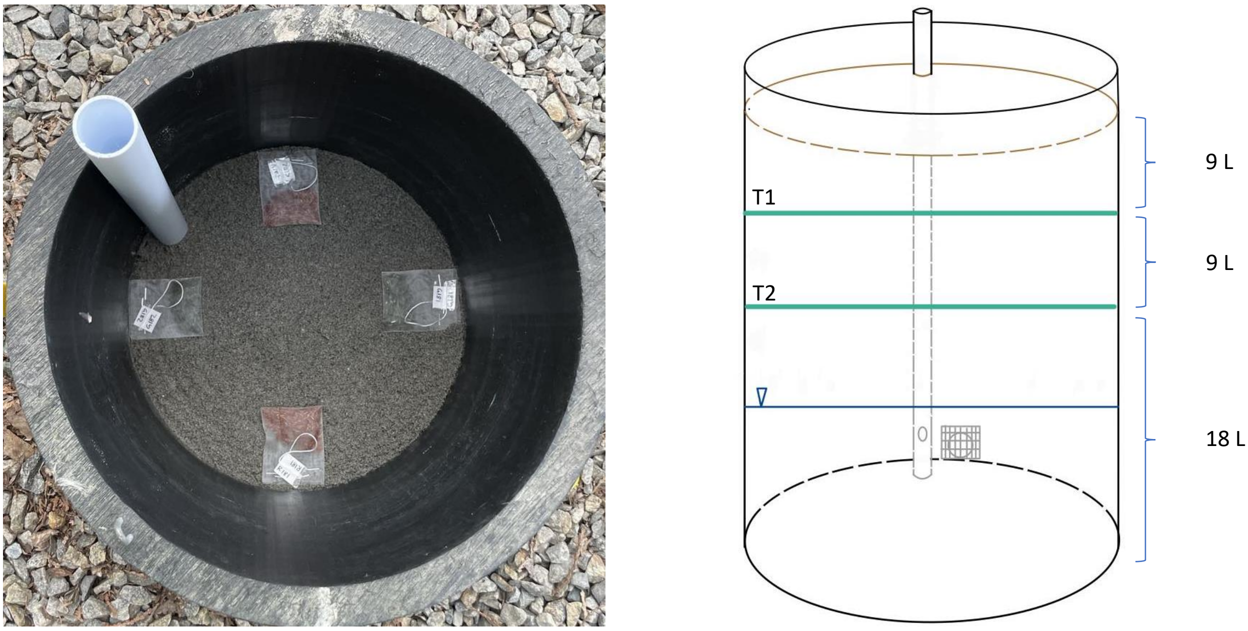


Figure 6: Demonstration of the placement of the teabags (left), with two replicates of both green tea and rooibos buried against the wall with the labelling facing upward. The illustration of the lysimeter (right) show visually the design of the teabag experiment, with the two tea layers (T1 and T2) and corresponding volumes of soil. The water level (blue line) was controlled to be 15 cm from the lowest part of the bottom of the lysimeter.

The teabags remained buried from early July to early October (excavated the 8 – 10th of October) and preserved in a freezer until analysis to prevent further biological degradation.

Handling of the teabags

Soil particles attached to the surface of the teabags were removed by soaking the teabags in water and rubbing the surface gently with fingers. They were then oven dried at 40℃ for three days (72 hours). As a final step, the total weight was measured. Before they were weighed, the teabags had been placed inside the lab for approximately 12 hours to adapt to normal atmospheric conditions, under which they were originally prepared.

2.3.2 Infiltration

A mini disk infiltrometer (METER, n.d.) with a disk radius of 2.5 cm, was used to measure infiltration rate of the artificial and natural sands. The infiltrometer apparatus allowed application of negative potential which exclude macropores of pore size equivalent to the pressure head. Infiltration tests were performed on the soils in setup 2 (30 cm diameter lysimeters with no teabags) for suction rates of 1, 3, and 5 cm. Three sets of tests were conducted for each suction rate. While near-saturated infiltration was measured at three suction levels, in this thesis only one of those (suction =1 cm) were assessed.

Procedure

The infiltrometer was placed at a suitable flat part of the soil surface, preferably near the centre of the lysimeter. In some of the lysimeters, stones, moss, or grass was removed to ensure good contact between the porous plate and the soil surface. Recording time started immediately when the infiltrometer was in contact with the soil surface. Change in water level (ml) was recorded at a selected timing interval, which varied from every 10 seconds to 20 minutes intervals, depending on the observed infiltration intensity. Time was recorded until the infiltration reached a steady rate which, for most of the soils, required swapping infiltrometers to sustain the measurement longer than what the capacity of one infiltrometer allowed. The replacement took place when the volume reached or approximated 0 (e.g. all of the water had infiltrated) and with continuous time recording to ensure continuous readings. The drainage outlet was kept open during the tests to prevent, as much as possible, water accumulation in the profile.

Calculations

Infiltration rate were calculated from the infiltrability equation (1) (Weil & Brady, 2017, p. 231) in equation 1, using the average of the last three[2] steady infiltration measurements.

$$i = \frac{Q}{Axt} \tag{1}$$

Where infiltrability i (cm/h) is the volume of water that infiltrated the soil *Q* (cm^3) divided by the area of which the water infiltrated A (cm^2), times the time interval *t* (h). It should, however, be noted that infiltration measured with a mini disk tension apparatus is *three dimensional*. For estimations of hydraulic conductivity properties from such data, lateral capillary water flow should be accounted for, for which various approaches exist, like Zhang, (1997). See Fatehnia et al., (2014) for a more extensive discussion of hydraulic conductivity estimations obtained from mini disk infiltrometer. The estimations of infiltrability in this study must therefore be considered a simplified approach to water flow characterization.

The simple capillary rise equation (2), described in Weil & Brady. (2017, p. 209) was used to predict the equivalent pore radius (largest pore size contributing to infiltration, see *Appendix C*, Table C5)

$$r = \frac{0.15}{h} \tag{2}$$

[2] In cases where a steady state was not considered constant, the average of the last *six* measurements were utilized for the calculation of infiltrability.

2.4 Lab analysis

Soli physical analysis and water retention measurements were performed in the laboratory on soil samples from setup 1 (30 cm diameter lysimeters with teabags). The samples were taken with 100 cm^3 steel cylinders between the two layers of tea following the procedure of Krogstad et al. (2018), and preserved in a fridge until their analysis started (5-7 days). Soil samples for chemical analysis and water retention measurements at 15000 hPa were not taken from the lysimeters, but in plastic bags directly from the delivered soil.

2.4.1 Water retention

To characterize the water holding capacity, volumetric water content (vol/vol %) was estimated at 9 matric potential levels, ranging from 0 to 15000 hPa. A sandbox was utilized for the lowest potentials (0-50 hPa) and pressure chambers for the highest (100-15000 hPa). The RETC program (van Genuchten et al., 1991) was used to fit the 4-parameter analytical model of van Genutchen (1980) to the observed water retention data.

Procedure

The soil samples had first been soaked in a vessel with water for 48 hours to obtain the saturated water content (at 0 hPa). Next, the samples were placed in a sandbox apparatus by the Royal Eijkelkamp Company, Netherlands (Royal Eijkelkamp, n.d.) for measurements at 1.75, 10, 30, and 50 hPa. To prevent water from being lost to evaporation the sandbox was covered with a lid during each of the equilibrium phases. Pressure plate extractors and ceramic porous plates by the Soil Moisture Corporation, CA, USA (Soilmoisture, n.d.) were used to equilibrate the samples to 100, 333,1000 , and 3000 hPa before drying them in the oven at 105°C for 48 hours. Water content at wilting point was obtained with unconsolidated soil sampled in plastic bags. 2-3 teaspoons of the soil[3] was poured into small rings (32 mm) to equilibrate at 15000 hPa before drying in the oven at 105°C for 48 hours. For detailed description of the full procedure see Krogstad et al. (2018).

Calculations

The water content Mw (g) was easily obtained from the difference in weight between the increasing matric potentials. As density of water was approximated at 1 g/cm3, the conversion to volumetric water content θ (vol/vol %) was obtained with equation 3.

[3] This soil was not collected from the lysimeters as the other samples but collected directly from the delivery piles and stored in plastic bags until analysis. Preferably this soil should have been sieved prior to the measurements to avoid particles> 2mm.

$$\theta = \frac{Vw}{Vt} \quad (3)$$

For the samples subject to 15000 hPa, (with unknown volume Vt), conversion to θ was calculated with equation 4 with the gravimetric water content (GWC) obtained from the two weights (before and after subject to 15000 hPa) divided by dry weigh, and bulk density obtained from the samples in the 100 cm^3 steel cylinders (equation 5).

$$\theta = (GWC\ x\ bulk\ density)\ x\ 100 \quad (4)$$

$$bulk\ density\ (\frac{g}{cm3}) = \frac{Ms}{Vt} \quad (5)$$

Fitting water retention curves to observed data

To parameterize the water retention curves (pF curves) for qualitative analysis of water holding capacity and pore size distribution, a water retention model was fitted to the measured data of each soil sample. The RETC program was used to fit the 4-parameter van Genuchten (1980) model to retention data, using the frequently made assumption that the m parameter is dependent on the n shape parameter as m = 1-1/n.

In order to initialize the model fit, the soil type was selected according to the texture classification (Nr was selected *loamy sand*, the rest as *sand*).

Evaluation of the curve fit was based on the sum of squares (SSQ) and visual proximity of the curve shape to the observed data points. Optimisation of the fitted data to the observed data included adjustments of the weighting coefficient. Due to high uncertainty related to the water content at saturation[4], the weighing coefficient was adjusted from 1 to 0.1 for this data point for all soil types. The observed data point at 1000 and 3000 hPa[5] was also given low weight due to uncertainty related to the observed data.

Finalization of the water retention curves

The parameters *thetaS* (θs*), thetaR* (θr*), alpha* (α), and *n* from the model output were used to visualize the fitted water retention curves by programming the 4-parameter van Genuchten (1980) equation into MS Excel (see *Appendix C*, Table C6 for model output). θs specifies the volumetric water content

[4] In sandy soils there is a high risk of losing gravitational water when the samples are lifted from its saturated state on to the scale for weight measurement. It is therefore likely that the observed water content at pF close to 0 is underestimated.
[5] It was discovered that one of the porous plates in the pressure chamber during equilibrium at 3000 hPa had tilted, which may have caused insufficient contact between the soil and the plate.

at saturation. θs specifies the volumetric water content at saturation representing the maximum water a soil can hold (Van Genuchten et al., 1991). *ThetaS* parameter should be interpreted carefully since *thetaS* is normally 5-10 % lower than total porosity due to entrapped or dissolved air (van Genuchten et al., 1991). The residual water content θr indicates the amount of water in a soil that may be left in it as crystal water (van Genuchten et al., 1991), but must not be confused with "wilting point" which refer to the theoretical amount of non-available water for plants approximated by the -15000 hPa measurement. Parameter α is the air entry pressure (cm^{-1}) and *n* is a dimensionless curve-shape parameter. For more detailed explanation of the mathematical expression behind the model see van Genuchten et al. (1991).

2.4.2 Basic soil physical properties

Estimations of the basic soil physical properties followed the procedures described in Krogstad et al. (2018).

Total porosity

The total porosity was estimated from the volumetric air and water content at field capacity (100 cm of water pressure) according to the following equation:

$$porosity\ [vol\%] = volume\ of\ air + volume\ of\ water \quad (6)$$

Air volume

The volume of air was determined with the gas pycnometer method on soil samples with a water content equilibrated at field capacity (-100 cm). The method is based on Boyle's law of volume-pressure relationship (Danielson, R. E. Sutherland, P. L., 1986), which mathematically can be expressed as presented in equation 7.

$$P1V1 = P2V2 \quad (7)$$

In the pycnometer apparatus the air volumes are constant (P1) and set to 1000 kg/cm2. P2 is recorded from the pressure gauge when the volume V2 is known (100 cm^3). The pycnometer provides a semi-closed air pressure system so that air pressure can be applied to the sample and stabilize relative to the air-filled pores.

To estimate the correct volume from the pressure readings, a calibration curve was established (Figure 7) relative to the atmospheric pressure at the time of measurement, using a steel cylinder of 100 cm^3 with removable steel disks of known volume. See Krogstad et al. (2018) for further description of establishing the calibration curve. Air pressure was then applied to each soil sample and the response pressure recorded. The air volume (y) was calculated for each sample using the obtained calibration equation (below) and the pressure reading as its input.

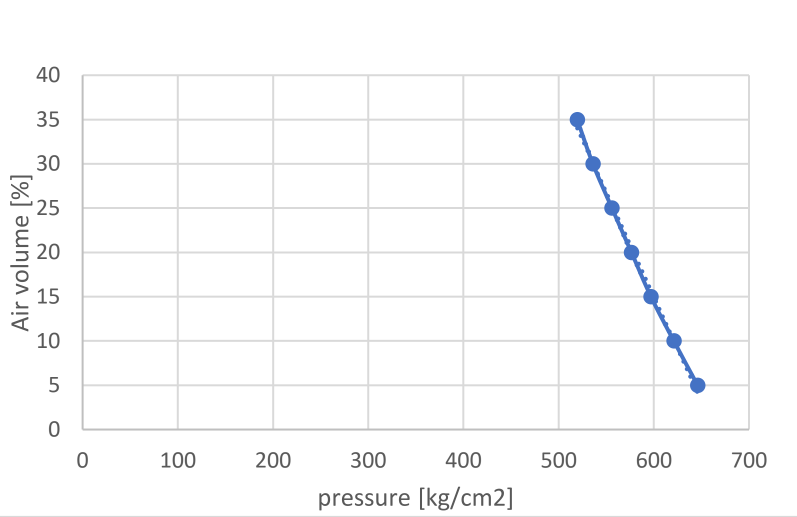


Figure 7: Calibration curve of air volume (y-axis) relative to pressure (x-axis) used for determination of air volume at field capacity.

$$y = 0{,}00039199x^2 - 0{,}69260682x + 288{,}87540735$$

Bulk density

Bulk density is the weight of soil by a given volume and represent the mass of the soil including the voids and pores. After the soils had been dried in the oven at 105° C for 48 hr the dry weight was measured, and the bulk density calculated with the following equation (8):

$$Bulk\ density = \frac{dry\ weight\ (g)}{soil\ volume\ (100cm^3)} \tag{8}$$

2.4.3 Shape characterisation and flakiness

Particle shape

A visual estimation method with four roundness classes (Olsen, 1983) was used to characterize the surface shape/angularity of the artificial and natural sand particles. To perform the visual assessment 10 sand grains of approximate same size were randomly selected after sieving with water through a 2 mm mesh. Each sand grain was assigned one of the following classifications according to the photo attached in *Appendix D*, Figure D1.

- well rounded (WR)
- rounded (R)
- subrounded (SR)
- angular (A)

Simple 2D images were taken with an iPhone camera as a support for the visual interpretation.

Flakiness

The flakiness of a particle gives information related to its 3D dimension and indicates how flakie ("flat") the particle is shaped. In engineering, the flakiness index defined as *"*the percentage by weight of aggregate particles whose least dimension is less than 0.6 of their mean dimensions" (Patrick, 2019), and is a common test to determine this shape characteristic. In this thesis, we calculated the percentage *by number of particles* instead of by weight as the particles were approximately the same size. The flakiness was determined by measuring the length (mm) in three dimensions with a digital caliper that measures with 0.01 mm resolution.

2.5 Grain size distribution and chemical analysis

The grain size distribution, which is the proportion of a particle fraction (g / 100 g) of the total sample volume, and the textural classification was performed by the accredited laboratory Eurofins Agro Testing Norway.

The chemical analysis included pH, loss on ignition (LOI), phosphorus(P), potassium (K), magnesium (Mg), Calcium (Ca), and Sodium (Na). The nutrients were determined with the AL-method (Egnér et al., 1960), and performed by Eurofins Agro Testing Norway As. The procedure of pH and loss on ignition (LOI) was also performed Eurofins.

2.6 Statistical analysis

Before choosing the statistical analysis to test for significant differences (of mass loss) between the soil types, assumptions of normality were checked by visual interpretation of histograms, and with the Shapiro-Wilk normality test (*Appendix A*, Figure A1-A4). Considering that the assumptions of normality were met, differences in mass loss of tea were tested with analysis of variance (anova) as the statistical analyse method with a p value of 0.05. the Tukey post hoc test was further used to identify which of the soil types were significant from each other. The statistical analyse was performed in R version 4.3.2.

3 Results

3.1 Decomposition of tea

The buried teabags were recovered after three months, and the total mass loss (g) used as early indicators of each soil's decomposition potential. The pre-burial weight was approximately three grams for each teabag, and the greater mass loss of tea, the greater assumed decomposition. The value distribution of mass loss (g) of green tea in upper layer (GT1), rooibos upper layer (RT1), green tea lower layer (GT2), and rooibos lower layer (RT2) were compared between the eight soil types as presented in Figure 8, 9, 10, and 11. Results from the statistical analysis is included in the figures as letter of significance (see *Appendix A* for output values). Soil types with different letters indicate significant difference in mass loss. The average values are listed in *Appendix B*, Table B1.

3.1.1 Upper layer

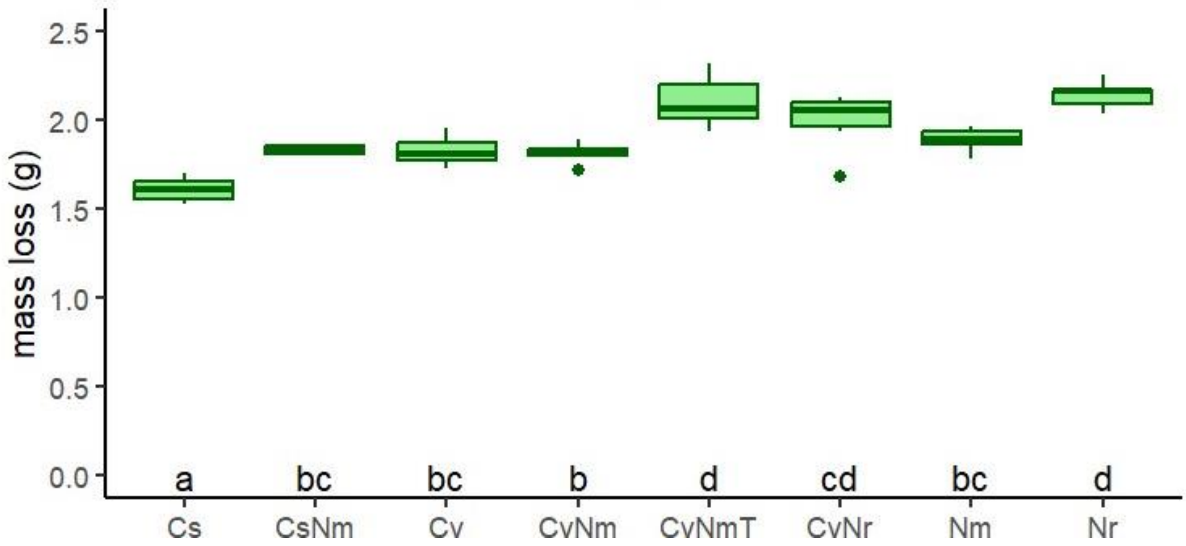


Figure 8: Mass loss (g) of green tea from teabags buried in the upper soil layer of crushed sands (Cv and Cs), natural sands (Nm and Nr), and mixes of these, including one mix with organic topsoil (T). Total weight of teabags pre-burial was approximately three grams.

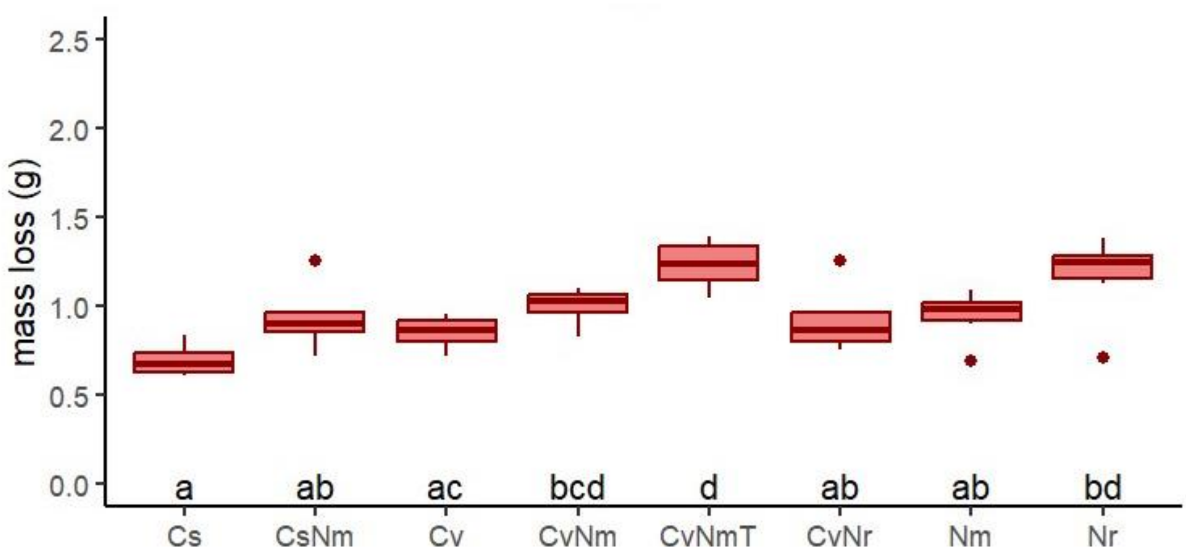


Figure 9: Mass loss (g) of rooibos tea from teabags buried in the upper soil layer of crushed sands (Cv and Cs), natural sands (Nm and Nr) and mixes of these, including one mix with organic topsoil (T). Total weight of teabags pre-burial was approximately three grams.

General trends

Decomposition in the upper soil layer generally seemed to be lower in the crushed sands compared to natural sands and mixing with topsoil seemed to result in greater decomposition. From Figure 8 and Figure 9, mass loss (g) of tea in the upper soil layer followed the same trend irrespective of type of tea, where mass loss was lowest in Cs, and highest in Nr and CvNmT. The mass loss was significantly lower in Cs and Cv compared to Nr for both green tea and rooibos. Mass loss was also lower in the crushed sands compared to Nm, but the difference was only significantly lower in Cs with green tea.

Soil mixes

Mixing crushed sand with natural sand resulted in greater mass loss (g) in some of the soil types. Mixing with the topsoil T (CvNmT) resulted in significantly greater mass loss than Cv, independent of type of tea. The mass loss was also greater compared to CvNm, but only significant for green tea. Mixing with Nm had most effect on Cs (less with Cv), which resulted in significantly greater mass loss of green tea. The effect of mixing with Nr was only tested with Cv, and resulted in greater mass loss, but only with green tea, and the difference was not significant. Importantly, mixing crushed sand with natural sand did not result in less mass loss compared to the crushed sands alone.

3.1.2 Lower layer

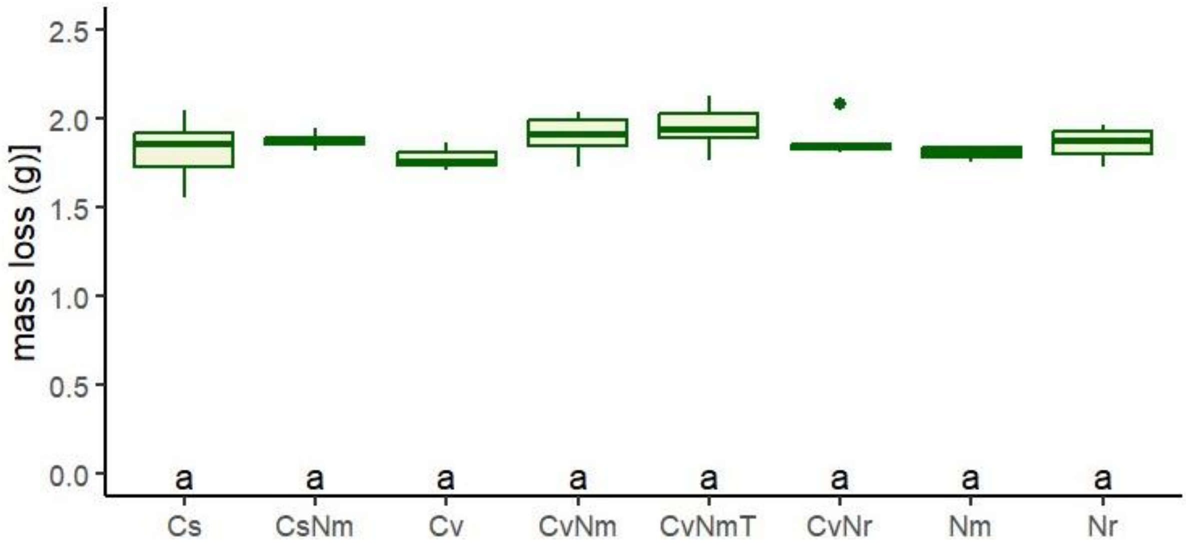


Figure 10: Mass loss (g) of green tea from teabags buried in the lower soil layer of crushed sands (Cv and Cs), natural sands (Nm and Nr) and mixes of these, including one mix with organic topsoil (T). Total weight of teabags pre-burial was approximately three grams.

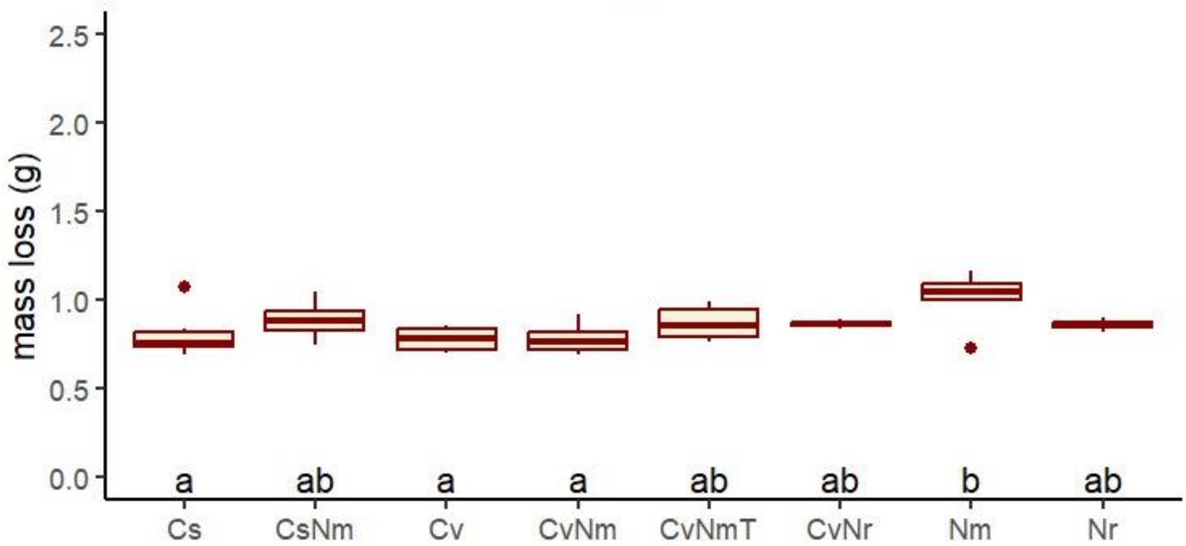


Figure 11: Mass loss (g) of rooibos from teabags buried in the lower soil layer of crushed sands (Cv and Cs), natural sands (Nm and Nr) and mixes of these, including one mix with organic topsoil (T). Total weight of teabags pre-burial was approximately three grams.

General trends

The mass loss of tea (g) seemed to not follow the same trend in the lower layer as in the upper layer. From the results in Figure 10, there was no clear differences in mass loss of green tea between any of the soil types. On the other hand, mass loss of rooibos was significantly lower in the crushed sands Cs and Cv than the natural sand Nm (Figure 11). The average mass loss of green tea unexpectedly increased in Cs, CvNm and CsNm compared to the upper layer. The same was observed for rooibos, where mass loss increased from upper to lower layer in Cs and Nm. The increase was, however, minimal (*Appendix*, Table B1). From the results of mass loss in the lower soil layer, it generally seemed like there was no differences in decomposition between the crushed and natural sands, and that decomposition decreased in most soils compared to the upper layer, expect in Cs and Nm, and the mixes CsNm and CvNm.

Soil mixes

The results of mass loss (g) in the lower layer showed no significant difference in the soil mixes compared to the crushed sands alone. However, mixing with Nm resulted in slightly greater mass loss of green tea in Cv (CvNm) and slightly greater in Cs with rooibos (CsNm). Mass loss was on the average slightly greater in CvNmT compared to Cv, irrespective of tea type.

3.2 Infiltration rate

To obtain data of water flow rates, infiltration was measured *in situ*, first at 1 cm suction rate, and then with 3 and 5 cm suction. In that way macropores were excluded from conducting water respective to pores > 1 mm diameter (3 cm suction) and pores > 0.6 mm diameter (5 cm suction) approximately. For this thesis, results obtained from 1 cm suction are selected to be presented in this section as they would be sufficient for comparison across soil type. However, data from the other suction rates can be obtained in *Appendix C*, including an estimation of the proportion pores in different pore size range that was active in conducting water relative to the 1 cm suction value (*Appendix C*, Figure C4).

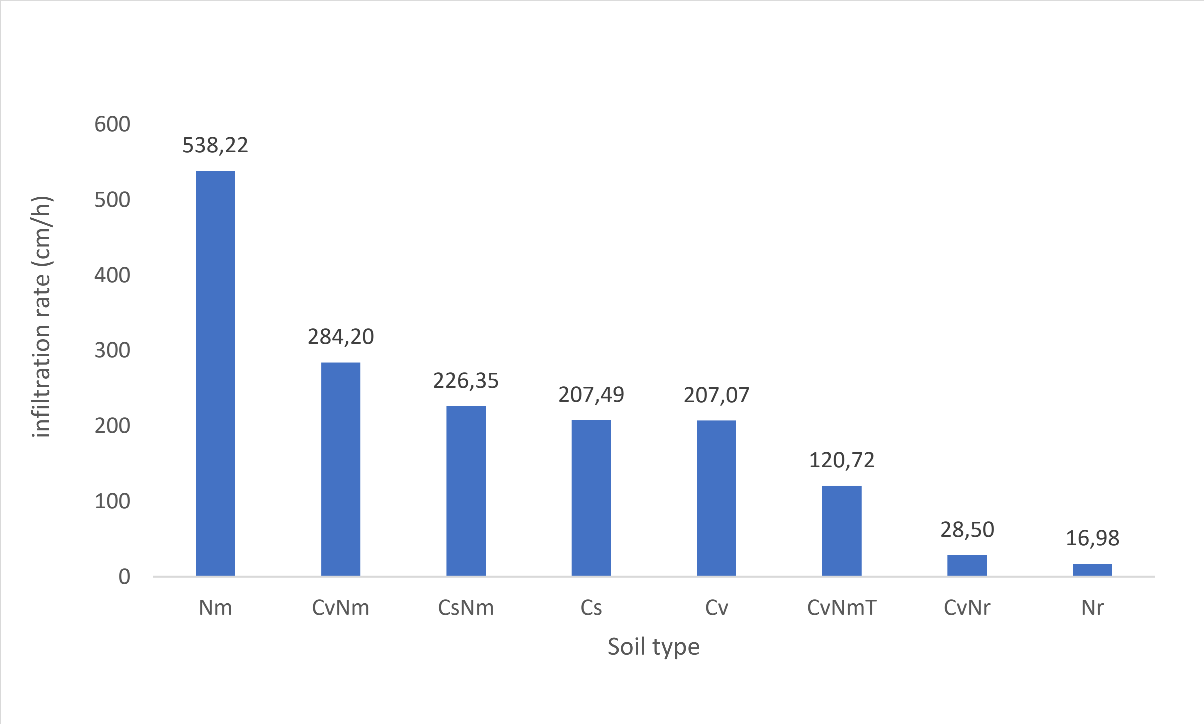


Figure 12: Average infiltration rate (cm/h) of crushed sands (Cv and Cs) and natural sands (Nm and Nr), and mixes of these, including one mix with organic topsoil (T), measured with a suction rate of 1 cm.

General trends

From the results in Figure 12, the differences in average infiltration rate were ranging from 16 to more than 500 cm/h, were the lowest and highest infiltration rate were observed in the natural sands (Nr and Nm). The crushed sands (Cs and Cv) performed in the range between the natural sands, with very similar infiltration rate of approximately 200 cm/h.

Soil mixes

The mixed soil types seemed to perform in the range between their original soil components. Mixing with Nm resulted in a higher infiltration rate, but only notable in Cs (CsNm). In contrast, mixing with Nr resulted in a slower infiltration rate, but this was only tested for Cv. The same was observed in the mix with topsoil T (CvNmT), which had a slower infiltration rate compared to that of Cv and CvNm.

3.3 Water retention characteristics

To analyse the soil's capacity to retain water, the volumetric water content was measured at increasing pressure from 0 to 15000 cm of water pressure as presented in the fitted pF curves in Figure 13-17. The measured volumetric water content is attached in *Appendix C*, Figure C7. pF curves were used as a proxy for pore size distribution, using the capillarity rise equation.

Table 2: Water content at field capacity (FC), wilting point (WP) and the difference between these, which is the available water content (AWC), for crushed sands (Cv and Cs), natural sands (Nm and Nr), and mixes of these, including one mix with organic topsoil (T).

Soil type	FC (100 hPa)	WP (15000 hPa)	AWC (FC-WP)
Cv	10.9	0.8	10.1
Cs	11.8	3.2	8.6
Nr	24.0	6.0	17.9
Nm	3.7	1.4	2.4
CvNm	7.3	1.0	6.3
CsNm	7.6	2.6	5.0
CvNr	16.8	3.0	13.8
CvNmT	16.4	1.5	14.9

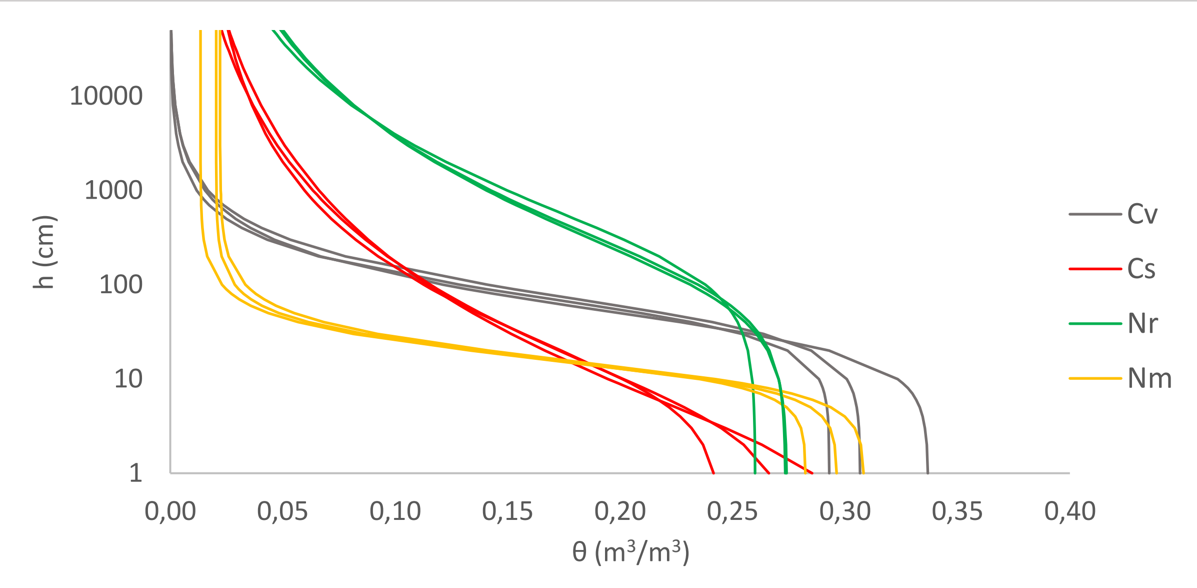


*Figure 13: Water retention curves of crushed sands (Cv and Cs) and natural sands (Nr and Nm) showing the relation between volumetric water content θ (m^3/m^3) on the x-axis and matric potential on the y-axis, the latter expressed as a pressure head **h** (cm water pressure).*

General trends

The results from the water retention analysis indicates differences in the potential to retain water between crushed and natural sands, but also between the natural sands (Figure 13). Nm had the sharpest decline in the curve and had lost most of the water when exposed to only 10 cm of water pressure. At field capacity (100 cm) less than 5 % water was retained by the soil, and the estimated plant available water was critically low (2.4 %) (Table 2). Conversely, we see that Nr lost very little water at the lowest potentials, and retained about 24% water at field capacity, whereas approximately 18 % is plant available (Table 2:), considerably higher than that of Nm.

Based on the results and the shape of the pF curves, the crushed sands retained some more water than Nm, but less than Nr. Cv mostly started to lose water when subject to 10 to 20 cm of water pressure while Cs seemed to already lose water when subject to the lowest pressure (1.7 cm). The water content measured at field capacity (100 cm) was low in both of the crushed soils, and the resulting plant available water was only 8-10 % (Table 2).

Note that the water content at saturation (0 cm of water) was varying within the replicates and was generally low for all soils, particularly Cs (approximately 24-28 %).

Soil mixes

The water retention characteristics of the soil mixes were generally performing in the range between the crushed and natural sands. Compared to the crushed sands, this resulted in generally lower water content for the same matric potential in the mixes with Nm (Figure 14 and 15), and generally higher water content in the mix with Nr (Figure 16). Mixing with topsoil (T) also increased the amount of water retained according to the results in Figure 17.

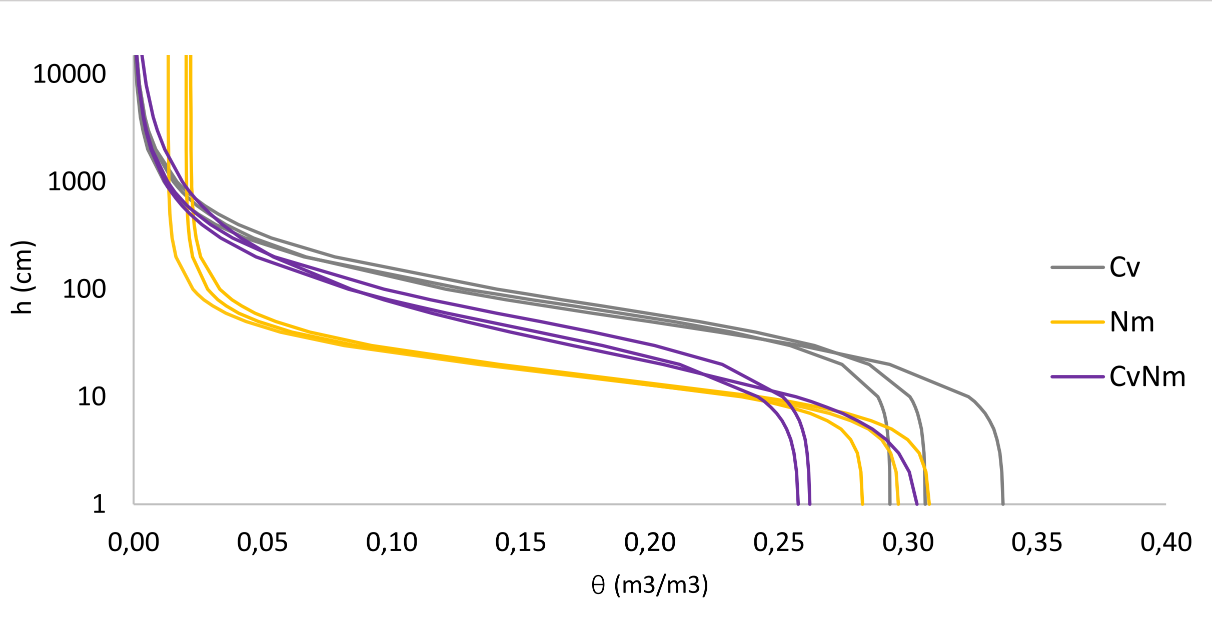


Figure 14 Water retention curves of crushed sand Cv, natural sand Nm, and mix of these. The curves show the relation between volumetric water content θ (m^3/m^3) on the x-axis, and matric potential on the y-axis, the latter expressed as a pressure head h (cm water column).

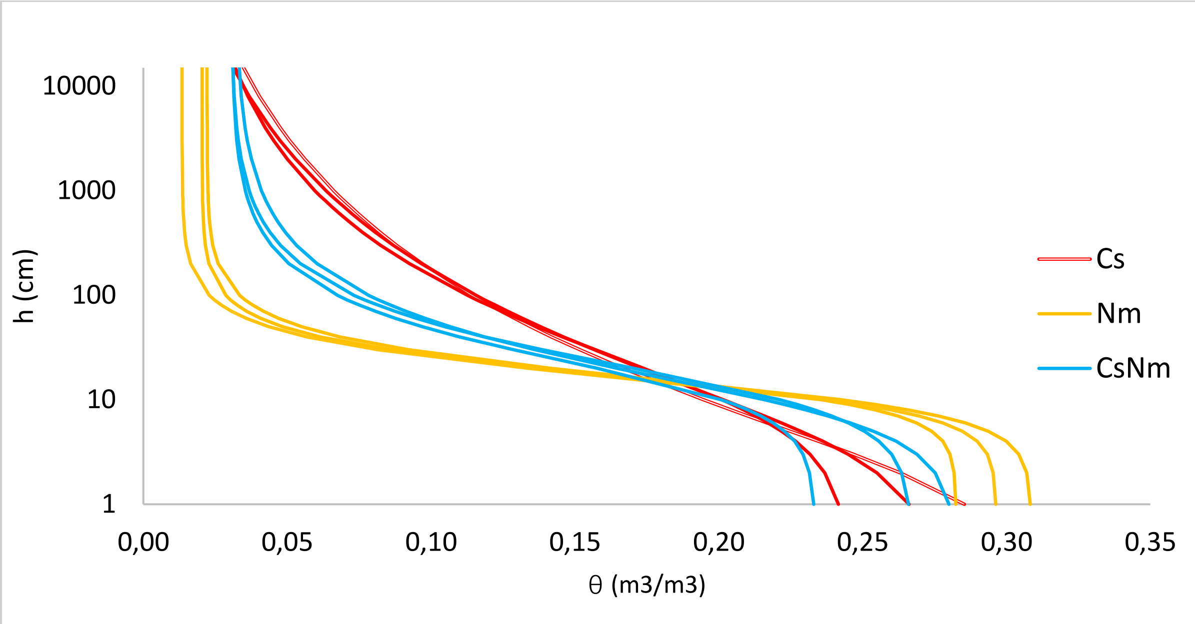


*Figure 15 Water retention curves of crushed sand Cs, natural sand Nm, and mix of these. The curves show the relation between volumetric water content θ (m^3/m^3) on the x-axis, and matric potential on the y-axis, the latter expressed as a pressure head **h** (cm water column).*

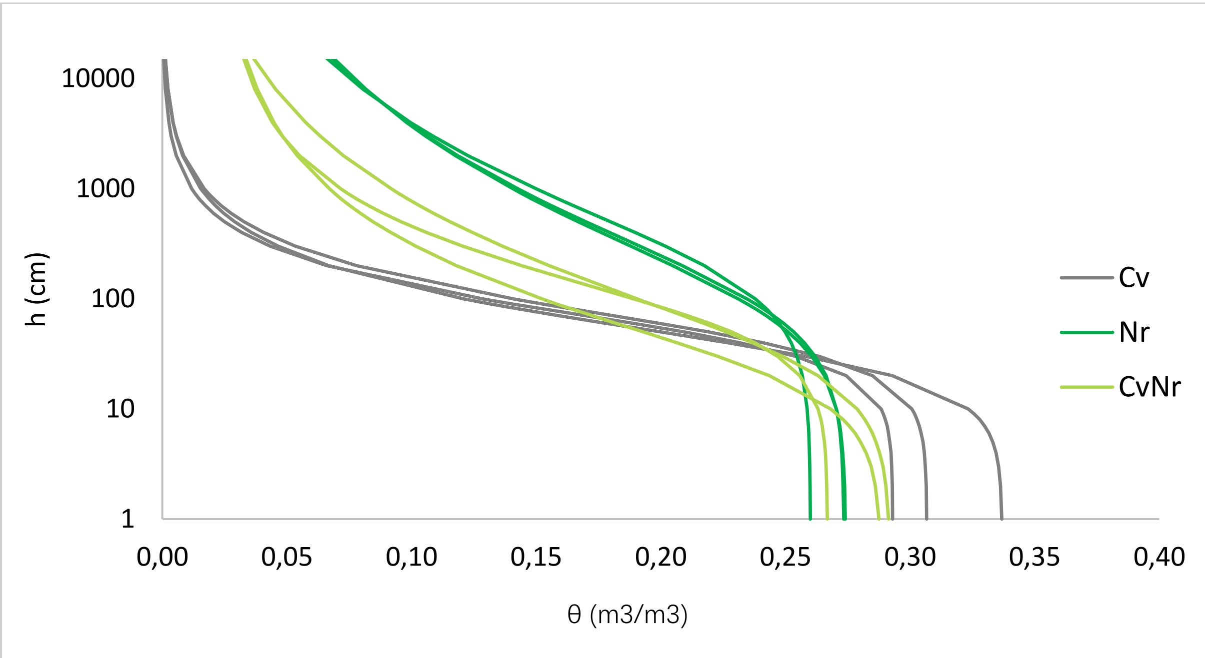


Figure 16 Water retention curves of crushed sand Cv, natural sand Nr, and mix of these. The curves show the relation between volumetric water content θ (m^3/m^3) on the x-axis, and matric potential on the y-axis, the latter expressed as a pressure head h (cm water column).

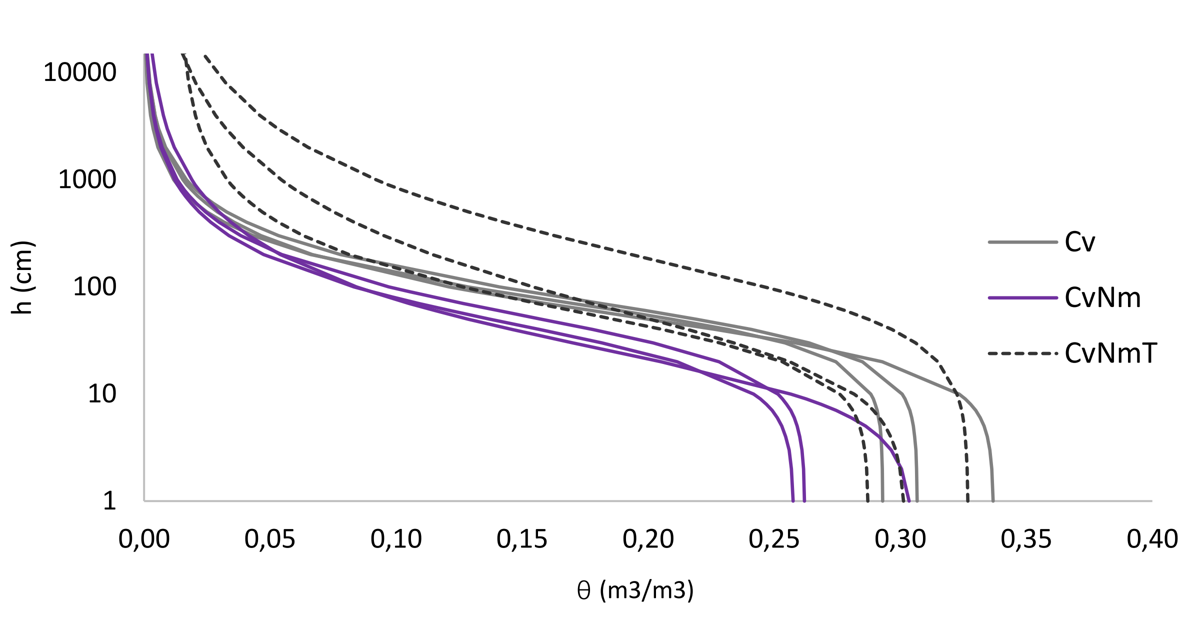


Figure 17: Water retention curves of crushed sand Cv, the mix with natural sand Nm, and the mix with Nm + topsoil T. The curves show the relation between volumetric water content θ (m^3/m^3) on the x-axis, and matric potential on the y-axis, the latter expressed as a pressure head h (cm water column).

3.4 Standard physical properties

Standard soil physical properties like bulk density and total porosity were determined from samples taken from the soils in the lysimeters.

Table 3: Average bulk density (g/cm^3) and average total porosity (%) of crushed sands (Cv and Cs) and natural sands (Nm and Nr), and mixes of these, including one mix with organic topsoil (T). The total porosity was estimated by totalling air and water filled porosity from samples equilibrated at field capacity (-100 cm).

Soil type	Bulk density (g/cm^3)	Total porosity (%)
Cv	1.54	44.7
Cs	1.58	47.8
Nr	1.55	42.0
Nm	1.45	47.9
CvNm	1.56	43.2
CsNm	1.61	43.7
CvNr	1.67	38.5
CvNmT	1.57	42.3

General trends

From the results, there seem to be some indications that the artificial sands had higher bulk density, than the natural sands, but only consistently higher than Nm. Regarding the total porosity, the results did not indicate consistently lower total porosity. The largest difference in total porosity were in fact between the natural sands (Table 3). From the non-mixed soils, Nr had the lowest total porosity of 42 % while Nm had the highest of approximately 47.9 %, just slightly higher than that of Cs. From these results, it does not appear that the crushed sands consistently had lower total porosities than the natural sands. The measurements of bulk density, however, show that both of the crushed sands had higher bulk density than that of Nm, although Cs and Nm apparently had the same total porosity. According to the results Cs had higher bulk density than both natural sands.

Soil mixes

It appears from the results in Table 3 that all the mixed soils had lower total porosity and higher bulk density than their original soil components, particularly CvNr with a bulk density of 1.67 g/cm^3, and a total porosity of only 38 %.

3.5 Particle characterisation

Part of the hypothesis suggested that crushed sand grains were sharper (more angular) than natural sands, thus we were interested in characterising the surface shape by visual assessment of angularity of particles between 2-4 mm. In addition, we were interested in the degree of flakiness, which is considered important for how the particles consolidate and settle.

Angularity

Table 4: Assessment of particle angularity. Shows the number of particles that were either angular, subrounded, or rounded from a total of 10 particles in the size 2-4 mm, and the quantity of particles whose least dimension scored less than 0.6 on their average dimension in the flakiness test.

Soil type	Angular	Subrounded	Rounded	Well rounded	Flakiness
Cv	8/10	2/10	0/10	0/10	7/10
Cs	8/10	2/10	0/10	0/10	5/10
Nm	1/10	4/10	5/10	0/10	1/10
Nr	2/10	4/10	4/10	0/10	0/10

The results from the visual assessments show that particles of the crushed sands were mostly angular (Table 4).

Both Cv and Cs had the highest proportion of angular sand grains (8 out of 10) compared to only 1-2 particles of the natural sand particles (Nm and Nr). 40-50 % of the selection of natural sand particles were rounded, while none of the crushed particles were assessed to this classification. The flakiness test show that the crushed sands had a high proportion of flaky particles, particularly Cv.

Figure 18: 2D picture of sand particles >2 mm to demonstrate the differences in particle shape between two types of crushed sands (Cv and Cs) and two types of natural sands (Nm and Nr). Foto taken by Sigrid Esmeralda Arnestad.

2D pictures in Figure 18 present the sample selection of the crushed and natural sand particles, which demonstrate that both crushed sands are angular with more sharp edges compared to particles of the natural derived sands.

3.6 Grain size distribution

Table 5: Grain size distribution of of crushed sands (Cv and Cs), natural sands (Nm and Nr), and mixes of these, including one mix with organic topsoil (T), (analysis performed by Eurofins).

Soil type	Clay <0.002 mm	Silt, fine 0.002< x <0.006 mm	Silt, medium 0.006< x <0.02 mm	Silt, coarse 0.02< x <0.06 mm	Sand, fine 0.06< x <0.2 mm	Sand, medium 0.2< x <0.6 mm	Sand, coarse 0.6< x <2.0 mm	Fraction > 2,0 mm total of sample	Texture classification
Nm	2	0	0	1	7	34	55	18	Coarse sand
Nr	7	3	7	9	16	36	22	42	Loamy medium sand
Cv	2	0	0	3	12	27	56	5	Coarse sand
Cs	4	1	3	5	8	20	59	24	Coarse sand
CvNm	2	0	1	5	15	39	39	12	Coarse sand
CvNmT	2	0	1	5	20	43	29	14	Medium sand
CsNm	5	1	2	4	10	36	42	17	Coarse sand
CvNr	4	1	1	6	21	38	29	28	Medium sand

General trends

According to the grain size distribution in Table 5, the crushed sands and Nm were classified as coarse, all of which had more than 50 % of the total volume in the coarsest sand fraction. The content of fine particles (silt+clay) was less than 5 % in Cv and Nm, and a little higher in Cs (13 %). In contrast, 26 % of the sample volume in Nr was clay and silt, resulting in a different textural class, respectively a *loamy medium sand*.

Soil mixes

Most of the soil mixes were coarse sand except CvNr and CvNmT, which are medium sand.

3.7 Chemical analysis

Table 6: Chemical analysis of crushed sands (Cv and Cs), natural sands (Nm and Nr), and mixes of these, including one mix with organic topsoil (T), (analysis performed by Eurofins).

Soil type	Volume, weight kg/l	pH	Phosphorus (P-AL) mg/100g	Pota-ssium (K-AL) mg/100g	Magne-sium (Mg-AL) mg/100g	Calcium (Ca-AL) mg/100g	Sodium (Na-AL) mg/100g	Loss on ignition %TS	Acid soluble Pota-ssium (K) mg/100g
Nm	1.7	8.4	2.2	2.1	3.9	260	<1	0.5	23
Nr	1.5	7.4	4.8	6.1	5.5	230	1.2	3.0	94
Cv	1.6	7.7	2.0	2.5	3.3	150	<1	0.2	160
Cs	1.7	9.0	3.3	4.2	17	1200	2.3	1.0	63
CvNm	1.6	7.9	1.9	2.6	4.0	200	1.1	0.3	130
CvNmT	1.6	7.1	1.8	3.0	4.3	180	1.3	0.8	130
CsNm	1.7	9.0	3.9	2.5	11	660	2.0	0.7	42
CvNr	1.5	7.3	3.1	4.3	4.2	160	1.6	1.1	150

The chemical analysis shows a large variation in pH between the soil types from near neutral to basic (7.1-9) (Table 6). Of the non-mixed soils, Cs had the highest pH of 9.0, while Nr had the lowest of 7.1. Mixing generally seemed to influence pH. Mixing with Nm resulted in increased pH from 7.7 to 7.9, and reduced drastically to 7.1 when additionally mixing it with the topsoil (CvNmT, indicating a strong influence from the topsoil. Unfortunately, we had no pH measurements of the topsoil. The pH also decreased when mixing with Nr, as the pH reduced from 7.7 (Cv) to 7.3 (CvNr).

Cs had considerably higher amount of magnesium and calcium compared to the rest of the soils. Measurements of loss of ignition (LOI) showed that Nr had the highest content of organic matter (3 %), while the rest of the soils had 1.1 % or less. It should be noted that Cs had higher content of organic matter (1 %) than that of Nm (0.5 %) which is unexpected, and that the mix of Cs and Nm had similar pH as Cs, although it was mixed with a natural soil with lower pH and lower calcium content. This might reflect some inaccuracy.

4 Discussion

The results indicates that mass loss of tea is generally lower in artificial sands compared to natural sands, which is in line with the second hypothesis, although this significance were primarily in the upper soil layer. We found that mass loss of rooibos and green tea was significantly lower in the artificial sands compared to either of the natural sands. The differences were, however, not as significant in the deepest layer compared to the upper layer. On the other hand, in several of the coarsest soil types, decomposition did not decrease by soil depth as generally expected, and the impact of soil depth on these texture classes seem to matter less than the impact of other properties of these soils, like low potential to retain water. The differences in physical and hydraulic properties between the artificial and natural sands seem to depend on differences in texture and grain size distribution. Moreover, this study demonstrates that the surface shapes of the artificial sands are sharper than that of natural derived sands, and with an overall greater flakiness. In terms of chemical properties, it appears that artificial sands generally have more alkaline pH, and low content of organic matter. On the other hand, some of these characteristics were also associated with one of the natural sands, which demonstrate that potential differences between natural and artificial sands highly depends on the natural variation of soils.

The discussion section will address the physical and hydraulic characteristics, and some chemical parameters, that may have influenced the observed differences in decomposition between the soil types, with particular focus on the optimal conditions for microbial activity. Upper and lower layer will be discussed separately as different trends were observed. Additionally, the most important trends observed from the effect of mixing natural with artificial sands will be addressed. Ultimately, limitations of the study and critical evaluation of the methods will be discussed.

4.1 Variables affecting decomposition in the upper layer

4.1.1 Texture

Texture is recognised as an important variable for microbial decomposition due to its influence on air and moisture status in the soil, as addressed in the introduction. This section includes the influence of texture on the decomposition of tea regarding the pure sand types, i.e. not the mixed soils, which are discussed later (see *Effect of soil mixing*).

Based on the texture analysis, both artificial sands (Cv and Cs) and one of the natural sands (Nm) have more than 55 % of the total volume in the coarsest sand fraction, which indicate that they are very coarse textured (Table 5). If compared to the ideal grain size distribution for grave soils proposed by Økland et al (2022), these soils are *coarser than recommended* (Figure 19). These soils also showed significantly lower decomposition of tea in the upper layer than the natural loamy medium sand (Nr), which in contrast have much higher content of finer particles (Table 5), and is within the recommended texture interval (Figure 19). These results coincide with the theoretical ideal interval by Økland et al (2022) and indicate that very coarse soil may limit decomposition.

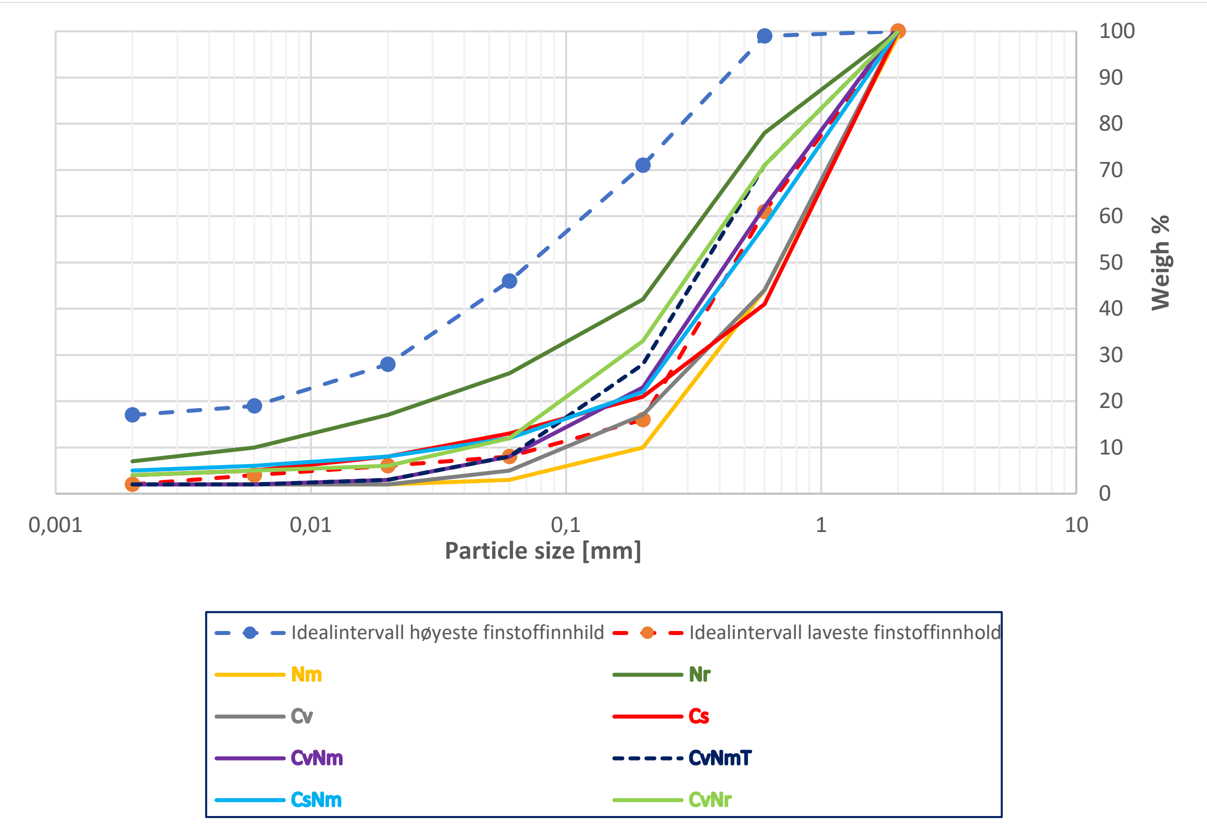


Figure 19: Grain size distribution curves of artificial, natural, and mixed sands (N = natural, C = crushed) compared to the theoretical ideal grain size distribution interval for grave soils, with finest recommended texture (blue-dotted curve) and coarsest recommended texture (red-dotted curve). The recommended grain size curves are from Økland et al., (2022), p. 101.

4.1.2 Moisture

As coarse textured soil is associated with weak retention capacity due to their high quantity of macropores, both artificial soils (Cv and Cs) and the coarse natural sand (Nm) pose a risk of being too dry to sustain microbial metabolism. It may therefore be suggested *that lack of moisture* was limiting microbial activity in the upper layer, resulting in significantly less decomposition than that of the loamy medium sand (Figure 8, Figure 9). This is in line with other studies of plant litter by De Santo et al. (1993) who observed limited decomposition of litter due to dryness, and by studies of rats (although this is different biological material), which decomposed greater in wet sandy soils than dry sandy soils. (Carter et al., 2010). Carter et al. (2010) suggested in fact that moisture could be the most important factor controlling microbial cadaver decomposition, which give emphasise to the assumption that moisture was a limiting factor in the upper layer.

The suggestion that limited moisture may have restricted microbial decompositions in the upper layer in the artificial and natural coarse sand, can be further supported from the water retention analysis and the resulting shape of the pF curves in Figure 13. The low water content at field capacity (-100 cm of matric potential) for Cs, Cv, and Nm (Table 2), indicate two important characteristics, which is:

1. Their dominating pore size fraction is likely in the range of 0.03 – 3 mm, as this is the equal pore size diameter to a matric potential of -100 cm to -1 cm.
2. As gravity overcome capillarity in these macropores most of the water is likely drainable rather than retained by the soil matrix.

Their hydraulic behaviour indicates much lower capacity to retain water than that of the loamy medium sand (Nr), considering its more gradual curve shape, and higher water content at field capacity (Table 2). This indicate a larger fraction of micropores (<0.03 mm), where capillary forces keep more water from being drained. It may therefore be assumed that the moisture content was generally higher in the loamy medium sand than the coarse sands, and that this has been more optimal for microbial activity resulting in the observed higher decomposition rate (Figure 8, 9).

Theoretical optimal moisture content

Although we do not have actual moisture data from the field, the above statement can be substantiated with a theoretical calculation of the matric potential at which we can expect optimal moisture conditions for microbial activity. If we assume that optimal moisture conditions for decomposition in soil is when about 60 % of the total pore space is filled with water, as suggested by (Weil & Brady, 2017, p. 553) then already at -10 cm of matric potential, the water content in Cs and Nm would theoretically be too low to sustain optimal microbial activity (Table 7). The other artificial soil (Cv) may sustain optimal moisture conditions around -30cm of matric potential, which is still at considerably high potential (relatively wet conditions), compared to the loamy medium sand (Nr) which reaches its optimal water content around field capacity (-100 cm of matric potential). This demonstrates that even a short time after a rainfall, moisture may be depleted in the upper layers of Cs and Nm particularly, but also Cv. The natural loamy sand will likely be able to provide sufficient moisture under drier conditions.

Table 7: Comparison of optimal volumetric water content (calculated) for decomposition in soil, versus volumetric water content at increasing matric potential (measured) in artificial and natural sands. Optimal moisture conditions assume that 60 % of total pore volume is filled with water and is calculated with regard to the average total porosity of each soil type.

soil type	Texture	Total pore volume (%)	-10 cm	-30 cm	-50 cm	-100 cm	Optimal volumetric water content (60 % of total porosity)
Cv	Coarse sand	44,7	30,2	27,3	21,5	10,9	26,8
Cs	Coarse sand	47,8	19,7	15,1	13,4	11,8	28,7
Nr	Loamy medium sand	42,0	25,9	25,2	24,7	24,0	25,0
Nm	Coarse sand	47,9	24,6	7,4	4,7	3,7	28,7

Despite the fact that the water table was fixed in this study, and the soils regularly watered (about twice a week) this approach further supports the likelihood of dry conditions in the *upper layer* of the artificial sands (Cs and Cv) and the coarse natural sand (Nm). This may have restricted some of the microbial decomposition compared to that of the loamy medium sand (Nr). It should nevertheless be considered that the assumption of 60 % water filled porosity for optimal biological activity is a simplified approach, and that activity and abundance of microbes depend on other variables like pH, organic matter content, periodical stress etc (Klingberg, 2005; Weil & Brady, 2017, pp. 528, 553). It should also be noted that the optimal water content in Table 7 is calculated from the average *total porosity* of each soil type, which, for any measurement, has an associated uncertainty.

4.1.3 pH and organic matter

With support from the observed texture and associated hydraulic characteristics, it was previously suggested that moisture may have been restricted in the upper zone of the artificial sands, and the natural coarse sand (Nm), limiting the decomposition of tea in the upper layer. However, according to the results in Figure 8 and 9, the mass loss of tea was also different between the coarse textured soils, and significantly lower in Cs compared to Nm. As moisture was likely limited in both of these soils, this indicates that other factors have influenced decomposition in this upper layer.

In the introduction, it was suggested that optimal pH for microbial activity is around neutral, but that some fungi also may thrive in soils with lower pH (Weil & Brady, 2017, pp. 528, 553). This may support why decomposition was lowest in the artificial sand Cs, considering its notable high pH of 9 compared to most of the other soils (Table 6). The results of pH in general for the artificial sands coincides with the findings of similar crushed sand in the study by Haraldsen & Pedersen (2003), although Cs had even higher pH (9 compared to 8 in that study), supporting, however, that artificial sand have alkaline characteristics. Further, in the soils with greatest decomposition, like the natural loamy sand (Nr), pH was much closer to 7. In this soil, the organic matter content was also 3 %, which was the highest of all the soils. As microorganisms depend on nutrient supply to exist, a higher content of organic matter may have contributed to greater abundance of microorganisms in the first place in Nr, thus resulting in more diverse microbial community and activity. This is in line with Klingberg (2005), who pointed out that in cases were bodies did not decompose in sandy soils, this might be due low content of soil organic material and absence of microorganisms.

Effect of soil mixing may also support the assumption that higher organic matter content and near neutral pH is favourable for decomposition. Mixing Cv with Nm+T (the latter was an organic topsoil) resulted in a decrease in pH from 7.7 to 7.1, while decomposition showed to be significantly higher in the mixed soil type (Figure 8, 9). Mixing with the topsoil have likely increased the organic matter content, as supported by the slightly increase in loss on ignition (Table 6), and possibly increased the microbial community. On the other hand, caution should be exercised in concluding that lower pH and increased organic matter alone caused the observed positive increase in decomposition, as other parameters may also have changed with the mixing. For instant, the CvNmT mix also seem to have greater retention capacity than Cv and Nm (Figure 17), which is likely due to better retention properties of the topsoil. Greater potential to retain water might as well have contributed to improve optimal conditions for microbial activity as previously discussed.

Although it seems to be a general trend that soils with alkaline characteristics (high pH) have lower decomposition in the upper layer, there is some inconsistency that do not support this assumption. As shown in Figure 8, decomposition was significantly greater in CsNm compared to Cs in the upper layer despite the fact that both measured a pH of 9.0 (Table 6). From the chemical analysis we also see that organic matter content in the CsNm mix was slightly lower than Cs (0.7 vs 1.0 %) Thus, greater decomposition in CsNm cannot be explained by either a change in pH or greater organic matter content. Based on the shape of the pF curve of CsNm compared to that of Cs (Figure 15) (Weil & Brady, 2017, pp. 653–654), there is a slight indication that CsNm retains more water at the lowest matric potentials (closer to saturation), thus it might have contained more moisture to drive microbial metabolism. However, as with any measurements, there is an uncertainty related to both the chemical analysis, and the measured mass loss (see *Methodological limitations and uncertainty*). It may be that the pH of CsNm is somewhat inaccurate (too high), as this measurement deviates from the trend of the other mixes and did not change as a response to mixing with Nm.

Inconsistent results reflect possible uncertainties related to the methodology, but also highlights the complexity of interpreting observations from processes that are governed by various parameters. The soil, although disturbed, is a heterogenous material with high spatial variability, and at a microscopic level, few millimetres can make contrasting difference in the living environment for microorganisms (Paul, 2014). Hence, there might exist conditions or variables not explicitly reflected in the results, and thus not accounted for in the interpretation and discussion.

4.2 Soil importance in the lower layer

Soil type matter less in the lower layer

The significant differences in mass loss of tea between the soil types in the *upper layer* support the suggestion that soil type is important for microbiological decomposition. However, from the results in Figure 10 and 11, the differences in decomposition between soil types in the *lower layers* were in contrast mostly insignificant, and do not show the same clear trends as in the upper layer. The average decomposition decreased by depth in most soils, which can be assumed to result from depleted oxygen levels due to the nearby water table likely resulting in a higher water-filled porosity. The matric potential at this depth was expected to be higher (closer to zero) than in the upper layer due to the nearby water table. This may have caused partly anaerobic conditions through the filling of pores through capillary water rise. The assumption of anaerobic conditions in the lower layer may be further supported by the experience of a strong odour of “rotten eggs” when excavating teabags from the lower layer. These gases may be associated product from anaerobic respiration (Weil & Brady, 2017, pp. 653–654) and support that anaerobic conditions have been at least partly present in some of the soils although it was not registered from which soil type this occurred. However, due to the mostly insignificant difference in decomposition between the soil types observed in the lower layer, it may appear as if the effect of soil type is less substantial at this depth, which may indicate that water status is more important than other properties of the soil. In other words, soil properties may not be of particular importance if the soil is waterlogged or near saturation anyway.

Soil type does matter with depth

Although it appears like the effect of soil type on decomposition is minimal in the lower layer, the absence of change, or even increase in mass loss by depth in some of the soils might on the other hand reflect some important property differences. The average mass loss of green tea increased slightly in three out of eight soil types, and in two out of eight soil types with rooibos (see *Appendix B*, Table B3-B4). These soils, respectively Cs, Nm, CsNm, and CvNm, have in common to be *coarse sands* as indicated by the grain size distribution in Table 5. As no statistical analysis was performed to identify whether this positive increase in mass loss was significant, there is no basis for dismissing this difference as coincidental. It should also be recalled that decomposition in some of these soils were the lowest in the upper layer compared to other soil types, so decomposition was likely already limited. However, the *absence of negative change* from upper to lower layer in these soils may still reflect important differences in hydraulic properties and provide a basis for assuming that the conditions for microbial decomposition was not further limited in the lower layer from that in the upper layer.

It might be suggested that because of their textural properties, oxygen levels were not limited by depth in these soils. A high quantity of macropores could have neglected upward capillary water movement from the water table below the teabags, as Cs, Nm, CsNm and CvNm were coarse sands. This would prevent pores from filling with water and possibly maintain optimal air-filled porosity. This suggestion can be further supported by the significant greater decomposition in the natural coarse sand compared to the artificial sands in the lower layer (Figure 11). From previous discussions above it was suggested that Nm had weaker capillarity than the artificial sands, which may have prevented water from moving with upward capillarity and contributed to better aeration at this depth, thus, resulting in greater microbial decomposition. However, this assumption is subject to uncertainty considering that we could not observe the same trend for both tea types in the lower layer. In addition, the water table level was controlled to be the same in all soil types, but small variations did occur. If the water level was more frequently at a lower depth in these soils, the oxygen level might have been sufficient to maintain decomposition approximately the same. Another possibility may be that an unequal amount of water was applied to adjust to the correct water level. Each addition of fresh, oxygenated water introduced both extra water and oxygen to the surroundings of the teabags, likely adding some undesired variation to our observations. However, based on the average consumption of water for each soil type (see *Appendix B*, Table B2) it does not appear as there was consistently less or more water added to soil types. Variations in water table were therefore assumed to be approximately the same over all soils, over time, thus having a minimal effect on the observed decomposition.

4.3 Effect of soil mixing

A part of the study aim was to investigate the effect of mixing natural derived sand with artificial sand. Considering the scope of this thesis, I discuss only select, important parameters and trends.

4.3.1 Effects on decomposition of tea

Table 8 propose a summarization of the effect of mixing the natural sands with the artificial sands, and it may seem that mixing with organic topsoil has positive impact on the decomposition rate in coarse sand. The combination with topsoil (CvNmT) was the only mixed soil that showed consistently significantly better decomposition of both tea types in the upper layer. This supports that the effect of mixing with an organic soil may improve conditions for microbial decomposition. As suggested in previous discussion, this may be due to the incorporation of a more biological active soil (higher organic matter content, thus more microorganisms), which was emphasised by Klingberg (2005). A more favourable pH closer to neutral, and/or possibly better capacity to retain moisture than the sandy soils alone. It is likely that these factors combined have contributed to the positive effect observed from mixing with organic topsoil in the upper layer. It must be considered, however, that decomposition was not significant in CvNmT in the layer closest to the water table: This suggest that a possible positive effect of mixing artificial and natural coarse sand depends on the moisture status in the soil.

The effect of mixing with Nr and Nm seem to be mostly insignificant and not consistent across tea type, thus the results are likely not conclusive. The significantly greater decomposition in one of the mixes with the natural coarse sand (CsNm) however, should be recognised. Interestingly the same was not observed with when Nm was mixed with the other artificial soil (CvNm). This may indicate that the effect of the mixing with natural sand, if any, also depends on the properties of the artificial soil.

Table 8: Effect of mixing artificial sands (Cs and Cv) with natural sand (Nm and Nr) and topsoil (T), on decomposition of two types of tea in upper and lower layer. The effect is summarized in significantly greater (green), greater but not significant (black) and no notable change (red).

Mixed soil	Upper layer Green tea	Upper layer Rooibos	Lower layer Green tea	Lower layer Rooibos
CsNm	Significantly greater than Cs	Greater than Cs, but not significant	No notable change	Greater than Cs, but not significant
CvNm	No notable change	Greater than Cv, but not significant	Greater than Cv, but not significant	No notable change
CvNmT	Significantly Greater than both Cv and Nm	Significantly greater than both Cv and Nm	Greater than Cv and Nm, but not significant	No notable change
CvNr	Greater than Cv, but not significant	No notable change	No notable change	Greater than Cv, but not significant

4.3.2 Effect on physical and hydraulic properties

From the water retention analysis (Figure 14-17) and the infiltration capacity (Figure 12) there seem to be a consistent trend that mixed soils generally perform between its original soil components. In practice, this highlights the importance of knowing the characteristics of the natural soil types, possibly enabling a controlled change of properties. It should also be noted that mixing, without exception, resulted in a general decrease in total porosity, while the bulk density increased (Table 3). This indicates that mechanically mixing of different soils may lead to denser soil and decreases the total pore space. This may be due to a more well graded/poorly sorted soil as illustrated in the introduction (*1.4 Importance of physical properties*). The mixing of possibly different sizes and shapes of particles from the different sand types may compact into a tighter packing arrangement when consolidating, leading to the above observation, emphasised in the introduction (*Importance of physical properties*). This may be further supported by the more angular and flakier particle shape that characterize the artificial sand grains compared to the natural sand grains (Figure 18)

However, any significant negative impact of mixing artificial with natural sands in terms of decomposition could not be observed. It may therefore be assumed that a possible decrease in total porosity and increased density from mixing soils have minor negative effect on *short term* microbial decomposition, although the effect in the long term remains uncertain.

4.4 Physical characterisation of artificial sand

It has initially been suggested that artificial sand particles are shaped differently than naturally derived sand, underlying the assumption that artificial sand may be packed denser, decreasing the total porosity. Simple 2D pictures of the particle surfaces and visual assessment of angularity support the initial hypothesis that artificial sand grains are more sharp-edged/angular, and flakier than natural sand (Figure 18 and Table 4). The results also support, to an extent, that artificial sands may be packed more densely than natural sand according to the higher bulk density of Cv and Cs compared to Nm (Table 3), all of which are in the same textural class. This may support part of the initial hypothesis. In contrast, estimations of total porosity did not indicate any particular differences between the artificial and natural sands. However, field observations from an ongoing project (May, 2024) indicates that there might be differences in the total pore volume. That project incorporates a subset of soil types identical to those utilized in the present thesis, including the artificial sand Cv and the natural sand Nm, and conduct pig decomposition experiments in larger but identical lysimeters. Recently, these lysimeters were refilled with equal amount of water after being drained for winter conditions. However, the response in water level was considerably different in the artificial sand Cs compared to Nm and their mix, where the artificial sand Cv filled up to saturation in all of its replicates (six lysimeters), with ponding water on top in some of them. This was not applicable to the natural soil type (Nm), which indicates a lower total pore space in the artificial sand compared to the natural sand. It should be considered that these observations were not systematically described, and they should therefore be interpreted carefully. Further studies on the effect of surface shape on long term consolidation, and the soil pore system and resulting functional soil hydraulic properties, is encouraged.

4.5 Artificial sand in a future perspective

The purpose of utilizing sand in cemetery soils is to improve the drainage capacity and ensure that water is not stagnating. Substituting with artificial sand may in a drainage perspective contribute to a relatively fast water transportation. Based on the physical and hydraulic characterisation of artificial sands, as discussed throughout this section, the results indicate some similarities with coarse *natural* sand in terms of macroporosity and drainage capacity. Results from the infiltration test showed a high ability to rapidly infiltrate and conduct water, although the crushed sand types had slightly lower infiltration on average than the coarse natural sand (Figure 12). These findings coincide well with the texture analysis and the assumption of a higher macroporosity. High capacity to conduct water is desirable in a grave soil to ensure sufficient air-filled porosity and facilitate faster gas rate exchange. The latter effect is addressed in Carter et al.(2010) who found better decomposition of rats in wet sandy soil than wet fine-textured soil.

At the same time, this study also revealed the vulnerability of using coarse sand (whether artificial or natural) in terms of drought stress. During drier periods, and times with less precipitation, moisture conditions are likely to be unfavourable low for microbial decomposition in sands that are coarser than the theoretical recommended interval (Økland et al., 2022). This with support from the results in this study (see *section 4.1.1* and *4.1.2* previous in the discussion). In addition, trees and other vegetation are important for the general aesthetic, and used as a measure to divide between the different fields inside a cemetery (Klingberg, 2005). If the plants are to thrive, the soils must also provide sufficient plant available water. Utilization of soils with poor retention capacity (although high drainage capacity) will be prone to drought stress. Considering the artificial and natural coarse sand's limited plant-available water (:), these soils are likely not suitable for sustain plants with sufficient moisture, particularly during drier periods. In times of global warming and changing climate, increased precipitation and extreme drought events are projected (I. Hanssen-Bauer et al., 2017). Therefore, cemeteries constructed today must remain functional in future climate. In order to guide future cemetery design, further research investigating the impact of climate change on soil, and artificial soil dynamics on decomposition within cemeteries are necessary.

4.6 Methodological limitations and uncertainty

In controlled scientific experiments there will always be a limitation inherent in the choice of methodology, the methodological performance, and the handling and analysis of data. A general challenge is data representation, and the attempt to explain observations on a general basis based on few replicates. In this study, results related to physical and hydraulic properties mostly derives from triplicates, which likely is a low selection to represent natural variability. The artificial sands, however, are made according to a standard protocol, and can be assumed to be relatively uniform. The results should nevertheless be interpreted carefully and with the proviso that the data does not necessarily reflect the complexity and variability of soil in general.

4.6.1 Saturated water-filled porosity

Although data uncertainty is not always directly visible, some of the results from this study are peculiar. From the pF curves from the water retention analysis (Figure 13-17) we see that each replicate deviates from each other to a greater extent under the lowest matric potentials (near saturation). In addition, the volumetric water content at saturation (near 0 cm of matric potential), for each soil type is about 10 % less than the estimated total porosity (Table 3) (24-34 % vs 38-48 %). Because these soils in general are coarse-textured, they are vulnerable to rapidly losing gravitational water (aka. drainable) during weight measurements at saturation. The time it takes from lifting the pre-saturated soil (from the water filled vessel) onto the scale for weigh measurements might result in some loss of water, thus underestimating the actual water content at saturation. This issue is described in the RETC code, where it is emphasised that saturated water filled porosity from the retention analysis should not be used as an estimate of total porosity (van Genuchten et al., 1991).

4.6.2 Volumetric water content

For accurate measurement of water retention in a pressure chamber, it is crucial that the soil sample have good contact with the pressure plate. If it does not, water will not drain appropriately in response to the prescribed pressure and the measurement will therefore lead to an overestimation of the volumetric water content at the given pressure. Two pressure plates had dislodged within the pressure chamber and tilted during the 1 bar pressure equilibrium for water retention analysis, potentially causing insufficient contact between the soil samples and plates. Imprecise estimation of volumetric water content at 1000 cm of matric potential must therefore be considered. Consequently, water content corresponding to 1 bar pressure was generally given low weight during the curve fitting.

4.6.3 Infiltration capacity

Capturing an average rate of water movement in soil poses a challenge due to the multitude of approaches describing water flow, each incorporating different assumptions and simplifications. The infiltration capacity was estimated from infiltration measurements assuming *one dimensional* flow, which does not take into account that the water moves in a three-dimensional matrix, and secondly that the infiltration rate reached a steady state. The steady state rate was likely not fully achieved during some of the trials, but this was handled by using the average reading of the last six rather than the last three measurement. It should nevertheless be considered the possibility that the infiltration capacity is somewhat overestimated, and a simplified approach to describe water rate movement. On the other hand, the infiltration capacities coincide with the expected flow rate that can be assumed from the texture and retention results, where a higher proportion of fine particles corresponds to a lower infiltration rate. This give reason to believe that the infiltration values in all provide a simple but good indication of the capacity to conduct water and is valuable for internal comparison between the soil types in this study.

4.6.4 Decomposition of tea

As plant material was used instead of animal proxies, the results of decomposition from this study should not be directly applied to inform assumptions regarding the decomposition rates of human corpses. The results reflect, however, the habitability of the soils and soil properties that can be assumed to affect microbial activity. Results from this experiment can therefore be considered relevant for topics that address grave soils and their suitability for decomposing human corpses.

It should, however, be considered that other factors than microbial activity may have influenced the total mass loss of tea. Litter decomposition (in terms of mass loss) is also subject to leaching of water soluble compounds (Couˆteaux et al., 1995). Blume-Werry et al. (2021) concluded that in the early stage of decomposition, mass loss of rooibos, and green tea particularly, is rather due to passive leaching than microbial decomposition. We should therefore be careful of interpreting mass loss solely as a reflection of microbial decomposition. The teabags were also washed by hand after excavation, thus some material might have been lost during this procedure. According to the tea bag index by Keuskamp et al. (2013) washing is not recommended on the basis of this risk (Teatime4Science., n.d.). Their approach with drying, and weighing only what's inside the mesh, was tested but considered problematic as soil was strongly attached to the mesh surface. Despite the possibility that mass loss was overestimated, since all tea bags received the same treatment, there is reason to believe that this potential loss applies to all replicates without any systematic tendency, and that the method likely have not affected the differences between the soil types.

Conclusion

This study shows that artificial sand crushed from rock can limit the microbial decomposition of organic components in soil, which supports the initial hypothesis. Assuming that the total mass loss of tea was mostly due to microbial decomposition, it can be suggested that microbial activity may be limited by high pH and low organic matter content associated with the artificial sands, and that too coarse texture may restrict microbial activity due to lack of moisture. This effect seems however independent of origin (artificial vs natural). The study indicates that coarse textured sand may provide better oxygen conditions than loamy medium sand deeper in the soil and close to a water table, possibly due to absence of upward capillary movement preventing too high water filled porosity. This effect should not, however, be considered prominent as decomposition was mostly insignificant across soil types in the lower soil layer. The latter may indicate that soil type is less important for short term decomposition in too wet conditions, although we could not confirm the actual moisture level. Estimations of total porosity do not indicate that pore volume is consistently lower in the artificial sands compared to natural sands as the second hypothesis suggested. On the contrary, this study supports the assumption that artificial sands exhibit a more angular and flakier particle shape than natural sand, and the long-term effect of this difference on pore volume and packing is uncertain.

In all, results from the decomposition experiment must be seen in the context of its limitation, and caution should be exercised regarding using these results to predict decomposition rates of human corpses in soil burial. I nevertheless suggest that artificial coarse sand likely have lower potential to facilitate a diverse microbial activity, as this study give little support that similar soil components, in its pure form, would contribute to any considerable positive effect on the decomposition of corpses if utilized in cemeteries.

5 References

Blume-Werry, G., Di Maurizio, V., Beil, I., Lett, S., Schwieger, S., & Kreyling, J. (2021). Don't drink it, bury it: Comparing decomposition rates with the tea bag index is possible without prior leaching. *Plant and Soil*, *465*(1), 613–621. https://doi.org/10.1007/s11104-021-04968-z

Carter, D. O., Yellowlees, D., & Tibbett, M. (2008). Temperature affects microbial decomposition of cadavers (Rattus rattus) in contrasting soils. *Applied Soil Ecology*, *40*(1), 129–137. https://doi.org/10.1016/j.apsoil.2008.03.010

Carter, D. O., Yellowlees, D., & Tibbett, M. (2010). Moisture can be the dominant environmental parameter governing cadaver decomposition in soil. *Forensic Science International*, *200*(1), 60–66. https://doi.org/10.1016/j.forsciint.2010.03.031

Couˆteaux, M.-M., Bottner, P., & Berg, B. (1995). Litter decomposition, climate and liter quality. *Trends in Ecology & Evolution*, *10*(2), 63–66. https://doi.org/10.1016/S0169-5347(00)88978-8

Danielson, R. E. Sutherland, P. L. (1986). *Methods of soil analysis. Part 1-Physical and Mineralogical Methods. Second edition.* Madison.

Dannevig, P., & Harstveit, K. (2022). *Klima i Norge*. Retrieved 16 March 2024 from https://snl.no/klima_i_Norge

De Santo, A. V., Berg, B., Rutigliano, F. A., Alfani, A., & Floretto, A. (1993). Factors regulating early-stage decomposition of needle litters in five different coniferous forests. *Soil Biology and Biochemistry*, *25*(10), 1423–1433. https://doi.org/10.1016/0038-0717(93)90057-I

Dent, B. B., Forbes, S. L., & Stuart, B. H. (2004). Review of human decomposition processes in soil. *Environmental Geology*, *45*(4), 576–585. https://doi.org/10.1007/s00254-003-0913-z

Drøbakveien jord. (n.d.). *Soldet Matjord*. Retrieved 14 May 2024, from http://www.drobakveienjord.no/soldet-matjord.html.

Egnér, H., Riehm, H., & Domingo, W. R. (1960). *Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoff zustandes der Böden*.

Fatehnia, M., Tawfiq, K., & Abichou, T. (2014). Comparison of the methods of hydraulic conductivity estimation from mini disk infiltrometer. *Electronic Journal of Geotechnical Engineering*, *19*, 1047–1063.

Fiedler, S., Berns, A. E., Schwark, L., Woelk, A. T., & Graw, M. (2015). The chemistry of death – Adipocere degradation in modern graveyards. *Forensic Science International*, *257*, 320–328. https://doi.org/10.1016/j.forsciint.2015.09.010

Forbes, S. L., Stuart, B. H., & Dent, B. B. (2005). The effect of the burial environment on adipocere formation. *Forensic Science International*, *154*(1), 24–34. https://doi.org/10.1016/j.forsciint.2004.09.107

Frugo. (n.d). Retrieved May 2023 from https://www.fruugonorge.com/

Fründ, H.-C., & Schoenen, D. (2009). Quantification of adipocere degradation with and without access to oxygen and to the living soil. *Forensic Science International*, *188*(1), 18–22. https://doi.org/10.1016/j.forsciint.2009.03.005

Granøe, H. A. (2024, March 22). [Personal communication].

Gravplassforskriften. (1997). Forskrift til lov om gravplasser, kremasjon og gravferd (FOR-1997-01-10-16). Lovdata. https://lovdata.no/dokument/SF/forskrift/1997-01-10-16

Gravplassloven. (1997). Lov om gravplasser, kremasjon og gravferd (LOV-1996-06-07-32). Lovdata. https://lovdata.no/dokument/NL/lov/1996-06-07-32

Haraldsen, T. K., & Pedersen, P. A. (2003). Mixtures of crushed rock, forest soils, and sewage sludge used as soils for grassed green areas. *Urban Forestry & Urban Greening*, *2*(1), 41–51. https://doi.org/10.1078/1618-8667-00022

I. Hanssen-Bauer, E.J. Førland, I. Haddeland, H. Hisdal, S. Mayer, A. Nesje, J.E.Ø. Nilsen, S. Sandven, A.B. Sandø, A. Sorteberg, & B. Ådlandsvik. (2017). *Climate in Norway 2100 – a knowledge base for climate adaptation* (NCCS Report 1/2017). Miljødirektoratet.

Keuskamp, J. A., Dingemans, B. J. J., Lehtinen, T., Sarneel, J. M., & Hefting, M. M. (2013). Tea Bag Index: A novel approach to collect uniform decomposition data across ecosystems. *Methods in Ecology and Evolution*, *4*(11), 1070–1075. https://doi.org/10.1111/2041-210X.12097

Klingberg, H. (2005). *Den nye kirkegårdsboka*. Ars Longa.

Kremasjonsandelen. (2024). Statsforvalteren i Vestfold og Telemark. https://www.statsforvalteren.no/vestfold-og-telemark/gravplassmyndighet/kremasjonsstatistikk/

Krogstad, T., Børresen, T., & Almås, Å. R. (2018). *Field and laboratory methods for the analysis of soil*. Faulty of environmental sciences and natural resource management, NMBU.

Leknes, S., & Løkken, S. A. (2022). *Befolkningsframskrivinger for kommunene 2022*.

Lutgens, F., Tarbuck, E., & Tasa, D. (2015). *Essentials of Geology, Global Edition* (12th ed.). Pearson. https://www.perlego.com/book/812160/essentials-of-geology-global-edition-pdf

METER. (n.d.). *MINI DISK INFILTROMETER.* Retrieved 13 May 2024, from https://metergroup.com/products/mini-disk-infiltrometer/

Danielson, R. E., & Sutherland P. L. (1986). *Methods of soil analysis. Part 1-Physical and Mineralogical Methods. Second edition.* Madison.

NOU 2014:2. (2014). *Lik og likskap*. Kulturdepartementet. https://www.regjeringen.no/contentassets/9c7c0328863d4c15a53aa60e84a89e82/nn-no/pdfs/nou201420140002000dddpdfs.pdf

Økland, I. H., & Haraldsen, T. (2020). Nedbrytningsforhold på gravplasser. En sammenfatning av faglig kunnskap og NIBIOs konsultasjonsgrunnlag for egnet jord til kistegraver våren 2020. *NIBIO Rapport* 6(70). 28p. NIBIO. https://nibio.brage.unit.no/nibio-xmlui/handle/11250/2731611

Økland, I. H., Jayesingha, M., Skrutvold, J., Halvorsen, R., & Haraldsen, T. (2022). *Egnet jord til kistegraver*. NIBIO Rapport 8(97). 113p. https://nibio.brage.unit.no/nibio-xmlui/handle/11250/3009633

Olsen, L. (1983). *Rundingsanalyser på grus- og steinpartikler: Et nytig hjelpemiddel ved undersøkelser av løsmassenes genese*. Universitetsforlaget.

Patrick, S. (2019). *Guide to Pavement Technology Part 4K: Selection and Design of Sprayed Seals*.

Paul, E. (2014). *Soil Microbiology, Ecology and Biochemistry*. Academic Press.

Pless, J., Worrell, M., & Clark, M. (1996). Postmortem Changes in Soft Tissues. In W. Haglund & M. Sorg (Eds.), *Forensic Taphonomy*. CRC Press. https://doi.org/10.1201/9781439821923.ch9

Royal Eijkelkamp. (n.d.). *Sandbox for the pF determination of soil samples*. Retrieved 13 May 2024, from https://www.royaleijkelkamp.com/products/lab-testing-equipment/soil-physical-research/pf-determination/sandbox-for-pf-determination/

Schnürer, J., Clarholm, M., & Rosswall, T. (1985). Microbial biomass and activity in an agricultural soil with different organic matter contents. *Soil Biology and Biochemistry*, *17*(5), 611–618. https://doi.org/10.1016/0038-0717(85)90036-7

Schultz, J. J. (2007). Variables Affecting the Gross Decomposition of Buried Bodies in Florida: Controlled Graves Using Pig (sus Scrofa) Cadavers as a Proxy for Human Bodies. *Florida Scientist*, *70*(2), 157–165.

Soilmoisture(n.d.). *1600 EXTRACTOR* Retrieved 13 May 2024, from http://www.soilmoisture.com/1600/

Teatime4Science. (n.d.). *Stepwise protocol.* Retrieved 28 March 2024, from http://www.teatime4science.org/method/stepwise-protocol/

Teo, C. H., Hing, H. L., Hamzah, N. H., & Hamzah, S. P. A. A. (2021). The Effect of Different Coverings on Total Body Score Development of Buried Carcasses. *The Malaysian Journal of Medical Sciences : MJMS*, *28*(4), 103–112. https://doi.org/10.21315/mjms2021.28.4.11

Utengen, S. K. (2024, February 27). [Personal communication].

Van Genuchten, M. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal*, *44*(5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Van Genuchten, M., Leij, F., Yates, S., & Williams, J. (1991). The RETC Code for Quantifying Hydraulic Functions of Unsaturated Soils. *EPA/600/2-91/065, R.S.*, *83*.

Weil, R., & Brady, N. (2017). *The Nature and Properties of Soils. 15th edition*. Pearson.

Zhang, R. (1997). Determination of Soil Sorptivity and Hydraulic Conductivity from the Disk Infiltrometer. *Soil Science Society of America Journal*, *61*(4), 1024–1030. https://doi.org/10.2136/sssaj1997.03615995006100040005x

6 Appendix

Appendix A: Statistics

Appendix B: Decomposition of tea

Appendix C: Infiltration and water retention

Appendix D: Other relevant information

Additional data can be further requested

Appendix A

Statistics

Green tea upper layer

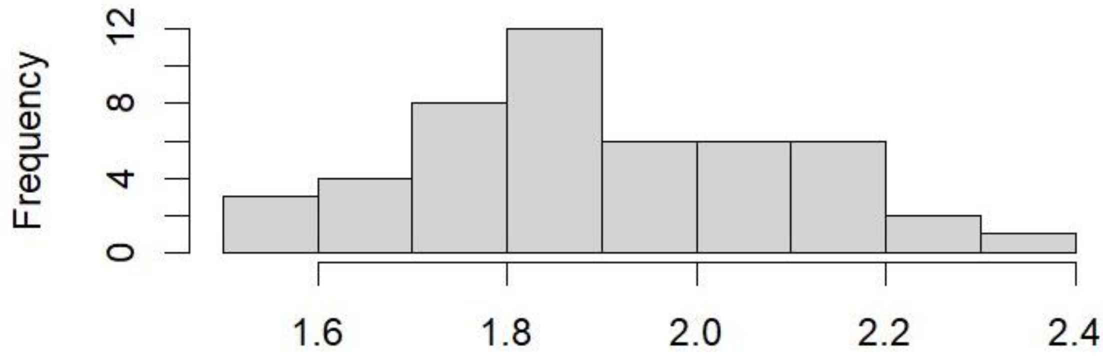


Figure A1: Data distribution of green tea upper layer.

shapiro-Wilk normality test
data: green_upper_data$weight_loss
W = 0.98327, p-value = 0.7183
p>0.05, Assumptions of normality met.

```
> summary(GT1_anova)
                      Df Sum Sq Mean Sq F value   Pr(>F)
as.factor(Soil_type)  7 1.2794 0.18277   19.16 5.98e-11
Residuals            40 0.3815 0.00954
```

p<0.05, statistical differences between one or more groups.

Green tea lower layer

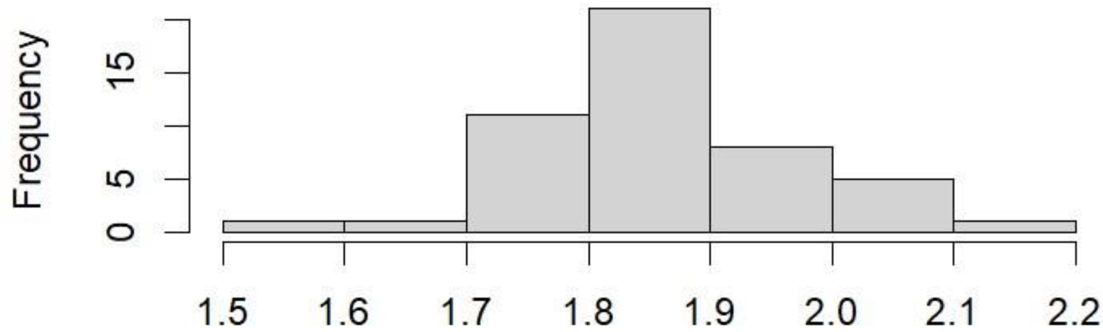


Figure A2: Data distribution of green tea lower layer.

Shapiro-Wilk normality test
data: green_lower_data$weight_loss
W = 0.97684, p-value = 0.4548
p>0.05, Assumptions of normality met.

```
> summary(GT2_anova)
                      Df Sum Sq Mean Sq F value Pr(>F)
as.factor(Soil_type)  7 0.1321 0.01887    1.77  0.121
Residuals            40 0.4265 0.01066
```

p>0,05. No statistical differences between the groups.

Rooiobos upper layer

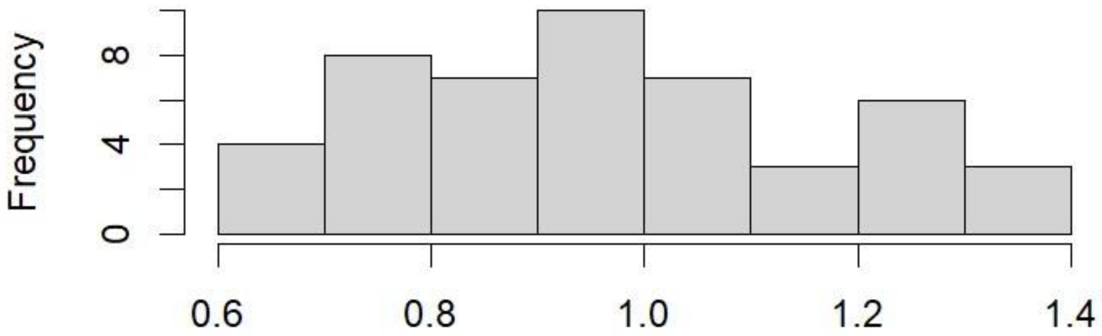


Figure A3: Data distribution of rooibos upper layer.

Shapiro-Wilk normality test
data: rooibos_upper_data$weight_loss
W = 0.96567, p-value = 0.1708
p>0.05, Assumptions of normality met.

```
> summary(RT1_anova)
                    Df Sum Sq Mean Sq F value   Pr(>F)
as.factor(Soil_type)  7 1.2099 0.17284   7.392 1.07e-05
Residuals            40 0.9352 0.02338
```

p<0.05, statistical differences between one or more groups

Rooibos lower layer

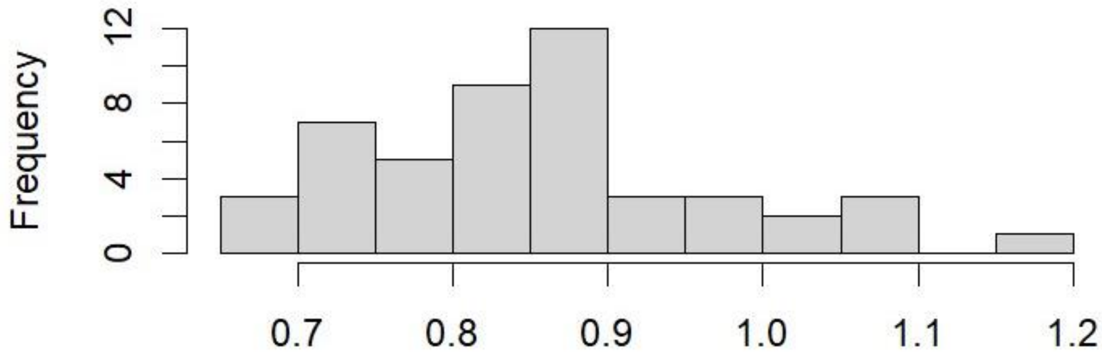


Figure A4: Data distribution of rooibos upper layer.

Shapiro-Wilk normality test
data: log(rooibos_lower_data$weight_loss)
W = 0.96412, p-value = 0.148
p>0.05, Assumptions of normality met

```
> summary(RT2_anova)
                    Df Sum Sq Mean Sq F value Pr(>F)
as.factor(Soil_type)  7 0.2394 0.03420    3.62 0.0041
Residuals            40 0.3780 0.00945
```

p<0.05, statistical differences between one or more groups

Appendix B

Decomposition of tea

Table B1: Average mass loss (g) and standard deviation (std) of green tea upper layer (GT1), green tea lower layer (GT2), and rooibos upper layer (RT1) and lower layer (RT2) in crushed sands (Cv and Cs), natural sands (Nm, Nr), and mixed sands. Arranged from lowest to highest mass loss.

Soil Type	GT1	std
Cs	1,610	0,069
CvNm	1,813	0,056
Cv	1,828	0,084
CsNm	1,833	0,030
Nm	1,893	0,069
CvNr	1,997	0,169
CvNmT	2,107	1,144
Nr	2,145	0,079

Soil Type	RT1	std
Cs	0,698	0,087
Cv	0,855	0,091
CvNr	0,923	0,184
CsNm	0,935	0,181
Nm	0,947	0,140
CvNm	1,003	0,100
Nr	1,168	0,239
CvNmT	1,235	0,133

Soil Type	GT2	std
Cv	1,777	0,059
Nm	1,810	0,036
Cs	1,827	0,174
Nr	1,862	0,093
CvNr	1,878	0,100
CsNm	1,880	0,045
CvNm	1,905	0,115
CvNmT	1,953	0,128

Soil Type	RT2	std
Cv	0,782	0,069
CvNm	0,782	0,084
Cs	0,810	0,141
Nr	0,862	0,027
CvNr	0,868	0,018
CvNmT	0,872	0,093
CsNm	0,890	0,105
Nm	1,015	0,152

Table B2: Average water (L) added to each soil type during the experiment period to adjust to the water level. Std is standard deviation.

Soil type	Average water adjustment (litres)	sd
Cv	10,0	1,5
Cs	5,7	2,5
Nr	3,7	1,2
Nm	4,3	1,0
CvNm	5,7	0,9
CsNm	7,8	1,6
CvNr	4,7	1,2
CvNmT	10,3	6,3

Difference in mass loss of tea between upper and lower soil layer

*Table B3: Average difference in decomposition of **green tea** (g) between upper and lower layer. Negative difference (red) mean that the mass loss was greater in the lower layer compared to upper layer.*

Soil type	green tea upper layer (g)	green tea lower layer (g)	Difference between upper and lower layer (g)	Interpretation
Cv	1.828	1.777	0.051	Decomposition decreased with depth, but less than 0.1 g
Cs	1.61	1.827	**-0.217**	Decomposition increased with depth
Nr	2.145	1.862	0.283	Decomposition decreased with more than 0.1 g with depth
Nm	1.893	1.81	0.083	Decomposition decreased with depth, but less than 0.1 g
CvNm	1.813	1.905	**-0.092**	Decomposition increased with depth
CsNm	1.833	1.88	**-0.047**	Decomposition increased with depth
CvNr	1.997	1.878	0.119	Decomposition decreased with more than 0.1 g with depth
CvNmT	2.107	1.953	0.154	Decomposition decreased with more than 0.1 g with depth

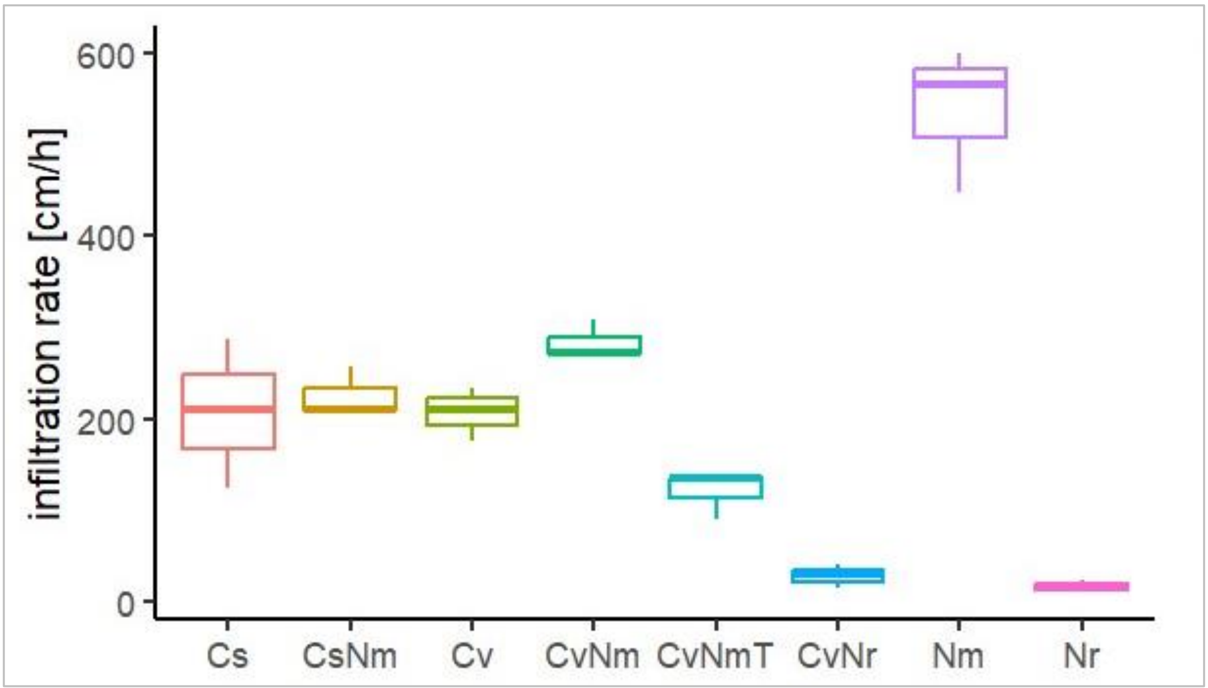
*Table B4: Average difference in decomposition of **rooibos** (g) between upper and lower layer. Negative difference (red) mean that the mass loss was greater in the lower layer compared to upper layer.*

Soil type	rooibos upper layer (g)	rooibos lower layer (g)	Difference between upper and lower layer (g)	Interpretation
Cv	0.855	0.782	0.073	Decomposition decreased with depth, but less than 0.1 g
Cs	0.698	0.81	**-0.112**	Decomposition increased with depth
Nr	1.168	0.862	0.306	Decomposition decreased with more than 0.1 g with depth
Nm	0.947	1.015	**-0.068**	Decomposition increased with depth
CvNm	1.003	0.782	0.221	Decomposition decreased with more than 0.1 g with depth
CsNm	0.935	0.89	0.045	Decomposition decreased with depth, but less than 0.1 g
CvNr	0.923	0.868	0.055	Decomposition decreased with depth, but less than 0.1 g
CvNmT	1.235	0.872	0.363	Decomposition decreased with more than 0.1 g with depth

Appendix C

Infiltration

Figure C1: Value distribution of the infiltration rate in cm/h) under 1 cm suction rate.



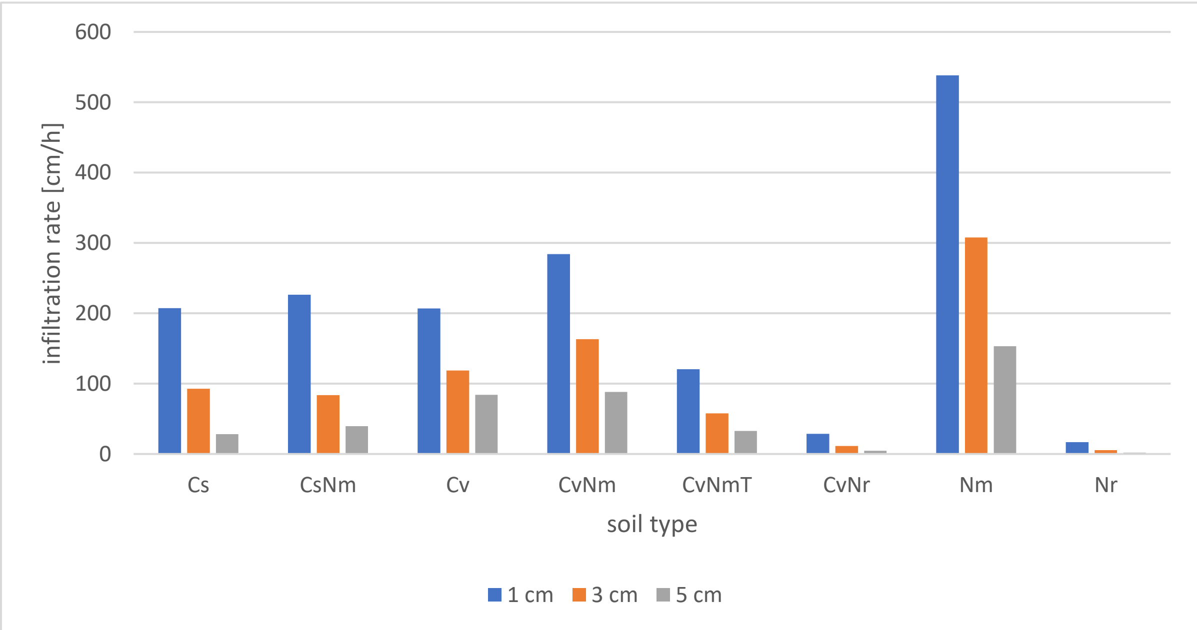


Figure C2: Mean infiltration rate in cm/h (y-axis) under 1 cm, 3 cm, and 5 cm of suction).

Table C3: Mean infiltration rate (ch/h) under 1, 3, and 5 cm of suction, and standard deviation.

Soil type	Mean 1 cm	Sd 1 cm	Mean 3 cm	Sd 3 cm	Mean 5 cm	Sd 5 cm
Cs	207.49	81.18	92.64	35.58	28.36	8.24
CsNm	226.35	26.14	83.83	32.82	39.40	15.37
Cv	207.07	29.15	118.47	8.63	84.32	7.22
CvNm	284.20	21.78	163.06	39.81	88.03	23.99
CvNmT	120.72	26.14	57.85	16.49	32.91	22.46
CvNr	28.50	12.66	11.39	1.03	4.37	1.97
Nm	538.22	79.16	307.73	92.56	153.42	35.66
Nr	16.98	6.92	5.59	4.07	2.01	1.10

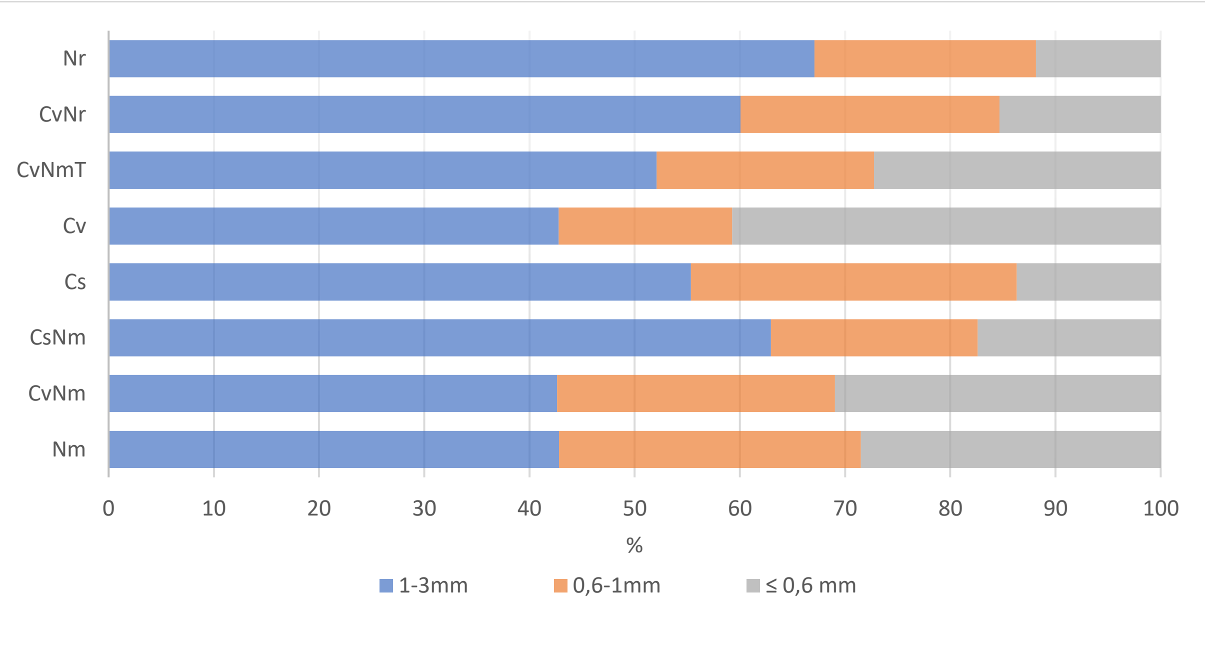


Figure C4: Proportion of infiltration at near saturation (1 cm suction) conducted by a certain pore size fraction, respectively 1-3 mm, 0.6-1 mm, and less than 0.6 mm diameter. 100 % equals the infiltration rate at 1 cm suction, assumed that 100% of the soil pores were conducting water at 1 cm suction.

Table C5: Calculation of the largest pore size (diameter) conducting water at 1, 3, and 5 cm suction rate

1 cm suction	3 cm suction	5 cm suction
$d = \left(\frac{0,15}{1cm}\right) x\ 2$ $d = 0,3\ cm = 3mm$	$d = \left(\frac{0,15}{3cm}\right) x\ 2$ $d = 0,1\ cm = 1mm$	$d = \left(\frac{0,15}{5cm}\right) x\ 2$ $d = 0,06\ cm = 0,6mm$
pores equal or smaller than 3 mm contribute to infiltration	pores equal or smalelr than 1 mm contribute to infiltration	Pores equal or smaller than 0.6 mm contribute to infiltration

WATER RETENTION

Output from RETC model

Table C6: Output of water retention curve parameters from the RETC. The sum of squares (SSQ) was used together with visual interpretation to assess the curve match. Large sum of square indicate larger distance between the observed and fitted data.

Ring nr.	Sol type	SSQ	ThetaR	ThetaS	Alpha	n
200	**Cv**	8.60	0.00	30.68	0.02	1.97
648	**Cv**	19.71	0.00	29.31	0.02	2.09
SV162*	**Cv**	15.91	0.00	33.70	0.03	1.92
SV158	**Cs**	1.55	0.00	31.37	0.69	1.24
1897*	**Cs**	0.78	1.31	24.50	0.13	1.33
278	**Cs**	2.68	0.00	27.62	0.28	1.26
SV38*	**Nr**	4.14	0.00	27.42	0.01	1.27
SV144	**Nr**	2.44	0.00	26.01	0.01	1.31
640	**Nr**	7.57	0.00	27.36	0.01	1.28
1537	**Nm**	17.75	2.04	28.25	0.07	2.78
44	**Nm**	9.54	2.21	30.85	0.08	2.57
301	**Nm**	3.00	1.35	29.64	0.07	2.69
H578*	**CvNm**	9.80	0.00	25.77	0.04	1.86
VG23	**CvNm**	29.60	0.00	26.21	0.03	1.89
464*	**CvNm**	8.58	0.00	30.50	0.07	1.66
H251*	**CsNm**	2.56	3.08	23.36	0.07	1.90
H335	**CsNm**	19.10	3.20	28.22	0.11	1.71
SV90*	**CsNm**	2.99	3.05	26.69	0.08	1.84
H538	**CvNr**	10.89	0.00	29.20	0.03	1.34
303*	**CvNr**	9.98	2.35	26.69	0.01	1.61
1534*	**CvNr**	18.23	2.05	28.84	0.04	1.47
1395	**CvNmT**	7.22	0.00	30.21	0.04	1.47
VG375*	**CvNmT**	5.92	1.42	28.73	0.03	1.80
795*	**CvNmT**	46.47	0.00	32.70	0.01	1.51

Figure C7: Volumetric water content (vol /vol %) for each replicate (Ring nr.) except measurements at 15 which were obtained from other samples (32 mm rings) and was randomly assigned to one of the replicates of the same soil types.

Ring nr	Sol type	field moist	saturation	1.7 cm	10 cm	30 cm	50 cm	100 hPa	333 hPa	1000 hPa (1 bar)	3000 hPa (3 bar)	15 000 hPa (15 bar)*
200	**Cv**	27,05	31.00	29.34	29.36	27.29	22.71	12.27	6.16	4.80	1.56	0.72
648	**Cv**	29.21	28.05	28.21	28.70	27.18	21.61	10.75	3.22	2.60	0.96	0.90
SV162*	**Cv**	30.01	33.00	32.34	32.56	27.29	20.03	9.82	3.87	2.34	0.44	0.80
SV158	**Cs**	17.93	30.49	26.96	19.18	14.95	13.54	11.91	9.39	6.29	4.46	3.30
1897*	**Cs**	23.46	25.47	23.65	20.25	15.06	13.17	11.25	8.08	6.13	4.00	3.26
278	**Cs**	18.79	25.93	25.95	19.74	15.36	13.98	12.30	9.13	6.19	3.61	3.16
SV38*	**Nr**	29.35	30.09	27.55	26.77	25.77	25.02	24.14	17.67	14.43	11.14	5.72
SV144	**Nr**	28.53	27.36	26.12	25.30	25.05	24.53	24.04	22.80	22.11	20.25	6.45
640	**Nr**	30.44	34.32	27.50	25.61	24.77	24.47	23.70	19.29	14.91	10.62	5.86
1537	**Nm**	8.44	30.48	27.56	24.66	6.95	4.34	3.41	2.85	2.06	0.82	1.44
44	**Nm**	14.27	33.33	30.42	24.90	7.96	5.04	4.27	3.28	2.39	0.95	1.37
301	**Nm**	12.50	32.09	29.38	24.10	7.36	4.77	3.51	2.10	1.93	0.72	1.28
H578*	**CvNm**	22.57	27.31	25.16	24.51	19.49	12.63	7.40	4.40	2.62	0.77	1.10
VG23	**CvNm**	25.43	26.72	25.46	24.95	20.71	13.01	7.45	4.99	4.47	1.42	1.07
464*	**CvNm**	23.90	26.74	25.48	25.64	18.31	11.79	7.10	5.67	5.25	1.31	0.97
H251*	**CsNm**	24.09	24.27	23.11	20.82	12.43	9.15	7.24	5.26	4.25	2.98	2.59
H335	**CsNm**	23.48	29.00	26.84	22.21	12.23	9.16	7.53	5.89	5.94	3.30	2.77
SV90*	**CsNm**	23.68	27.97	26.09	22.88	13.21	9.96	7.99	5.39	4.63	2.93	2.41
H538	**CvNr**	25.79	29.09	27.95	27.45	26.44	24.95	18.50	12.87	11.34	9.13	2.78
303*	**CvNr**	26.88	26.44	26.08	26.23	25.08	24.59	17.63	10.37	8.88	5.23	3.02
1534*	**CvNr**	23.42	30.74	27.34	27.16	22.72	18.74	14.31	13.07	12.00	9.63	3.14
1395	**CvNmT**	25.20	28.64	28.67	28.37	24.07	19.30	14.02	10.42	7.91	6.11	1.53
VG375*	**CvNmT**	27.22	29.34	28.18	27.71	24.23	17.83	11.63	7.31	6.04	3.69	1.49
795*	**CvNmT**	30.32	35.92	32.88	32.14	28.55	25.90	23.50	20.49	18.41	15.22	1.55

Appendix D

Surface shape assessment

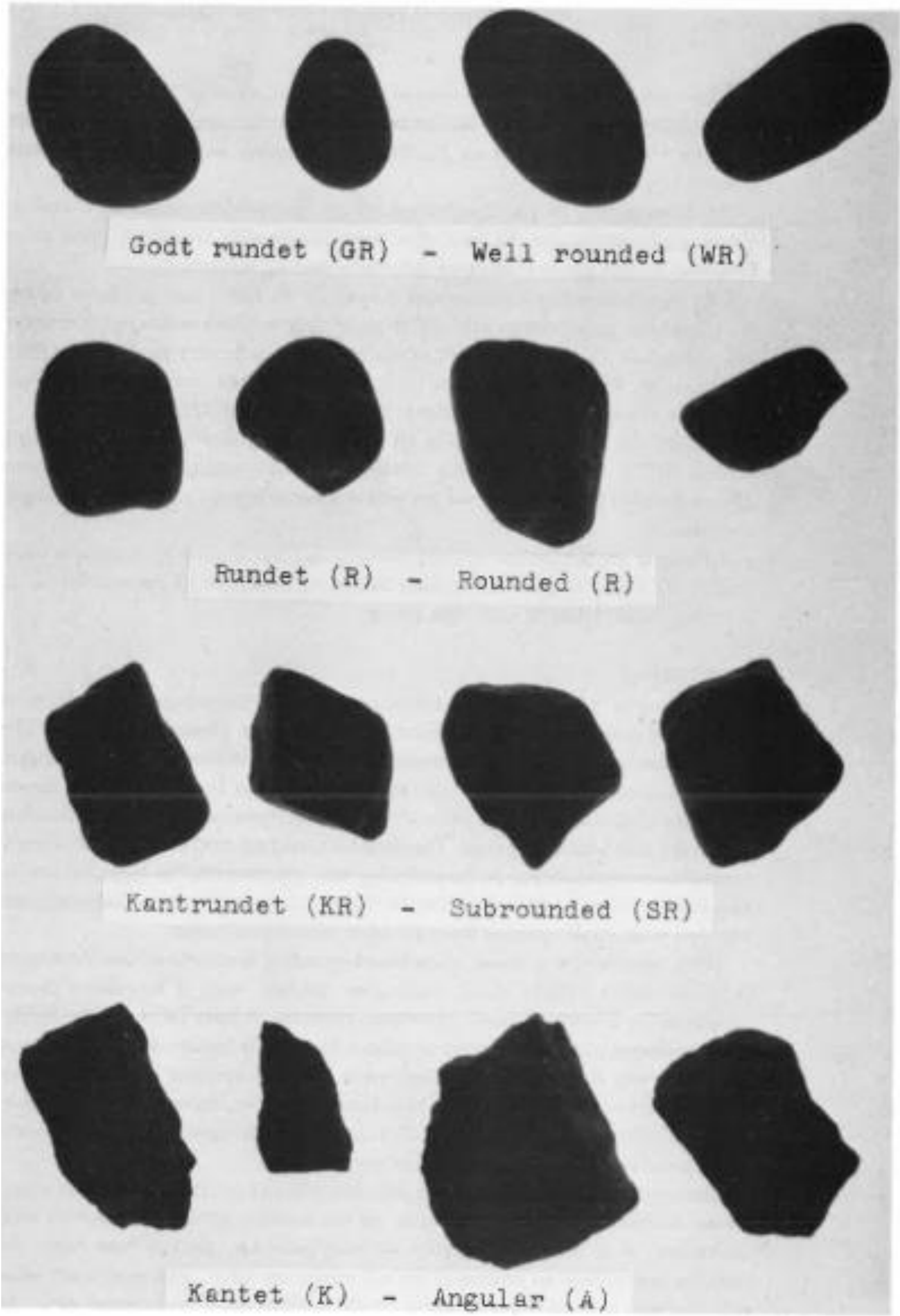


Figure D1: Guide for assessing the angularity of the particle shape. Image is taken from Olsen (1983) p.14.

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway