Testing the effect of a microbial-based soil amendment on soil aggregate stability and erodibility

Mponda J. Malozo
Agro Environmental Management
12th August, 2016

Faculty of Science and Technology
# Title Page

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AARHUS UNIVERSITY  
DEPARTMENT OF AGROECOLOGY  

12th August, 2016
Dedication

This work is dedicated to my daughter Aryaq, wife Dorah and young sister Mandua who bestowed trust, waited impatiently, gave me more than strength and a reason to go on.

I hope my daughter grows up inspired and learn to give her very best
Preface
This thesis is submitted to the Department of Agroecology, Faculty of Science and Technology, Aarhus University as a partial fulfilment of the requirement for a master's Degree award in MSc Agro-Environmental Management.

The study involved testing the effects of microbial soil amendment on improving soil aggregate stability and erodibility. The induced-effect of the microbial soil amendment was also compared with microbial agent carrier solution and commercial gypsum powder as soil amendments. Soil samples used were collected from Mwanza region in the northern Tanzania and in Denmark from Flakkebjerg and Risø in Zealand. These soils were known to have structural problems and therefore suited the aim of the study.

Microbial-based soil amendment and microbial agent carrier solutions were provided by Novozymes A/S Company. Commercial gypsum (calcium sulfate dihydrate) for the soil amendment was obtained from Yara A/S.

The study found out the treatment to have positive effect on increasing soil aggregate stability and reducing erodibility of the soil. The impact was more pronounced on the soil from Tanzania compared to the Danish soils. Both, microbial and microbial agent carrier solution induced significant impact on the formation and stabilization of soil macroaggregates. The gypsum treatment had more impact on the reduction of soil dispersible clay particles.
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At last, I would like to thank my late parents for their upbringing; my wife Dorah, daughter Aryaq and young sister Mandua, without whose loving understanding and selfless supports I could have never accomplished my studies.
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Abstract
Soil degradation problem in the world has been reported to have increased significantly in the past 50 years with nearly 2 billion ha of land are estimated to have been degraded of which 22% includes arable land. Soil erosion by water is the most common soil degradation problem in almost every country under varying climate, topography and land use practices. The impact of soil erosion often results into the reduction of land or soil productivity by wash away of nutrient on the top rich soil or by causing water quality problem through deposition of eroded sediment and nutrients into water bodies. Practices such as increasing of soil organic matter content, enhancing aggregate stability, macroporosity, infiltration capacity and reducing rainfall erosivity have been used to control soil degradation induced by water erosion. In this study a microbial-based soil amendment (MICRO) was tested to observe its impact on improving aggregates stability and reducing soil particle erodibility under the rainfall-runoff simulation. The treatment impact was compared to that of microbial agent carrier solution (CAR) and commercial gypsum (GYPS) with calcium sulfate dihydrate as soil amendment. The soil samples that were used was collected from Mwanza region in northern Tanzania and from Denmark at Flakkebjerg and Risø sites in Zealand. These soils had known history of structural problems. Water aggregate stability and clay dispersibility test were conducted at macro- and microaggregate level and also soil tensile strength test. The test results show that the microbial-based soil amendment had significant impact on increasing water aggregate stability, tensile strength and reducing soil erodible particles on the tested soils. The treatment was found to have small impact on reducing soil clay dispersibility compared to CAR and GYPS treatment. Compared to the CAR treatment, MICRO treatment also had less impact in increasing water stable aggregates on Flakkebjerg and Tanzania soil. The impact of MICRO treatment was generally more pronounced on sandier soil with low organic matter, silt and clay content at macroaggregate level.
Chapter 1: Introduction

1.1 Background
Maintaining good soil quality is essential for the preservation of soil's productivity, its filtration and storage functions as well as minimizing soil erosion. Soil structure, the heterogeneous arrangement of solids and pore space in the soil, is an important indicator of soil quality (Amézketa, 1999, Bronick and Lal, 2005). This is because, it affects key aspects of soil quality which includes water infiltration and storage, gas and heat exchange, nutrient cycling, biological activities such as root growth and soil erosion (Bronick and Lal, 2005). Hence, soil structural problems are often linked to soil degradation.

In general soil vulnerability to degradation is dependent on its pedological characteristics including age, influxes of material and soil management (Jie et al., 2002). It is estimated that between 1 and 6 billion hectare(s) of soil resources in the world have been degraded, of which about 35% is caused by agricultural activities and account for 1.24 billion hectare of the degraded land (Gibbs and Salmon, 2015, Bot et al., 2000). Activities such as overgrazing, deforestation (conversion of forest to farmlands) and overexploitation of soil vegetation associated with agriculture are dominant causes of the soil degradation to most of the agricultural lands (Bot et al., 2000). Interrill soil erosion process is identified to be among the major processes contributing to soil and water quality degradation on almost all arable lands on Earth (Wan et al., 1996, Kuhn et al., 2012). The processes involved in the interrill erosion are very complex and soil resistance varies depending on physical, chemical and mineralogical properties (Kuhn et al., 2012). The complexity of soil erosion processes also depends on soil properties, topography, climatic conditions and land use changes (Montgomery, 2007).

The impacts of erosion can be onsite through preferential erosion of nutrients on soil surface and offsite by deposition of sediments and nutrients in water bodies resulting into water quality problems and eutrophication (Holz et al., 2015, Kuhn et al., 2012, Schjønning et al., 2009). In many parts of the world soil erosion and loss of nutrients is the major cause of the soil quality loss resulting into an increase of soil and water management costs (Boardman, 2006). Soil structure and erosion problem can be improved and controlled
through best management practices which involves a broad spectrum of mechanical, physical and biological methods (Holz et al., 2015).

**1.2 Soil degradation problem**

In broader terms soil degradation includes lowering of soil potential capability to serve desired function for agricultural productivity, transportation, construction, recreation etc. (Jie et al., 2002). Therefore the term “degradation” has been used to refer to the reduction in land or soil productivity induced by human activities(Gibbs and Salmon, 2015, Bot et al., 2000). It is a challenge to set line between human induced and natural factors which cause soil degradation, because there are both natural and human induced constraints which impact the soil productivity (Bot et al., 2000, Gibbs and Salmon, 2015). The inherent soil constraints which impact the soil productivity includes poor drainage, low nutrient retention capacity, strong acidity, high ferric oxides level in clay fraction, cracking and erosion risks influenced by topography nature and soil type (Bot et al., 2000). In most countries agricultural related activities such as deforestation, overgrazing, improper land management, overexploitation of vegetation and industrial activities are the causative agents for human induced soil degradation (Bot et al., 2000). The human induced soil degradation processes are divided into two categories; degradation by displacement of soil materials and deterioration of internal physical and chemical soil properties through land management practices and chemical use (Oldeman et al., 1990).

The concerns for soil degradation differ between countries and depends on economic activities, topography, climate, population density and type of degradation processes induced (Bot et al., 2000, Oldeman et al., 1990). Out of 12 soil erosion types identified in Oldeman et al. (1990) report, the erosion by water is the most common soil degradation problem to almost every country under varying climate, topography and land use practices. The impact of the soil erosion by water is often through displacement of the soil materials, which may result into the reduction of land or soil productivity induced by wash away of nutrient on the top rich soil. The eroded materials upon deposition in water bodies may cause decline of water quality, eutrophication and disruption of aquatic ecosystem (Oldeman et al., 1990).
1.2.1 Soil degradation problem in Denmark
In Denmark a decline of soil agronomic productivity caused by the water erosion is considered low because of relatively low relief and rainfall erosivity (Schjønning et al., 2009). However, soil compaction, soil organic matter decline and erosion by water and tillage are important soil threats in the country because of their role in soil redistribution and transportation of nutrients, sediments and contaminants (Rasmussen and Olsen, 2009, He克rath et al., 2005, Schjønning et al., 2009). Sheet, rill and bank erosion became government priorities in order to protect aquatic environment from nutrients loss from arable land since 1986 when eutrophication problem appeared in Denmark (Schjønning et al., 2009, Veihe et al., 2003). Though soil erosion rates and rainfall erosivity are generally low high use of agrochemical and machinery as well as projected impact of climate change indicate risks of soil chemical contamination, compaction and water erosion induced more erosive rains projected in climate change scenarios for Denmark (Veиhe et al., 2003, Schjønning et al., 2009). Research needs and knowledge gaps are thus directed towards identification of risk areas, protection of aquatic environment from soil erosion, quantitative analysis of sustainable tillage and cropping systems to cope with the identified threats (Schjønning et al., 2009).

1.2.2 Soil degradation problem in Tanzania
In Tanzania soil degradation is recognized as threat to the country’s agricultural sector development, food security and social welfare (The United Republic of Tanzania, 2014, 2012a). This is because agriculture is a backbone of Tanzania economy and serves as the main form of employment to the majority of Tanzanians (The United Republic of Tanzania, 2006). Based on global soil degradation assessment by Bot et al. (2000) 27% of the land in Tanzania is degraded and 19% of it is caused by agricultural activities such as overgrazing and erosion by water. To a developing country like the United Republic of Tanzania, soil degradation has a devastating impact on national economy and exposes rural communities to livelihood insecurity due to reduction soil productivity (Malley et al., 2006, Wiig et al., 2001). The impact is more severe in overgrazed areas and on steep slopes where there is vegetation clearing, intensive cultivation and poor land management practices (The United Republic of Tanzania, 2012a). Other areas vulnerable to degradation are semi-arid regions.
of Tanzania where there is a wide spread of soil erosion problems caused by mainly wind and water (Aune et al., 1997, Christiansson, 1988, Hartemink, 1997, Kahiura et al., 1999, Kangalawe et al., 2008, Kimaro et al., 2008, Kiunsi and Meadows, 2006, Lal and Singh, 1998, Malley et al., 2006, Vaje et al., 2005, Vigiak et al., 2005, Vrieling et al., 2006). In the country land degradation and soil erosion problem have been combated through government program such as national strategy for growth and reduction of poverty and non-government organization through promotion of conservation agriculture, best management practices and counter farming on mountain areas (The United Republic of Tanzania, 2006, 2012a).

1.3 Soil degradation mitigation strategies and options

Mitigation options and strategies to combat soil degradation vary in space depending on the soil type, topography, land use etc. As a result, there are number of management practices which can be used to protect soils from degradation. Most of these practices aim to control degradation by increasing soil organic matter content, enhancing aggregate stability, macroporosity, infiltration capacity and reducing rainfall erosivity. Various soil conservation techniques and strategies are grouped into crop- and soil-management strategies such as cover crops and conservation tillage respectively can be used to protect soil against degradation agents such as water and wind. Experiments have also shown that an increase in soil aggregate stability increases infiltration rates, soil resistance to physical degradation and interrill erosion (Govers et al., 2004).

In order to address the problem of soil degradation, more specifically interrill erosion, the study aimed to test the effect of microbial based soil amendment on improving soil aggregate stability and reducing erodibility of soils with different origins collected in Tanzania and Denmark. Soil erosion by water account for about 75% of severely degraded soils in the world (Bot et al., 2000, Jie et al., 2002, Gibbs and Salmon, 2015, Oldeman et al., 1990) and aggregate stability improvement is among recommend practices to increase soil resistance to degradation (Govers et al., 2004). Soil amendment with biochar, organic materials and microbes have been used and shown to help improve the soil physical properties and reduce erodibility at varying levels with respect to physicochemical
properties of the soil (Lundkvist et al., 2007, Khademalrasoul et al., 2014, Abdollahi et al., 2014).

1.4 Objective of the study
The overall objective of the study was to test the effect of microbial-based soil amendment on aggregate stability and erodibility of three agricultural soils with contrasting management and degradation state. For comparison, microbial agent’s carrier solution and commercial gypsum were also used as soil amendments.

1.4.1 Specific objectives of the study
1. To test effect of microbial based soil amendment on reducing soil erodible particles.
2. To compare aggregate stability of microbial based amended soil to that of microbial agent carrier solution and gypsum amended soils.
3. To explain aggregate stability variation between soils, across treatments and influence of amendments.

1.4.2 Hypotheses
1. Addition of microbial based soil amendment increases soil aggregate stability and increases soil resistance to degradation by water.
2. Soil treated with microbial based soil amendment has more stable aggregates compared to soil treated with microbial agent carrier solution, gypsum and untreated.
3. Amendment induced-effect differs between soils and varies across treatments based on the soil inherent properties.
Chapter 2: Literature Review

2.1 Soil degradation Problem

Soil degradation is the problem referring to temporary or permanent reduction in the land productive capacity (Bot et al., 2000). Significant reduction of the land production capacity can be caused by processes such the decline of soil organic matter, acidification, soil compaction and hard setting, biological degradation and fertility loss (Jie et al., 2002). The soil degradation degree in the world increased significantly in the past 50 years, nearly 2 billion ha of land are estimated to be degraded in which 22% includes croplands, pasture, forest and woodlands (Bot et al., 2000, Gibbs and Salmon, 2015, Jie et al., 2002, Oldeman et al., 1990). Soil degradation can be grouped into: chemical deterioration such as loss of nutrients or organic matter; physical deterioration such as compaction, sealing and crusting; accretion such as accumulation of chemical components and erosion by water or wind (Jie et al., 2002, Oldeman et al., 1990). It is estimated that there are 58 countries with all the lands degraded in which 21 are in Europe (Bot et al., 2000). Impacts of land degradation are often undesirable as may lead to an increase in agrochemicals use in order to increase land productivity, increase in production cost and also increase in the commodity market price (Boardman et al., 2003).

Soil erosion by water accounts for 75% of strongly degraded soils in the world (Jie et al., 2002). And both wind and water erosion are the dominant types of soil degradation worldwide accounting for over 50% of the world’s land (Bot et al., 2000, Jie et al., 2002). In some African soils land productivity have declined by 50% as an impact of soil erosion (Jie et al., 2002). Mostly caused by agricultural activities such as farming practices, overgrazing, pollution from processing industries and deforestation for farmland expansion (Bot et al., 2000, Jie et al., 2002). The causes of soil degradation differ by region and countries, where overgrazing and deforestation is dominant in African and Asia while agricultural and bio-industrial activities are leading causes of degradation in Europe (Jie et al., 2002). On almost all arable lands interrill soil erosion is happening and can cause redistribution of the soil nutrient or deposition of nutrients and sediments into water bodies and cause eutrophication problems or water quality problems (Kuhn et al., 2012).
2.2 Role of soil structure on aggregate stability

Soil structure is an important entry point towards sustainable management of soil resource and combating the complex problem of land degradation. This is because nature of the soil structure can determine soil’s ability to retain its particle arrangement when stressed (Amézketa, 1999, Nciizah and Wakindiki, 2015). Soil aggregate stability is an important parameter with respect to soil structure. It has an impact on a wide range of physical and bio-geochemical processes in the soil, affecting movement and storage of water, aeration, erodibility and biological activities (Amézketa, 1999). Soil aggregates offers physical protection to the soil structure by influencing microbial community structure, controlling oxygen diffusion, determining nutrient adsorption and desorption, and infiltration (Six et al., 2004).

Maintaining high biotic activities in the soil is important for aggregate formation and stabilization, especially in soils with pH range of 5.5-7 which are less stabilized by either mineral oxides or CaCO₃ because of low positive charges in the soil (White, 2006). Hence, addition of soil organic matter can improve soil aggregate stability (Figure 1) through activation of soil microbial activities and production of soil binding substances by the microbes (White, 2006, Six et al., 2004, Tisdall and Oades, 1982, Abiven et al., 2009). However, soil aggregate stability induced by substrate addition decreases over time as the substrate is consumed by the soil microbes (Figure 2) (Tisdall and Oades, 1982, Abiven et al., 2009). Durability of the aggregates stabilized by soil microbes also depend on the nature of substrate added to the soil. A simple labile compound exhibits fast and strong effect on formation of stable soil aggregates while recalcitrant compounds have lower but longer time effect (Abiven et al., 2009). Therefore, appropriate management and soil supplement with suitable substrate can influence formation and stabilization of aggregates through activation of the soil microbial activities.
Soil microbes produce polysaccharides which are transient binding materials that help to form stable soil aggregates (Aspiras et al., 1971b, Aspiras et al., 1971c, Chang et al., 2015, Degens, 1997, Oades, 1993). Polysaccharides are rapidly produced and decomposed by the soil microbes, hence their effect last for shorter time. The effect of polysaccharides on improving soil aggregate stability can be longer if they are protected from decomposition by the soil microbes when they are associated with metal ions or adsorbed on clay surface (Tisdall and Oades, 1982). Size and range of soil biota involved in maintaining soil aggregate stability, including biopolymer producing microorganisms is enormous. Various experiments have shown that when microorganisms are supplied with suitable substrates the aggregates are stabilized through filamentous structures, extruded biopolymers and extracellular polysaccharides (Figure 2) (Six et al., 2004, Oades, 1993, Aspiras et al., 1971b, Aspiras et al., 1971c, Chang et al., 2015, Degens, 1997, Degens, 1998, Rashid et al., 2016, Degens et al., 1996).

**Figure 1:** Effect soil organic carbon on the soil particle aggregation and microbial binding agents produced in the soil. Source; White (2006) based on Tisdall and Oades (1982) publication.
A study by Abdollahi et al. (2014) found polysaccharides as an important agent in the soil aggregation processes. This could be caused by hydrophilic nature of microbial synthesized polysaccharides which tends to adsorb on mineral particles and increases inter-particle cohesion and leads to stable soil aggregates (Abiven et al., 2009). In most cases the ability of the soil microbes to provide mechanical aggregate stability of the soil depends on soil types, chemical and physical properties of the soil and also type of binding material synthesized by the microbes (Aspiras et al., 1971a). In order to maintain soil aggregate stability balance between synthesis and degradation of binding material needs to be attained through availability of soil carbon and energy source (Aspiras et al., 1971c). Hence, soils with structural weakness can be supplied with the carbon and energy sources to stimulate microbial activity (Degens, 1998, Oades, 1993, Abiven et al., 2009) needed to induce soil particle aggregation.

**Figure 2:** Effect of soil organic material addition in the soil on the formation and stabilization of the soil aggregates (Tisdall and Oades, 1982).
2.3 Soil aggregation processes

Soil aggregates are distinct soil structural units formed due to arrangement of sand, silt, clay and organic particles brought together by various forces (Brady and Weil, 2010). Biological and physicochemical processes are both involved in the formation of the soil aggregates. The aggregate is formed when there is greater cohesive forces between particles within aggregate than between aggregates (Oades, 1993). Electrostatic and van der Waals’ forces are cohesive forces involved in the process of soil particles aggregation (White, 2006). Based on Tisdall and Oades (1982) theoretical concept of soil organic matter (SOM) interaction, different binding agents acts at different hierarchical stages of soil aggregation. On the first stage free primary particles and silt sized soil particles less than 20 µm in diameter are bound together into microaggregate (20-250 µm in diameter) by soil oxides, aluminosilicates, organic matters and polyvalent metal cation complexes. Afterward, in the second stage the microaggregate formed are bound into macroaggregates >250µm in diameter by transient binding agents and microbial synthesized polysaccharides to form soil aggregate (Tisdall and Oades, 1982, Six et al., 2004).

The physicochemical processes of aggregate formation have dominant effect on fine textured soils such as clay, while biological processes are more pronounced in the aggregation of sandy soils because of little clay content (Oades, 1993, Brady and Weil, 2010). Reduction of electrostatic repulsive forces between negatively charged soil mineral particles by divalent cations facilitate binding of soil particles and induce soil particle stability through flocculation (Amézketa, 1999). Soil microbial decomposition of soil organic materials forms stable microaggregate by incorporating soil mineral particles with the soil organic matter, which bound into macroaggregate through synthesized microbial binding agents or polysaccharides (Figure 3) (Rashid et al., 2016).
Figure 3: An overview on the role of microbes in the binding of soil particles, formation of micro- and macro-aggregate (Rashid et al., 2016)

2.4 Soil structure destruction and aggregate breakdown mechanisms

Soil structure destruction and breakdown of aggregates may result from variety of physicochemical mechanisms caused by use of heavy machinery, poor land management practices, tillage and soil erosion. The use of heavy machinery on arable lands especially in developed countries is associated with soil compaction which may cause structural problems such as flooding, soil erosion and leaching (Schjønning et al., 2009). Soil aggregates compression cause formation of platy soil structure which affects soil porosity, fragmentation and soil bulk density (Obour, 2015). Soil compaction makes the soil vulnerable to degradation because it destroys soil pores and their distribution which affects infiltration, aeration and overall microbial activities in the soil (Wolkowski and Lowery, 2008, Whalley et al., 1995). The soil infiltration capacity reduction could cause an increase in surface runoff and trigger aggregate breakdown by the impact of water.

Water can induce breakdown of the aggregate in four ways which are (i) slaking (ii) differential swelling (iii) raindrop impact and (iv) physicochemical dispersion. These mechanisms differ based on the nature of inter-particle bonds, physicochemical conditions of the soil, disruption energy and kinetic processes involved, and soil properties (Table 1) (Le Bissonnais, 2016a, 1996).
**Table 1: Characteristics of the soil aggregates breakdown mechanisms induced by water (Le Bissonnais, 2016a)**

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Slaking</th>
<th>Breakdown by differential swelling</th>
<th>Breakdown by raindrop impact</th>
<th>Physicochemical dispersion</th>
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<tr>
<td>Type of forces involved</td>
<td>Internal pressure by air entrapment during wetting</td>
<td>Internal pressure by clay differential swelling</td>
<td>External pressure by raindrop impact</td>
<td>Internal attractive forces between colloidal particles</td>
</tr>
<tr>
<td>Soil properties controlling the mechanism</td>
<td>Porosity, wettability, internal cohesion</td>
<td>Swelling potential, wetting conditions, cohesion</td>
<td>Wet cohesion (clay, organic matter, oxides)</td>
<td>Ionic status, clay mineralogy</td>
</tr>
<tr>
<td>Resulting fragments</td>
<td>Microaggregates</td>
<td>Macro and microaggregates</td>
<td>Elementary particles</td>
<td>Elementary particles</td>
</tr>
<tr>
<td>Intensity of the disaggregation</td>
<td>Large</td>
<td>Limited</td>
<td>Cumulative</td>
<td>Total</td>
</tr>
</tbody>
</table>

Aggregate breakdown by slaking is triggered by compression of entrapped air inside aggregate during wetting. The breakdown fragments are mainly microaggregates and their sizes increases with clay content. Breakdown by differential swelling involves different physical processes resulting into aggregate microcracking during wetting and drying. Contrary to slaking, the differential swelling increases with increase in soil clay content and has mild breaking compared to that of slaking. Mechanical breakdown by raindrop depends on rain drop kinetic energy, if it’s enough to detach and displace soil fragments. The impact usually occurs in combination with other factors, and has a dominant role when the soil is wetter and aggregates are weaker. Physicochemical dispersion is caused by reduction of cohesive forces between colloidal particles while wetting. The physicochemical stability or dispersibility depends on cation size and valence. Polyvalent cations cause flocculation and monovalent cations cause dispersion (Le Bissonnais, 2016a, 1996).
2.4.1 Soil erodibility

Soil susceptibility to agents of erosion is commonly referred as erodibility. Wind and water are two main agents of soil erosion, though the latter is most common to almost all countries in the world (Govers et al., 2004, Bot et al., 2000, Oldeman et al., 1990). Soil aggregate breakdown is the first step which triggers soil erosion processes by producing microaggregates and primary soil particles which can be easily detached, transported and displaced by the agents of soil erosion (Govers et al., 2004, Holz et al., 2015). Displacement, disintegration and rearrangement of particles by the agents of soil erosion may cause formation of soil surface crust, reduce soil infiltration rates, increases surface runoffs and disruption of soil structure (LeBissonnais and Arrouays, 1997, Yan et al., 2008). Soil can be protected against disruptive forces by enhancing aggregate stability. The soil aggregate resistance to the beating action of rain drop, surface runoff and wind is a function of complex interaction between physical, chemical and biological soil properties (Yan et al., 2008, White, 2006). Soil with high organic matter interaction with clay particles has stable aggregates and is more resistant to breakdown because of strong chemical bonding and forces of attraction within particles (R.P.C.Morgan, 1986, LeBissonnais and Arrouays, 1997, White, 2006). Old systems and practices such as full dunging practiced in the foregoing centuries had helped to increase soil aggregate stability and infiltration through enhancement of soil microbial activities. The practice contributed to the reduction of top soil wash by erosion and enabled conservation of soil resource (Ploey, 1986). The old systems once suitable for soil conservation are nowadays disrupted by modern mechanized agriculture (ibis) hence a need for practices sustainable practices with induce formation, stabilization and enhancement of soil aggregates.

Soil degradation induced by erosion is an undesirable process on arable land and aquatic ecosystems because it may result in negative impacts on-and off- the site. The effects on site includes removal or displacement of valuable fertile top soil leaving behind unfertile and less productive soil. The offsite impacts are mostly associated with deposition of sediments and nutrients into aquatic ecosystems causing pollution or eutrophication problems. Sediments carried by water may also carry toxic metals and organic compounds

2.5 Soil amendment for structure improvement

Soil amendment is an inorganic or organic substances which can be mixed into the soil to improve physical properties such as water retention, infiltration, drainage, aeration and structure (Davis and Whiting, 2013). Inorganic soil amendments are either mined or man-made and includes substances like vermiculite, perlite etc. Organic amendments on the other hand are mostly derived from living things such as plants and plant products (Stauffer et al., 2016). Agronomic practices such as application of compost, humus, lime, gypsum, manure, conservation tillage and good soil nutrient balance improves soil structure by increasing water holding capacity, pore space, aeration and creates favorable environment for soil microbial functioning (Traunfeld and Nibali, 2013, Sullivan, 1999).

Use of soil amendment is an ancient art on which the choice of amendment depends on the soil improvement needs (West Coast Seeds, 2011). The type, mix and amount of soil amendment to be incorporated vary depending on soil degradation level and desired structural improvement (West Coast Seeds, 2011). In most cases organic amendments provide essential nutrients necessary for rebuilding soil organic matter content and establishment of microbial population (U.S. EPA, 2006). Also, inorganic amendments such as gypsum, lime and fertilizer have been commonly applied for improving aggregation, regulating soil pH and increase an overall productivity of the land (Anikwe et al., 2016, Sumner, 1993, Traunfeld and Nibali, 2013, U.S. EPA, 2006, West Coast Seeds, 2011, Keiblinger et al., 2016).

Gypsum has been widely used because of its high divalent cations exchange level and rather soluble calcium which tend to coagulate soil colloid and flocculate clay particles (Figure 4), which helps improve soil particles aggregation and develop structure of the soil (Anikwe et al., 2016, Sumner, 1993, Chen and Dick, 2011, Loveday, 1976, Miller et al., 1988, Roth and Pavan, 1991, Shanmuganathan and Oades, 1983). Soil particles flocculation is a necessary process for the formation and stabilization of the soil structure (Chen and Dick, 2011). The effect of gypsum aggregation is mostly experienced at microaggregate level.
where soluble calcium has an influence at organo-mineral complexation (Six et al., 2004). Because of this the use of gypsum in soil promotes particle aggregation and reduce (Chen and Dick, 2011) which contribute on the improvement of the soil structure.

![Figure 4: Illustration on the effect of soluble Ca flocculation and Mg on dispersion of soil particles (Chen and Dick, 2011)](image)

2.6 Methods for characterization of soil aggregation and structural stability

There are different methods used for soil aggregate characterization and structural stability measurements (Munkholm, 2011, Le Bissonnais, 2016a, 1996). Most of these measurements are based on distinction of elementary breakdown mechanisms for the aggregate in relation to the soil physicochemical properties at micro-and macro-scopic level, where different energy rates are used by different methods (Le Bissonnais, 2016a, 1996). Aggregates are divided into three aggregation levels in the soil; clay level <2 μm, microaggregates level < 250 μm and macroaggregates level > 250 μm, all have different stabilization mechanisms and thus different responses to physical stress and therefore different methods for aggregate characterization (Amézketa, 1999). Soil aggregate stability is a pertinent indicator of soil susceptibility to erosion by surface runoff, hence aggregate stability tests are widely used to indicate soil erodibility at laboratory level (Bartoli et al., 2016, Yan et al., 2008, Shi et al., 2010, Nciizah and Wakindiki, 2015).
Methods used to characterize macroaggregates stability are commonly referred to as aggregate stability tests and those used for microaggregates stability are commonly termed as dispersion tests. At macroscopic scale soil aggregation is tested by subjecting a representative soil sample to disruptive forces, usually wet-sieving. The aggregates retrieved from the wet-sieve represent water stable aggregates which do not break into smaller portions after being subjected to disruptive force (Angers et al., 2008). At microscopic level where silt and clay size particles are found, testing involves subjecting of soil representative sample on turbidimetry or densitometry disruptive forces and dispersed particle recovered determines soil particle dispersion (Angers et al., 2008). There exist several other methods for determining soil aggregate stability but most of them are variation of these methods (LeBissonnais, 1996, 2016a, Angers et al., 2008, Amézketa, 1999).

The choice between wet sieving and dispersion method depend on the prevailing soil properties. The dispersion test is mainly used on dispersive soils while wet sieving is on soils with low dispersible particles (Nciizah and Wakindiki, 2015). In studies by Nciizah and Wakindiki (2015), Bartoli et al. (2016) and Legout et al. (2005) a comparison between soil aggregate stability and rainfall-simulation experiment results were found to be correlated. This shows that the aggregate stability measurement corresponds to aggregate breakdown mechanism under the impact of rain drops (Figure 5) (Nciizah and Wakindiki, 2015, Bartoli et al., 2016, Legout et al., 2005). This is important because aggregate stability indices are used for parameterizing the traditional soil erodibility factor (K) used in the modelling of soil erosion (Shi et al., 2010, Valmis et al., 2005, Yan et al., 2008, Bartoli et al., 2016, Le Bissonnais, 2016b).
2.6.1 Soil structural stability characterization

Soil structural stability is characterized by determining soil resistance to externally applied mechanical stresses. Soil response to mechanical stress is influenced by the soil structural properties and failure happens when the applied stress exceeds soil strength (Dexter, 1988). Soil tensile strength and friability are useful indicators of the soil structural condition, because the soil tensile failure is the result of soil aggregate breakdown without disturbance to soil microstructure which is a desired feature for plant growth and tillage (Munkholm and Kay, 2002, Imhoff et al., 2002). Whereas the soil friability is an important soil physical property used to understand important information related to soil workability such as energy requirement for tillage, ability to support plant growth and impacts of soil amendment to the soil microstructure (Munkholm, 2011, Dexter, 1988). Both, the soil tensile strength and friability are influenced by several soil factors including content of dispersed clay, water, organic matter, mineralogical composition, exchangeable cations etc. as explained in details by Causarano (1993), Imhoff et al. (2002) and Munkholm (2011).

Crushing test is a commonly used method for tensile strength measurements because of its application over a wide range of particle sizes compared to drop-shatter test which doesn't work on small or strong aggregates (Dexter, 1988). The test apply force on a stable soil
aggregate enough to cause soil tension failure (Imhoff et al., 2002, Dexter and Krosbergen, 1985). The soil tensile strength is then determined by measuring the force needed to crack an individual aggregate between flat parallel plates (Munkholm, 2011, Munkholm and Kay, 2002).

Soil friability assessment can be done at the field or laboratory level using either qualitative or quantitative methods and at different scales to measure different soil friability aspects. Methods include visual assessment, drop shatter tests and tensile strength assessments. The latter is a common and widely used assessment method for the soil friability because it gives essential quantitative information and it is sensitive to soil management practices such as tillage, compaction and organic matter, compared to visual and drop shatter assessment methods. However, it is difficult to determine soil tensile strength with water content level similar to field conditions, hence most of soil friability assessment derived from the tensile strength measurements are based on air or oven dried soils (Munkholm, 2011).

Strength of unconfined soil generally increases with increase in clay content and depends on clay minerology e.g. smectite clay dominated soils are stronger than kaolinite dominated soils. The strength also depends on composition of exchangeable cation in the order of Na>Na−Mg>Na−Ca>Mg>Ca−Mg>Ca where cations with greater flocculation capacity have lower tensile strength. Soils with high amount of readily dispersible clay have shown to have higher tensile strength on dry aggregates and lower friability values. Soil organic matter plays key role in soil structural formation, positively related to friability but negatively to tensile strength of the soil. This is because soil organic matter as a bonding material may form complex structural units with primary soil minerals and secondary structural units, and reduce soil bulk density (Munkholm, 2011).
Chapter 3: Materials and Methods

3.1 Soil samples and sampling sites
Soil samples were collected on a cultivated land from the Mwanza region in northern Tanzania (Figure 6) and in Denmark (Figure 7) from two different experimental sites managed, respectively, by the Technical University of Denmark (DTU) at Risø and the Department of Agroecology, Aarhus University (AU), at Flakkebjerg. Both the Danish sites have been under arable management with mouldboard ploughing for decades and were known to have soil structural problems. At the Flakkebjerg and Risø sampling sites straw has always been removed since 2002 and 1990, respectively (Getahun et al., 2016, Sun et al., 2014). Flakkebjerg had received pig slurry for some years – although with very low dry matter content, while Risø had not received any animal manure. The samples from Tanzania were collected in July of 2015 during the dry season and in Denmark in September the same year. The sampled areas were within the actual agricultural fields in Denmark, while in Tanzania the samples were taken immediately adjacent to the fields to avoid disturbance. The Tanzania is cultivated annually in September by hand hoe and planted with maize and legumes. The soil at the site was loose and easily eroded because it is adjacent to cattle pathway and seasonal river.

The Mwanza region is located at coordinates 2°45′S 32°45′, elevated at 1,140 meters above sea level, with mean temperature ranges between 25 and 30 °C in hot season from September to December and 15 and 18 °C in the cooler months from June to August. The average annual rainfall received is 930mm in the range of 700 mm and 1000mm in the two distinct rain seasons in the months of February to May and October to December. The topographic feature is characterized by gently undulating granites and granodiorite rocks with isolated hill masses and inselberg rocks. The soil characteristics are well drained sandy loam generated from cretaceous period. Vegetation cover is typical savannah with scattered tall trees and grasses. Out of 2 million ha of dry land area in the Mwanza region 700,000 ha are planted with annual crops (The United Republic of Tanzania, 2012b, Mwanza City Council, 2016).
Figure 6: Mwanza sampling site location in Tanzania

Figure 7: Risø and Flakkebjerg sampling site locations in Denmark
The sampling process at all the sites involved collection of top 15 cm of soil, comparable to the soil depth vulnerable to physical stresses and exposed to agents of erosion. A total of 40 kg soil samples were collected from Tanzania, packed in 2 kg air tight bags and boxes before being transported to the Department of Agroecology, AU Foulum. Likewise, a total of 50 kg of soils from Risø and Flakkebjerg were packed in sealed boxes and sent to AU Foulum. Packing and transportation were carefully handled to avoid aggregate disintegration.

3.2 Soil characteristics

The basic soil characteristics are summarized in Table 2. The soil from Tanzania was coarse, slightly acidic with low organic matter content (Table 2). Both soils from Denmark, derived from glacial till of the Weichsel glaciation were sandy loams with moderate organic matter contents forming hard soil peds upon drying. The soil at Flakkebjerg and Risø have been described in more detail by Munkholm et al. (2008) and Hauggaard-Nielsen and Jensen (2001), respectively. The Danish soils had similar and higher Water holding capacity (WHC), organic matter content (OM), silt and clay content compared to the Tanzania soil. However, the Tanzania soil had highest content of sand, electrical conductivity (EC) and lowest amount of silt, clay, OM, cation exchange capacity (CEC) and WHC. The Risø soil had distinctive feature of having detectable level of CaCO₃ absent in both Tanzania and Flakkebjerg soil.

**Table 2: Physicochemical characteristics of the soil prior to treatment application**

<table>
<thead>
<tr>
<th>Soil</th>
<th>WHC</th>
<th>pH</th>
<th>MC</th>
<th>EC</th>
<th>CEC</th>
<th>OM</th>
<th>CaCO₃</th>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>µS</td>
<td>meq</td>
<td>%</td>
<td>g 100 g⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flakkebjerg</td>
<td>44</td>
<td>6.5</td>
<td>1.6</td>
<td>94</td>
<td>9.849</td>
<td>2.4</td>
<td>undetected</td>
<td>10.5</td>
<td>27.2</td>
<td>59.9</td>
</tr>
<tr>
<td>Risø</td>
<td>45</td>
<td>7.8</td>
<td>1.4</td>
<td>176</td>
<td>14.239</td>
<td>2.3</td>
<td>2.49</td>
<td>13.6</td>
<td>27.4</td>
<td>54.2</td>
</tr>
<tr>
<td>Tanzania</td>
<td>26</td>
<td>6.4</td>
<td>0.9</td>
<td>285</td>
<td>4.382</td>
<td>0.7</td>
<td>undetected</td>
<td>5.5</td>
<td>13.7</td>
<td>80.1</td>
</tr>
</tbody>
</table>

*WHC, water holding capacity; EC, electrical conductivity; OM, organic matter; clay (< 2 µm), silt (2 - 63 µm), sand (63 – 2000 µm); CEC, cation exchange capacity; MC, moisture content.
3.3 Soil pre-treatment in the lab
Soils were taken through a series of pretreatment processes after arriving in the lab, to establish similar initial conditions for accurate comparison between them, before treated with amendments. The soils were air dried at 30 °C for 24 hours followed by carefully 8 mm sieve. The sieving involved careful breaking of large peds by hand into smaller pieces along natural structural faults to avoid loss of inherent soil structure. From each soil a representative 1 kg was further <2 mm sieved for physical and chemical analysis.

3.3.1 Soil water holding capacity analysis
Afterward, water holding capacity (WHC) and volumetric water content (WC) of the soils were determined in triplicate from a representative samples following the approach which was adapted from Asankom (2015). In measuring WHC, 50g of air dried soil representative sample was weighed into an aluminum tray in five replicates. A 75 mm funnel was placed atop 100 ml bottle and covered with a folded Whatmann 44 filter paper as shown in Figure 8. The folded filter paper was made to align with the funnel edges. The weighed soil was transferred into the filter paper in a funnel and deionized water was gently added until the soil was saturated. About 2 cm excess water was left to stagnate at the surface after saturation. A paraffin tape was used to cover the funnel to prevent water loss through evaporation. The system was left undisturbed for 24 hours to allow water to drain naturally. Thereafter, weight of the drained soil was measured prior to oven drying at 105 °C for 24 hours. The oven dried soil was again re-weighed and the difference between the drained and oven dried soil weight was used to calculate soil WHC.

The remaining soil fractions were carefully rewetted with 159, 164 and 92 volumetric g of water per kg dry soil to 40 % WHC for Flakkebjerg, Risø and Tanzania respectively with a spray flask. Water was added intermittently to soil spread out over a large plastic sheet whilst gently turning and mixing the soil from time to time. Afterwards, the re-wetted samples were pre-incubated aerobically in large, closed containers at 20 °C for 8 days. During pre-incubation soils were periodically turned to ensure aeration and homogeneous conditions.
Figure 8: Water holding capacity experiment setting

3.3.2 Soil water content measurement
For the measurement of the soil water content 10g moist representative soil sample was weighed into aluminum trays and oven dried at 105 °C for 24 hours. The soil was re-weighed after removal from the oven and the new weight recorded. The moisture content was calculated as the weight difference between the moist soil and oven dried soil per oven dried soil weight. The measurement was done in triplicate and the average value recorded.

3.3.3 Soil amendment treatment application
Four soil amendment treatments were applied on soil samples comprising of Novozymes A/S microbial-based soil improver (MICRO); microbial agent carrier solution (CAR); gypsum powder (GYPS) and untreated control soil (CON). Both MICRO and CAR amendments were colorless liquid solution said to contain microbes and glycerol, whereas for the latter treatment only glycerol was present (Schnorr, 2016). Commercial gypsum (calcium sulfate dihydrate) for the soil amendment was obtained from Yara A/S in a fine-grained form (<2 mm) as a by-product from the manufacturing of phosphoric acid.
The pre-incubated soil was again passed through an 8 mm sieve carefully before treatments were applied. This step had become necessary as the Flakkebjerg and Risø soil had formed larger aggregates again during the re-wetting process. For each the MICRO and the CON treatment 13 kg soil (oven-dry basis) was incubated while for the remaining treatments (CAR, GYPS) 3 kg soil of soil (oven-dry basis) was used.

The application of the MICRO treatment was done in two steps. First the product was added with a spray flask at a rate of 15 l m\(^{-3}\) dry soil followed by an application of 7.5 l m\(^{-3}\) dry soil a week later, assuming a bulk density of 1.2 g cm\(^{-3}\). The product was diluted with tap water so that soil moisture content was raised to 55% and 60% WHC in the amended soils after the first and second application, respectively. For application the soil was spread out on a plastic sheet and carefully turned intermittently to ensure homogeneous addition to the whole soil volume. After the first and second application samples were incubated aerobically at 20 °C for seven days. The same procedure and application rates were used for the CAR treatment.

Gypsum was added at a rate of 1.5 g kg\(^{-1}\) soil on a dry soil basis corresponding to a typical agronomic gypsum application of 5 tons ha\(^{-1}\) (Fyksen, 2011). The gypsum was applied with a 250 µm sieve to soil spread out on a plastic sheet. Immediately after gypsum application tap water was added to the soils with a spray flask raising soil moisture to 55% WHC. After one week’s incubation more water was added to bring soil moisture content to 60% WHC. For all the CON treatment only tap water was added to soils raising soil water content to 55% and 60% WHC before the first and second incubation following a similar procedure as before. After the end of the second incubation period the soils were stored at 2 °C until further use. For the erodibility test 12 kg (oven dry basis) of the MICRO and CON treatments were air dried at 30 °C for 24 hours, carefully sieved <8 mm, packed in boxes and sent to Planetary Surface Processes Laboratory at University of Basel, Switzerland. The remaining soils were used for aggregate stability, pH, EC and CEC analysis.

### 3.5 Soil and aggregate analysis

Soil and aggregate stability analysis was conducted for the treated and untreated soil samples. The analysis for soil pH, electrical conductivity (EC), water aggregate stability
(WAS), clay dispersion (CD), tensile strength was done at the Department of Agroecology, AU, Foulum while cation exchange capacity (CEC) and rainfall-runoff simulation analysis was conducted at the Planetary Surface Processes Laboratory at Basel University in Switzerland. The rainfall-runoff simulations were conducted to test how treatment-induced effects on aggregate stability and clay dispersion, together influenced soil's erosion-runoff response to rainfall. The tests for this soil erodibility experiment were only done for treatments with the microbial-based product and a control.

Macro and microaggregates stability were determined in batch experiments by means of water stable aggregates (WSA) and clay dispersion (CD) tests. These tests were preferred because they are widely used to determine physical indices for soil erodibility, but they are also rapid and less expensive compared to other in situ and modelling studies (Neiziah and Wakindiki, 2015, Bryan, 1968, Bartoli et al., 2016, Le Bissonnais, 2016b, LeBissonnais and Arrouays, 1997). The two tests were meant to characterize different aspects of aggregate stability separately. This is because, the formation and stabilization of macro- and microaggregates dependent on different soil conditions and characteristics (Six et al., 2004, Brady and Weil, 2010, White, 2006).

3.5.1 Data management and statistical analysis
The Microsoft excel software was used for data management, arrangement and calculations, while statistical analysis was done using SIGMA plot statistical analysis tool and SPSS 20 software. Tensile strength data were log transformed to yield normality prior One-way MANOVA statistical analysis using the SPSS software. Water stable aggregates and clay dispersion statistical analysis was done with two-way ANOVA using the SIGMA plot software. Statistical analysis was not conducted for the pH, CEC, EC and rainfall-simulation because number of repetitions were insignificant for the analysis.

3.5.2 Soil pH and electrical conductivity analysis
Soil pH and electrical conductivity (EC) were determined subsequently after suspending soil with demineralized water using pH and EC meter following the approach by Hendershot et al. (2008b). Prior to testing, soil was air dried at room temperature and sieved to <2 mm. Ten grams of representative soil was weighed and added into 50 ml
plastic bottle followed by 25 ml of demineralized water. The content was mixed with glass rod and left to settle for one hour at an upright position and remixed before measurements were taken.

The pH and EC meters were calibrated prior to measurement by dipping electrodes into buffer solutions of known pH (7 and 4) and EC at room temperature respectively. The measurements were taken by dipping a tip of the pH glass electrode into a soil solution in the plastic bottle and left to stay until the screen meter was stable. Afterward, the glass rod was removed, rinsed with demineralized water and wiped gently with a paper tissue before reintroduced into the next sample.

After pH, EC measurement was measured by dipping the EC sensor in the soil solution and left to stay in plastic bottle until the meter screen was stable. Between measurements the sensor was rinsed with demineralized water and gently wiped with a paper tissue.

All the measurements were done in triplicates and their average values recorded. High EC values were converted from mS/cm to µS/cm before the averages were calculated.

3.5.3 Cation Exchange Capacity analysis

Cation exchange capacity (CEC) was determined based on the method which was adopted from Janzen (1993) and Hendershot et al. (2008a) on measurement of effective CEC of the soil using BaCl₂ which is dependent on the soil pH. The measurement was done only for MICRO and CON treated soil. Three grams of soil was shaken in 30 ml of 0.1m BaCl₂ for 2 hours, thereafter filtered through a (munktell 132) filter paper. The CEC extract was then measured using ICP-OES machine in mgl⁻¹. The effective CEC was obtained by summing CEC values for Al, Ca, Fe, K, Mg, Mn and Na of the soil in meq 100 g⁻¹ of soil. The 3 g of soil in 30 ml extract corresponded to 100g of soil in 1000 ml of extract. Hence, the effective CEC was reported in meq 100⁻¹ g of dry soil based on equation 1 used to obtain CEC for each cation before effective summation.

\[
CEC \left( \frac{\text{meq}}{100\text{g}} \right) = \frac{\text{concentration} \left( \frac{\text{mg}}{\text{L}} \right)}{\text{cation equivalent weight} \left( \frac{\text{mg}}{\text{mmol}} \right)} \]  \hspace{1cm} (Eq. 1)
3.5.4 Water aggregate stability analysis

A Yoder-type wet sieving apparatus (Figure 9) was used for the determination of WSA (Water Stable Aggregate) based on the method adopted from Vendelboe et al. (2012). Prior to testing, the soil sample was retrieved from 2 °C storage room where they had been incubated for about 45 days. The soil was brought to room temperature and sieved in 8 mm sieve. Afterward, thirty grams of field-moist soil (on an oven-dry basis) were transferred into 250-μm sieve and placed in a container filled with artificial rain water. The soil was allowed to water-saturate through brief capillary contact with the artificial rain water, before it was exposed to a 2-min vertical sieving process. Material remaining on the sieve was recovered, dried and weighed. Afterwards this material was shaken in 0.002 M Na₂P₄O₇ for 24 hours and sieved again <250 μm to determine the weight of mineral particles >250 μm. The soil remaining on the sieve after the wet sieving minus the mineral particles >250 μm was regarded the amount of water stable aggregates which is reported as proportion of the original soil. All measurements were done in triplicate.

*Figure 9: Yode-type wet sieving apparatus*
3.5.5 Clay Dispersion analysis

As with the WSA test, soil samples were retrieved from incubation, brought to room temperature and sieved <8 mm. Ten grams of moist soil (oven-dry basis) were weighed into shaking bottles to which artificial rain water was added at a ratio of 1:8 by weight (Pojasok and Kay, 1990, Vendelboe, 2008). The artificial rain water was added carefully along the side of the shaking bottle to minimize energy on the soil aggregates (Figure 10). Afterward, the bottles were closed with the lid and shaken on an end-over-end shaking device (Figure 11) for 1, 2, 4 and 8 minutes respectively at 33 rpm. Thereafter the samples were left to settle for 3 hours and 50 minutes in an upright position. The top 60 ml of the suspension was then carefully transferred into 100 ml glass bottles with a pipette and a subsample dried at 110 °C to determine the weight of dispersed clay (DC). The remaining suspension in the shaking bottles was sieved <2 mm sieve and the weight of sediment >2 mm determined upon drying. The weight of particles above 2 mm was subtracted from the initial dry weight of the soil to obtain initial soil weight. The experiment was run in triplicate and weight of dispersed clay was determined twice. Dispersed clay is reported as a fraction of the original soil weight corrected for particles >2 mm. All measurements were done in triplicate.

Figure 10: Addition of artificial rain water into plastic shaking bottle to avoid introducing energy to aggregates. Photo courtesy Vendelboe (2008)
**Figure 11**: An end-over-end shaking device

### 3.5.6 Tensile strength and friability analysis

Tensile strength analysis was determined using soil compression device (Figure 12) based on a method which was adopted from Dexter and Kroesbergen (1985). Soil friability was calculated from the tensile strength measurements. Before the analysis, soil was air dried at room temperature and sieved into 16-32, 8-16, 4-8 and 2-4 mm soil aggregate sizes. However, because of insufficient number of aggregates required for comparison, only 4-8 mm aggregate size was used. Also analysis for both air dried and moist soil was done for the Tanzania soil only, because Flakkebjerg and Risø soil had to be air dried before separated into different size fractions.

The soil compressing device was calibrated, program for 4-8 mm aggregate size was set and 5 kN load cell with a piston of 59 mm was fixed and used as directed in the laboratory operation manual for the device. The aggregate was randomly selected from the pre-determine size group, diameter and height measurement were taken using Vernier caliper, weight measurement recorded and compressed on the soil compressor until they fracture and the peak load/force applied recorded. Forty soil aggregates for each soil sample were compressed and their respective values recorded.
Calculations for tensile strength were determined using the equation 2, effective aggregate diameter was calculated using equation 3 and soil friability calculated using equation 4 as they have been used in other studies (Dexter and Kroesbergen, 1985, Munkholm, 2011, Imhoff et al., 2002, Munkholm and Kay, 2002, Utomo and Dexter, 1981). In the equation F is the force in Newton; d is effective diameter; d1 is average diameter of aggregate size fraction; m0 is dry mass of an individual aggregate; m1 is mean dry mass of aggregate size batch; F1 is friability; σy is standard deviation and Ŷ is mean soil tensile strength of aggregate size fraction.

\[ Y = 0.576 \times \frac{F}{d^2} \] 

\[ d = d_1 \left( \frac{m_0}{m_1} \right)^{\frac{1}{3}} \]

\[ F_1 = \frac{\sigma_Y}{\bar{Y}} \]

Figure 12: Soil compression device for tensile strength measurement
3.5.7 Rainfall runoff simulation soil erodibility test
Rainfall-runoff simulation test for soil erodibility test was done following approach which was adapted from Hu et al. (2014). Two square flumes, each with a surface area of 0.04 m² were filled with about 10 kg sand followed by permeable cloth and then topped with 1.6 kg air-dried soil of the CON and MICRO treatments. Carefully packed to attain soil surface inclination of 10% which mostly used for the in the lab experiment. The two flumes, one of each filled with MICRO and CON treated soil were positioned next to each other and 2m beneath rain nozzles (Figure 13). The nozzle was a FullJet rain nozzle (¼ HH14WSQ) capable of generating multiple-sized raindrop (Hu et al., 2014). The flumes were ensured at horizontal position and placed at exact 10 cm from the rain nozzle and 20 cm from each other. Beside each flume two rainfall collectors were positioned for measuring rainfall intensity.

The dry soils in the flumes were pre-wetted during a short (30 minutes) rainfall simulation 18 hours before the actual rainfall runoff experiments. Runoff was collected continuously for 30 minute intervals during the 4-hour simulation at 30 mm h⁻¹ rainfall intensity and average energy of 113.9 J h⁻¹ m⁻². A study by Hu et al. (2014) found that the rainfall intensity used is suitable for prolonged observation of crust formation potential based on variable soil erosion responses. Simulations were done in four replicates alternating each time the position of the CON and MICRO treatment under the rainfall simulator. The amount of runoff for each 30-minute interval was determined by weight. After allowing sediment to settle in runoff samples, the supernatant was decanted and the remaining sediment was dried and weighed.
Figure 13: Rainfall-runoff simulation experiment setting for soil erodibility testing
Chapter 4: Results

4.1 Soil pH and electrical conductivity response

The response for electrical conductivity showed similar pattern on MICRO and CAR treatments across soils but lower compared to CON treatment on respective soil (Figure 14). Across soils GYPS treatment increased EC by more than twice compared to the CON treatment of the respective soil. Both CAR and MICRO treated soil showed increase in soil pH especially on Tanzania and Flakkebjerg soil. The MICRO treated soil had higher increase in the pH compared to CAR in the two soils (Figure 14). The pH increase on Risø soil was smaller and less distinctive when compared to CON and also the difference observed on Tanzania and Flakkebjerg soils (Figure 14).

The decrease on EC induced by CAR treatment on Flakkebjerg, Risø and Tanzania soil respectively was 54, 30 and 62 %, while the decrease induced by MICRO treatment on the same soils respectively was 56, 29 and 62% all compared to respective CON treatment. The EC increase induced by GYPS treatment was 244, 209 and 138% for Flakkebjerg, Risø and Tanzania respectively, all compared with respective CON treatments.

The soil pH increase induced by CAR treatment was 10, 1 and 16% respectively for Flakkebjerg, Risø and Tanzania soil and that of MICRO treatment was 13, 2%, and 19% respectively as compared to the respective CON treatment. In contrast to GYPS induced-effect on EC, the treatment induced a slight decrease in soil pH by 3, 2 and 2% for Flakkebjerg, Risø and Tanzania respectively also compared to the respective CON treatment in the soil.
Figure 14: Effect of soil amendment on EC and pH. Each bar and point is an average of three replicates. Error bars show standard error.

4.2 Cation exchange capacity soil response

Soil MICRO treatment amendment increased CEC in the soil slightly compared to the CON treatment (Figure 15). Across soils Risø had highest CEC of 14.2 meq 100 g⁻¹. The MICRO treatment in the soil induced CEC increase by 1% compared to CON. Flakkebjerg soil had 10 meq 100 g⁻¹ CEC value and MICRO treatment induced 3% CEC increase. The Tanzania soil had the lowest CEC of 4.4 meq 100 g⁻¹ CEC compared to Flakkebjerg and Risø, but had the highest induced-effect of MICRO treatment with an increase of CEC by 6% compared to the respective CON soil.
Figure 15: Induced-effect of MICRO treatment amendment on the soil CEC. Each bar is an average of two replicates. Error bars show standard error

4.3 Soil response to water aggregate stability test

The soil response to treatments amendment on water aggregate stability across showed an increase in water aggregate stability across soils (Figure 16). The increase on Tanzania soil was higher compared to Danish soils, and dominated by CAR, MICRO and GYPS treatment respectively. The MICRO and CAR treatment had the highest amount of water stable aggregates on Flakkebjerg and Risø soil. The GYPS treatment on the Risø and Flakkebjerg was, respectively, slightly higher and lower compared to the CON treatment.

Significant difference was found on Flakkebjerg soil for CAR, MICRO and GYPS treatment respective to < 0.001, 0.009 and 0.01 P value measured against the CON treatment at P=0.05. For the same soil there was no significance difference between CAR and MICRO treatment (P=0.202). In the Risø soil, significant difference was observed for the MICRO
and CAR treated with respective P values of 0.001 and 0.042 against CON treatment. There was also significant difference between MICRO and CAR P value of 0.029. All treatments had significant effect on the Tanzania soil with P values of < 0.001 on both MICRO and CAR and 0.03 for GYPS treatment all compared to the CON treatment. In the Tanzania soil no significant difference was observed between MICRO and CAR treatment (P=0.005).

Overall induced-effects of CAR, MICRO and GYPS treatments corresponded to water aggregate stability increase of 2.4, 1.4 and -4.9 % for Flakkebjerg; 0.3, 2.3 and 0.9 % for Risø and 173, 143 and 38 % for Tanzania respectively.

**Figure 16**: Induced-effect of soil treatment amendment on water aggregate stability of the soil after 2-minute oscillation in the Yoder-type wet sieving device. Each bar is an average of three replicates. Error bars show standard error. The bar labeled with same letter within the same soil are not statistically significant at P=0.05.
4.4 Soil response to clay dispersibility test

Clay dispersibility was rather low in all soils and treatments, in particular in the Tanzania soil (Figure 17). The CON and GYPS treatments tended to have, respectively, highest and lowest clay dispersibility in all soils. The effect of the CAR and MICRO treatments on clay dispersibility was rather similar, though the former often resulted in slightly lower dispersibility. The MICRO treatment indicate dispersibility increase on Risø and Tanzania soil with increase in shaking duration, except for Flakkebjerg where there was similarity between at fourth and eighth minute. Other treatments showed the decrease in clay dispersion from two and four minute, especially on the Flakkebjerg and Tanzania soil. However, the GYPS treatment on Tanzania soil continued to decrease from 2 minutes all the way to 8th minute. In the Tanzania soil, beyond fourth minute there was a slight increase in dispersion for the CAR and stability for the CON. The Risø soil was exceptional among the three because for the MICRO, CAR and CON clay dispersibility increased throughout. The GYPS treatment was the only one which decreased between the second and fourth minute and thereafter increased.

Statistical significance for Risø soil treatments existed only between GYPS and CON (P=0.011) and at time interval of 1 and 8 minute (P=0.008) shaking duration. In the Flakkebjerg soil, neither treatment had significance impact, although in terms of clay dispersibility there was significance difference between 1 and 2 (P=0.026), 1 and 4 (P=0.028) and 1 and 8 (P=0.007) minutes of sample shaking duration. For the Tanzania soil no significance difference was found at different shaking durations, however there was significant difference between CON and GYPS (P<0.001), CON and CAR (P=0.024), MICRO and GYPS (P=0.005) and CAR and GYPS (P=0.014) treatments. The difference between MICRO and CAR was not significant in the Tanzania soil.
**Figure 17:** Induce-impact of treatment amendment on the clay dispersibility of the soil after shaking in an end-over-end shaking device at different sample shaking durations. Each point is an average of three replicates.

### 4.5 Soil response to tensile strength and friability

The soil treatments had significant impact on the soil tensile strength expect on Risø soil (Figure 18). In Flakkebjerg all the treatments showed decrease in the soil tensile strength compared to CON soil. For the Risø, CON was slightly lower than both MICRO and GYPS and higher than CAR treated soil. Air dried Tanzania soil had exceptional higher tensile strength on MICRO treated soil compared to the rest. On moist Tanzania soil tensile strength was generally low for all treatments, but amended soils showed slightly lower strength especially MICRO treated soil compared to CON.

There was significant difference on Tanzania air dried soil for MICRO against GYPS (P=0.002), MICRO vs CON (P=0.003) and CAR vs MICRO (P=0.000). For the Flakkebjerg soil significance difference was between CAR and CON (P=0.005), and GYPS and CON (P=0.004). There was no significance difference between CAR and MICRO (P=0.208) treatment in the Flakkebjerg. In the Risø soil, there was no significance difference between any comparison.
Figure 18: Induced-effect of soil amendments on soils tensile strength for 4-8 mm aggregates. Error bars show standard error. The bar labeled with same letter within the same soil are not statistically significant at P=0.05.

The soil treatments also had impact on soil friability (Figure 19). For the Risø soil treatments decreased soil friability. The decrease induced by GYPS treatment was smaller compared to that of MICRO and CAR treatments. In Flakkebjerg soil MICRO treatment slightly increased soil friability, while CAR and GYPS treatments decreased. The latter had more decrease compared to the CAR treated soil. The impact of CAR, MICRO and GYPS treatment on Tanzania air dried soil was, respectively, similar, slightly higher and more increase in the soil friability. For the moist Tanzania soil all treatments induced the decreases in soil friability compared to CON soil. In the soil CAR treatment had the least friability followed by MICRO and GYPS treatment.
Based on Utomo and Dexter (1981) five soil friability index classes, F <0.05 is not friable, F=0.05-0.10 slightly friable, F=0.10-0.25 friable, F=0.25-0.4 very friable and F > 0.4 mechanically unstable induced-effect of the treatment can be quantified (Figure 19). The GYPS treatment induced significant change on the Flakkebjerg soil friability from mechanically unstable (F = 0.44) to very friable (F=0.31). The CAR treatment also had significant effect on Risø (F=0.41) and Tanzania moist soil (F=0.28) from the respective CON values of F=0.54 and 1.30. The induce-effect of MICRO treatment was significant only on the Risø soil by improving the soil friability from the mechanically unstable to very friable (F=0.41). The other treatment effects fell under mechanically unstable friability index (Figure 19).

![Figure 19: Induced-effect of soil treatment amendment on the soil friability the soil aggregate size of 4-8 mm.](image)
4.6 Soil response to rainfall-runoff erodibility

In all soils with the MICRO treatment sediment loss was low and remained rather stable through the whole runoff event (Figure 20). A visual comparison of the MICRO and CON treatments after the runoff simulation showed much more aggregate breakdown and crusting in the CON treatments (Figure 21). Compared to the control, MICRO treatments reduced sediment loss in total by 68, 48, and 88% in the Flakkebjerg, Risø and Tanzania soils, respectively.

Soil erodibility pattern was different across soils. The CON Tanzania soil showed increase of eroded sediment, followed by the decline, while on the MICRO treated soil there was slight gradual increase in sediment loss with time but lower compared to the CON loss (Figure 20). In Flakkebjerg and Risø soils there was almost similar pattern, even though Risø showed more of a zig zag pattern (more on MICRO) compared to Flakkebjerg. The MICRO treated soil on Flakkebjerg showed something like L pattern with initial decline in sediment loss (Figure 20) followed by stability. This behavior was almost the opposite of the CON treatment on the same soil (Figure 20).

![Figure 20: Induced-effect of MICRO treatment amendment on the soil erodibility under rainfall-runoff simulation for four hours. Each point is an average of four replicates. Error bars shows standard errors.](image-url)
Figure 21: Impact of MICRO treatment on physical visibilities of aggregate breakdown and crust formation on CON and MICRO treated soil after four hours of rainfall-runoff simulation.
Chapter 5: Discussion

5.1 Impact of the soil amendment on the soil

An overview of the soil analysis results shows that soil amendments induced impact on the soil's aggregate stability. Tanzania's soil in general has shown more response to treatments compared to Danish soils. For the Danish soils, Flakkebjerg had better response to treatments compared to Risø. Across soils, both MICRO and CAR treatment induced an increase in the soil pH and decreased EC of the soil (Figure 14). The GYPS treatment induced EC increase and a very small change on the pH change for all soils. The MICRO treatment induced small increase on CEC across soil types although there was more increase on the Tanzania soil compared to the Danish soils (Figure 15).

Soil water aggregate stability analysis showed significant increase of water stable aggregates on the Tanzania soil across treatments (Figure 16). For the Flakkebjerg soil there was also significant increase of water aggregate stability for all treatments, except between MICRO and CAR treatment (Figure 16). In the Risø soil, the impact of MICRO and CAR was significantly different, the two treatments also had significant impact on the increase of water stable aggregates compared to CON soils. GYPS treatment on the Risø soil had no significant impact compared to the CON and CAR treated soils (Figure 16).

Soil dispersibility for the Tanzania soil was generally lower compared to the Danish soils (Figure 17). CAR and GYPS treatments induced significant impact on the reduction of clay dispersibility on the Tanzania soil compared to untreated soil, while that of MICRO treatment was insignificant compared to both CON and CAR treated soils. In the Tanzania soil there were no significant differences on clay dispersibility at different shaking durations. In the Danish, soils both MICRO and CAR treatments had insignificant impact on the clay dispersibility. GYPS treatment on the other hand had significant impact on the reduction of clay dispersibility on the Risø soil. In the Flakkebjerg soil, clay dispersibility was significantly different at different duration of sample shaking, while on the Risø soil the difference was generally insignificant except at one and eight-minute shaking duration.

Except for Risø soil, treatments induced change on the soil tensile strength (Figure 18). Significant reduction on the tensile strength of Flakkebjerg soil was induced by CAR and
GYPS treatment. MICRO treatment on the other hand had insignificant impact on the Flakkebjerg soil tensile strength. However, the MICRO treatment induced significant increase of the soil tensile strength on air dried Tanzania soil. In the soil GYPS and CAR treatments had no significant impact compared to CON. However, there was significant difference between CAR and MICRO treatments induced effect where the latter increased soil tensile strength (Figure 18). For the moist Tanzania soil, only CAR treatment induced significant change in the soil respective to CON treatment.

Soil treated with MICRO amendment showed a reduction of surface sediment loss in four hours of rainfall-runoff simulation in all soils. Greater overall reduction was shown by the Tanzania soil followed by Flakkebjerg and Risø (Figure 20). Visually the soil treated with the MICRO amendment indicated more stable aggregates compared to the CON treated soil (Figure 21). Also visually observed, the crust formation seemed to be quicker and covered more surface area on the CON compared to MICRO treated soils (Figure 22, 23 and 24) on all soil.

**Figure 22**: Aggregate stability and surface crust formation on Flakkebjerg before, after 30 minutes and after four hours of rain simulation
Figure 23: Aggregate stability and surface crust formation on Risø before, after 30 minutes and after four hours of rain simulation

Figure 24: Aggregate stability and surface crust formation on Tanzania before, after 30 minutes and after four hours of rain simulation
5.2 Soil aggregate stability under the impact of water

Under the impact of water, soil aggregate stability varied between soils and across treatments. This could be attributed to the soil aggregate binding mechanism which is known to differ between biotic and abiotic soil amendment (Schjønning et al., 2002). In the former, microbial biotic process helps to bind soil structural elements into aggregates by inducing clay particles interaction with organic matter within the soil and influence binding of the soil mineral particles into aggregates (Schjønning et al., 2007, Tisdall and Oades, 1982). In the abiotic process soil aggregates can be formed and stabilized through inter-particle cohesive forces which can be produced by ionized soil particle or synthesized soil microbial products like polyuronic and amino acids which are generally negatively charged and possess adhesive characteristics capable of making bonds with clay particles in the soil (Rashid et al., 2016). Hence, variations on the induced-effect of treatments on water aggregate stability can be explained based on the two mechanisms.

The water aggregate stability observed on the Danish soils (Figure 16) is a bit low but almost similar to 85% of water stable aggregates observed by Elmholt et al. (2008). The higher amount of water stable aggregate in the latter study could be attributed to the fact that measurements were taken from undisturbed field soil and relative higher clay content of the soil. For the Tanzania soil, the amount of water aggregate stability was lower (Figure 16) compared to 46% water stable aggregate observed by Kuhn and Armstrong (2012). Higher aggregate stability in the latter study could be have been due to relative lower sand content and higher silt content in the soil.

Danish soils had smaller response on increasing water stable aggregates induced by treatments compared to the Tanzania soil. This could be attribute to the dominant cementing impact of clay minerals (Table 2) which tended to form dense soil clods even in the untreated soil. The cementing impact of clay minerals on formation of stable water aggregates was also noticed in the study of Elmholt et al. (2008). The clay cementing impact is generally influenced by abiotic processes which also influence gypsum binding mechanism. Comparing the impact of three treatments (Figure 16), GYPS treatment had least influence on the aggregate stability compared to MICRO and CAR treatment. This suggests that biotic processes induced by microbial activities were dominant processes on the increase of water stable aggregates in the soils. This also signifies itself on the greater
increase of water stable aggregates on the sandy soil (Tanzania) which is generally more influenced by biotic binding processes because of fewer clay particle explained by Oades (1993).

The weaker impact of both MICRO and CAR treatment on reducing clay dispersibility indicate weaker influence of biotic processes at microaggregate level. At the microaggregate level, abiotic processes have shown dominant influence on stabilizing soil aggregate as indicated by GYPS treatment dominance across soils. The GYPS treatment significantly reduced soil clay dispersibility by inducing higher EC (Figure 14), maintaining high ionic strength induced by divalent charge effect of the soluble calcium (Figure 4). The treatment also helps on formation of cation bridge which can neutralize negatively charged and organic acid dissociate molecules to overcome dispersive forces and cause particle flocculation (Miller et al., 1988, Chen and Dick, 2011, Blume et al., 2016). In Tanzanian soil, GYPS treatment increased reduction of dispersed clay amount with an increase in sample shaking duration from 2 to 8 minutes. This behavior of continued flocculation not observed in other soil and treatments could be associated with the method of application where the finer gypsum powder could have been dissolved completely, and their desorption were increasing with increase in shaking duration and thus cations were more available to react with the soil particle and cause flocculation.

Even though biotic process appears to have small influence on clay dispersibility, but both MICRO and CAR had induced small but sometimes significant impact on the soil clay dispersibility. This could be explained by the fact that soil microbial activities had impact on other factors which influences soil clay dispersibility. These include clay mineralogical composition, amount and strength of binding materials, ionic strength, pH and magnitude of surface particle charges (Seta and Karathanasis, 1996). Hence, the small decrease in dispersed clay caused by the MICRO and CAR treatment could be related to amendments induced-effect on the soil microorganisms. Clay dispersibility difference between soil can be explained by the respective total clay content of the soil (Figure 17 and Table 2). Because, the increase in soil clay dispersibility has been found to increase with the increase in total clay content of the soil (Anders Lindblad Vendelboe et al., 2012, Getahun et al., 2016, Schjønning et al., 2002). Despite the lower clay content in the Tanzanian soil the significant and dominant impact of GYPS treatment on clay dispersibility as opposed to
significant and dominant impact of CAR treatment on water aggregate stability suggest that abiotic processes have greater influence at the microaggregate level, while biotic processes induced greater influence at macroaggregate level (Figure 16 and 17).

5.3 The impact of EC, pH and CEC on the soil aggregation

Induced-effect of treatment on soil EC, pH and CEC had great influence on the overall aggregate stability of the soil, because of the induced change in the soil ionic strength. The increase in EC induced by GYPS treatment had shown impact on the reduction of dispersible clay and increase water stable aggregate by increasing inter-particle cohesive forces (Figure 4) needed for colloidal flocculation, formation and stabilization of aggregates (Figure 16 and 17) (Shanmuganathan and Oades, 1983, Rhoton and McChesney, 2011, Hamza and Anderson, 2002, Anikwe et al., 2016, Chen and Dick, 2011, Miller et al., 1988). A big change on the soil CEC and EC was not expected on neither MICRO nor CAR treated soils because microbes and glycerol composed in the treatments were not thought to have induced strong ionization impact in the soil. But this could be explained by the fact that the microbial population developed in the soil could turn into organic debris with variable negative charges and induced significant change to the soil CEC and EC (Blume et al., 2016). But, there are also some studies which show that there are soil bacteria which can weather soil minerals, mobilize soil cations and form complexes of varying stability with organic and inorganic ligands (Rashid et al., 2016, Uroz et al., 2009, White, 2006). Perhaps the soil treatments were also able to stimulate this type of microbes in the soil and induced change to the soil ionization.

However, effective cation exchange capacity ($\text{CEC}_{\text{eff}}$) of the soil is greatly influenced by soil clay minerology, organic matter content and pH (Blume et al., 2016). The last two factors are proportional to the increase of the soil humic substances and so does $\text{CEC}_{\text{eff}}$ (Blume et al., 2016). Hence an increase in soil pH (Figure 14) could be related to the increase in $\text{CEC}_{\text{eff}}$. The relationship seems plausible because $\text{CEC}_{\text{eff}}$ increase appears to be relate to the change in the soil pH of the respective soil. The increase in soil pH can also be associated with the induced impact of MICRO and CAR treatment because a similar effect was not observed in GYPS treated soils. However, soil microbial activities were expected to reduce soil pH and not increase by discharging proton, produce organic or inorganic acids through acidolysis (Rashid et al., 2016) or CO$_2$ respiration which tend to form weak carbonic acids. But,
studies by Yan et al. (1996) and (Barekzai and Mengel, 1993) found that soil microbial activities can induced soil pH increase through organic anions decarboxylation process which consume proton according the following equation: R-CO-COO- + H+ → R-CHO + CO2. Soil treatment with organic residuals have also been found to induced soil pH increase by Butterly et al. (2013); which also signifies the role of organic carboxylic group decarboxylation as explained by Yan et al. (1996) and Barekzai and Mengel (1993).

The increase in the soil pH induced by CAR treatment was consistently lower compared to that of MICRO treatment (Figure 14). But amount of water stable aggregates induced by MICRO treatment were also lower compared to CAR treatment especially on the Tanzania and Flakkebjerg soil (Figure 16). Perhaps this was induced by microbial activity level stimulated by the treatment in the soil. High microbial activities levels in the soil could also lead into rapid synthesizes of microbial polysaccharides binding agents, but can also cause rapid degradation of the same polysaccharides as explained by Tisdall and Oades (1982).

5.4 Treatment impact on soil aggregate resistance to deformation

Soil resistance to deformation was determined by looking at the soil tensile strength and friability. Both factors were highly influenced by the soil treatments (Figure 18 and 19). The tensile strength range observed on the tested soils cannot be compared effectively with other studies and soils because only one aggregate size was used to determine the tensile strength and friability. Many studies have used different soil aggregate size to compute the average tensile strength of the soil with low range starting from 22 kPa in Causarano (1993) to 750 kPa found by Elmholt et al. (2008). The wide range is not surprising because there are many factors which can influence soil tensile strength (Causarano, 1993).

The soil tensile strength range observed in Figure 18 falls within the range observed from other studies. Differences on treatments induced-effect across soil samples on both tensile strength and friability could be explained by factors known to influence soil tensile strength which includes clay, silt and organic matter (Imhoff et al., 2002, Causarano, 1993, Rahimi et al., 2000, Munkholm and Kay, 2002), perhaps soil microbial activities as well. Studies by Imhoff et al. (2002) and Munkholm and Kay (2002) found a positive relationship between soil tensile strength and clay, silt and organic matter soil content as observed on figure 18 and table 2, which show Risø soil with highest amount of clay content to have
highest tensile strength among the soil. But, in the Risø soil all treatments had no significant impact on changing soil tensile strength. This could be caused by high base saturation of more than 90% corresponding to 7.8 pH value as described by CLEMSON (2015) and presence of CaCO₃ (Table 2) would also mean that more ions were covered by Ca which might have influenced soil aggregate binding and reduced treatment impact on the soil. The latter is plausible because of the smaller change in the soil pH observed on the Risø soil as well as small change on CECeff. The small change induced by MICRO and CAR treatment in the soil were able to improve soil friability index from mechanically unstable to very friable (Figure 19).

Significant reduction on soil tensile strength was induced by all treatments on Flakkebjerg soil when compared with CON soil. The decrease was not expected because improvements on water aggregate stability has been associated with the increase in the soil tensile strength (Causarano, 1993, Munkholm et al., 2002). But this could be explained by the impact of the treatment on the soil aggregation mechanism it caused increase in soil porosity. If treatments had improved soil porosity, it’s like the particles were loosely bonded between pores and therefore weaker tensile strength.

The weaker tensile strength of the Flakkebjerg soil could also have been induced by redox effects, because of rusty patterns observed (Figure 25) on the soil specifically to CAR and MICRO treated soils. A study by Duiker et al. (2003) and many others have shown important role of Ferric iron and other soil oxides on the stabilization of the soil aggregates and therefore tensile strength. Therefore, microbial reduction and redistribution of Ferric iron in the soil could have impact the aggregate strength. The rusty pattern observed on the soil was thought be caused microbial redox processes. Many studies have found existence of soil microorganisms with Ferric iron reducing capabilities under anaerobic conditions (Lovley, 1991, Lovley, 1993, Lovley et al., 2004, Lovley and Phillips, 1986). The reduction of Ferric into Ferrous iron which is soluble in water is therefore thought to be induced by the soil microbes while the soil was incubated because the pattern was not present on neither CON nor GYPS treated soils and found inside soil aggregate. The dissolved Ferrous iron might have translocated in the moist soil because the Flakkebjerg soil was felt wetter. The soil wetness could be induced by an error during measurement or method adopted for calculating soil water holding capacity. However, the dissolved translocated iron could
have re-oxidize after being exposed for to room temperature during measurement to form the rusty pattern observed. These processes were also attributed to soil microbial activation.

MICRO treatment did not improve soil friability this could be caused by the lack of significance on the treatment tensile strength compared to the CON treated soil. CAR and GYPS treatment despite inducing lower tensile strength had improved soil friability index from mechanically unable to very friable which could also be justified by the significant effect of the treatment on tensile strength.

![Image of soil aggregates](image)

**Figure 25:** Rusty pattern on CAR and MICRO aggregates for Flakkebjerg soil, seen on neither CON nor GYPS treated aggregates

Significant increase of tensile strength on air dried MICRO treated Tanzania soil was in consistence with the significant increase of water stable aggregates on MICRO treated soil. In sandy soils macroaggregate formation and stabilization is dominated by microbial processes which helps to bind together soil particles in hyphae network produced by soil microbes (Oades, 1993). The process which might have induced water aggregate stability on the MICRO and CAR treated soils (Figure 16). The soil microbes can also induced formation and stabilization soil microaggregate through production of microbial mucilage (Six et al., 2004) the process which could have account for the reduction of clay
dispersibility induced by MICRO and CAR treatment (Figure 17). Therefore, the soil tensile strength increase on the air dried Tanzania soil could be attributed to impact of soil microbial activation induced by treatments.

It was however surprising to observe insignificant effect of CAR treatment on the tensile strength of the air dried Tanzania soil (Figure 18), after having significant and dominant impact on inducing water aggregate stability (Figure 16). However, a similar trend was shown by the CAR treatment on the other soils as well. The similar behavior was on observed for the MICRO treatment especially on Risø and Tanzania soil. There did not appear to be a better explain as to why this happened apart from being associated to the soil treatments incorporated. The major difference that existed between MICRO and CAR treatment was the absence of microbes in the latter. This way the impact of the CAR treatment on the reduction of tensile strength and increase was water aggregate stability could be on the interaction between inherent soil microbes and the CAR treatment.

The fact that Tanzania soil (with more pronounced impact) had low clay and organic matter content with high sand content (Table 2) indicate that the soil tensile strength is more influenced by the microbial binding agents. Microorganisms differ widely in their ability to provide soil mechanical aggregate stability (Aspiras et al., 1971b) and rate of production and consumption of polysaccharides in the soil depends on the nature of carbon substrate present in the soil (Degens, 1997, Aspiras et al., 1971c). Continued contribution of polysaccharides as organic binding agents to induces aggregate stability therefore depend on the availability of carbon and energy source in the soil for microorganisms (Aspiras et al., 1971c). Also, contribution of biological processes are substantial on maintaining strength, stability and longer duration of the soil aggregates formed by the microbes (Tisdall and Oades, 1982). Therefore, it has been difficult to identify a specific factor which could have induced lower tensile strength and higher water aggregate stability as observed on Figure 16 and 18. Perhaps there was faster decomposition of the soil binding materials produced by the microbes after soils were removed from the incubation, acclimatized to room temperature and then air dried before tensile strength measurements were taken.
At low water content, soils have small friability values and large tensile strength while at high water content it’s the opposite (Utomo and Dexter, 1981) as observed on the dry and moist Tanzania soils (Figure 18 and 19). At high water content soil have relatively small strength and becomes more friable because of the increase in soil failure induced by the increase in soil water content which tend to weaken inter-particle forces of attraction (Utomo and Dexter, 1981, Munkholm, 2011, Causarano, 1993). Hence the weaker tensile strength of the moist Tanzania soil and higher friability values could be explained by the weaker forces of attraction induce by more water in the soil.

5.5 Soil aggregate breakdown and loss in an open system

Reduction in sediment loss induced by MICRO treatment on rainfall-runoff simulation (Figure 20) was anticipated, because of the existing relationship between soil aggregate stability improvement and soil erodibility as explained in many studies (LeBissonnais and Arrouays, 1997, Bryan, 1968, Adornis, 2012). The soil aggregate stability governs infiltration, breakdown and detachment of aggregates at the top soil (Bartoli et al., 2016, Yan et al., 2008). Erodibility of the top soil depend on amount of soil aggregate, size and stability (Bryan, 1968). Hence, soil aggregate stability can be used to predict mechanical breakdown of soil aggregates by raindrops impact (LeBissonnais and Arrouays, 1997, Yan et al., 2008, Shi et al., 2010).

The soil aggregate breakdown induced by rain drop releases primary soil particles which are displaced and rearranged by raindrop-impacted flow to form denser and continuous seal structure (crust) on the soil surface. Rainfall energy and intensity has been shown by Kuhn and Armstrong (2012) to have potential role on erosion process induced by the rain. The rainfall which has high intensity and energy (45 mm h⁻¹ at 400 J h⁻¹ m⁻²) was found to possess more non selective erosive power compared to rainfall intensity 30 mm h⁻¹ and average energy of 113.9 J h⁻¹ m⁻². The used low intensity and energy rainfall is similar to that (25 mm h⁻¹ at 222 J h⁻¹ m⁻²) used in the Kuhn and Armstrong (2012) study which induced selective erosion process that entrains mainly small and light soil particles because of limited aggregate breakdown.

With more crust development a coherent layer of washed and compacted finer particles forms beneath loose aggregate fragments resulting to smoother soil surface which requires
less energy for particle transportation (Bartoli et al., 2016, Shi et al., 2010, Yan et al., 2008). The increase of aggregate breakdown could be reflected on the amount of sediment eroded which also depends on level of crust development. If crust is still under development broken aggregate particles would be trapped with the soil and less sediment would be eroded. If crust is full developed, the broken aggregate particles would be easily eroded by surface runoff water. In the latter stage, rate of erosion would also depend on surface roughness and presence of unstable aggregates continue to break under the impact of rain water.

Weaker aggregates of untreated Tanzania soil produced more sediment compared to the stronger Flakkebjerg and Risø aggregates. As shown on Figure 20 soil with more water stable aggregates were more resistant to the impact of raindrop compared to weaker soils. The rate of crust formation on the latter soil is also faster compared to soils with stronger aggregates (Figure 22-24). Hence, a direct relationship between soil aggregate breakdown and crust formation could also be established. Based on visual observation of the soil surfaces and amount of sediment eroded, surface roughness also seems to have influenced the amount of eroded materials collected. Risø soil with the most stable aggregates (Figure 16) and roughest surface (Figure 21) produced the lowest amount of eroded sediment (Figure 20). This agrees with the general understanding that surface roughness helps to reduce erosive power of surface flow by reducing velocity, trap water on the soil surface and influence infiltration, hence limited erosion (Quinton et al., 2001)

The selective erosion process induced by the low rainfall intensity and energy showed different sediment discharge behavior across soil samples and treatments. On CON Flakkebjerg the discharge plateau at relatively high level after two hours of rainfall simulation; Risø CON was rather stable at moderate level while Tanzania CON had declined from high level after two hours of rainfall simulation. The decline indicates depletion of erodible material (Figure 24) and some larger grain or aggregate on the surface created armoring effect. For the MICRO treatment there was initial discharge decline on the Flakkebjerg, again rather stable erosion at moderate low level on Risø and slight gradual increase on the Tanzania soil. Similar behavior was observed by Kuhn et al. (2012) and attributed to surface roughness.
Average amount of discharged sediment under the rainfall simulation condition similar to the ones used in this was of 37 g h⁻¹ for conventional soil and 9.8 g h⁻¹ for organically farmed soil in Kuhn and Armstrong (2012) study. In another study by Kuhn et al. (2012) the average value for the sediment discharge was 80 and 28 g h⁻¹ for conversional and organic soil respectively. A comparison of the two studies indicate that the CON Risø soil had relatively low discharge compared to the conversional soil discharge on both studies. Both Flakkebjerg and Tanzania CON soil were between conventional discharge range of the two soils. The Tanzania soil was on the higher end and Flakkebjerg on the lower. For the MICRO treated soil the reduction on discharged sediment is on the level of the organically farmed soil (10 g h⁻¹) from Kuhn and Armstrong (2012). Total sediment reduction induced by MICRO treatment on Tanzania soil (88%) is greater compared to the reduction induced by organic matter in the two studies. In Flakkebjerg the induced reduction (68%) is similar to that of Kuhn et al. (2012) but lower compared to the one in Kuhn and Armstrong (2012). The soil used by Kuhn et al. (2012) was silty loamy while sandy loam was used by Kuhn and Armstrong (2012). Although none of the soil had as high sand content as in Tanzania soil (Table 2), the greater reduction on sandy loam and Tanzania soil indicate soil organic matter have stronger influence on soils which are sandier.

As it has also been found by other studies (LeBissonnais and Arrouays, 1997, Nciizah and Wakindiki, 2015, Bryan, 1968, Bartoli et al., 2016, Le Bissonnais, 2016b, Shi et al., 2010, Valmis et al., 2005, Yan et al., 2008) that soil aggregate stability has been shown to influence reduction of sediment erosion under rainfall-simulation and present itself as an integrative indicator for various components contributing to soil erodibility. The increase in soil cation exchange capacity (Figure 15) water aggregate stability (Figure 16), tensile strength (Figure 18) and reduction of clay dispersibility (Figure 17) induced by MICRO treatment influenced resistance of soil aggregates to the impact of raindrops. However, difference on the total sediment reduction could be attributed to the inherent nature of the soil properties (Table 2) especially clay, organic matter and CaCO₃ content which have influence on enhancing soil aggregate strength as shown by lowest amount of discharged sediment on the Risø soil compared to Tanzania soil with contrasting properties.
Chapter 6: Conclusion

The rainfall runoff simulation test has shown that microbial-based soil amendment (MICRO) had significant impact on reducing erodible soil particles on all testes soils which had history of structural problems.

The microbial-based soil amendment had significant impact on the increased water aggregate stability for all soils. Compared to gypsum treatment (GYPS) the MICRO treatment was still found to induce more impact on the water aggregate stability. The impact of the MICRO treatment was lower on Flakkebjerg and Tanzania soil compared microbial agent carrier solution (CAR). Only in Risø soil the impact of MICRO treatment was more than CAR treatment on inducing water stable aggregates.

The MICRO treatment impact induced small reduction on dispersible clay across soil samples. Compared to the MICRO treatment CAR treatment induced slightly more reduction of dispersible clay particles in the soil. The GYPS treatment induced more reduction on clay dispersibility compared to both MICRO and CAR treatment.

In terms of tensile strength MICRO treatment caused an increase of the tensile strength on Risø and Tanzania soil and decrease on Flakkebjerg soil. The treatment impact was significant only on the Tanzania soil. Compared to MICRO treatment, CAR treatment lowered tensile strength across the soil samples. GYPS treatment had lowered tensile strength on Flakkebjerg and Risø soil compared MICRO treatment. Compared to CON both CAR and GYPS treatment induced tensile strength decrease on Tanzania and Risø soil and they had no impact on Tanzania soil.

MICRO treatment impact induced an increase in the soil pH across the soil, but significant increases were on Flakkebjerg and Tanzania soil. The treatment also induced a decrease in the soil electrical conductivity (EC) across the soil. Compared to MICRO, CAR treatment induced smaller increase in across soils. A very small change was induced by the GYPS treatment on the pH across soils. In terms of EC reduction, CAR treatment had similar impact as that of MICRO treatment, but GYPS treatment had induced significant increase in
the EC across soils. The MICRO treated also induced small increase in the cation exchange capacity (CEC) of the soils.

MICRO treatment improved soil friability of Risø soil from mechanically unstable to very friable and had no impact in any other soils. Compared to the MICRO treatment, CAR treatment improved soil friability of both Flakkebjerg and Risø soil from mechanically unstable to very friable. The treatment had no impact on Tanzania soil. The GYPS treatment also improved soil friability of the Flakkebjerg soil and had no impact on Tanzania soil.

The induced effect of MICRO and CAR treatments were at macroaggregate level and that of GYPS at microaggregate level. The effect of the former was linked to the activation of soil microbial activities resulting in the production of soil microbial binding agents which induced formation and stabilization of soil aggregates. The effect of GYPS treatment was related to the increase of soil ionic strength, which leads to an increase of inter-particle cohesive forces, flocculation of soil colloid and thus improved aggregate stability. Soil microbial activities influence the increase of soil pH, tensile strength, slight increase in cation exchange capacity and lowered electrical conductivity of the soil. Treatments induced-effects were more pronounced on sandy soil with low organic matter, silt, clay content compared to the ones with relatively high organic matter, silt and clay content.

Based on visual observation and feeling on the hand Risø and Flakkebjerg soil felt wetter than the amount of water applied. The wetness could not be verified in measurement. But the wetness was thought to have had impact the strength of Flakkebjerg soil through translocation of water soluble cations in the soil.
Chapter 7: Perspectives for using microbial soil amendment

The positive response shown by the microbial soil treatment present the potential to be used on improving weakly structured soils. The treatment has shown ability to improve soils of different origin from both humid and tropical climates which signifies wide geographic potential. Its ability to increase soil aggregate resistance to the impact of rain drop and reduces rate of soil crust formation makes it a good candidate for reducing nutrient loss by surface runoff, increasing the chances of nutrients to reach root zone which may result into nutrient use efficiency with best management practices. However, treatment application on arable land would be challenged by the land management practices such as cultivation and tillage which would interfere with the treatment induced impact on the soil. But perhaps the treatment can be used together with no till agricultural practices. Although this would also be challenged by the fact that the treatment has shown to perform better on soils with low organic matter content and sandy soils.

The use of treatment would be challenged by its affordability to users in comparison to the alternative methods of improving soil structure like the use of plant residue improve soil organic stability especially on arable lands. However, the treatment appears to be quicker on improving soil aggregate stability and in the study was observed to take place within a week after application and the impact was still there even after two months. This opens up possibilities for the treatment to be for dust control or improves soil structure in smaller hotspot areas like gardens.

Treatment application is perhaps more suitable for dust mitigation and control at construction sites, residential areas or urban areas where there could be minimal disturbances compared to arable land application. Hence, less need to reapply the treatment in short time intervals. This would make treatment application in those areas more economical apart from being thought to have fast response and longer durability. But, soils in the mentioned areas are often composed of low organic matter content which has shown to perform better with the treatment.

Despite the response, it was not possible to separate microbial induced-effect from other factors influencing soil aggregate formation. It appeared there was an interactive effect
among various factors influencing soil aggregate formation and stability. This is because the CAR solution was also able to induced similar effect as that of the MICRO treatment and at some incidence even more. Hence, it is essential to understand the physiological functioning of the soil microbes in the MICRO compared to the CAR treatment and understand the actual mechanism used by the microbes to bind and stabilize soil aggregates.

Factors such as temporal effect, appropriate ratios of soil microbe and carrier solution, strength of formed polysaccharides and their durability as well as impact of other soil microbes the product’s microbes which were not considered in the study would probably need to be understood better in order to increase potential of the product. It would also be interesting to understand the peak time for microbial induced-effect and for how long it could be retained under different environmental conditions with soils of different origins, especially because the effect attained in the study could be caused by proper mixing techniques which might be difficult to attain at field condition.

Because of the smaller flume sizes used and the fact that rainfall-runoff simulation cannot mimic to perfection actual rainfall event and their impact on soil aggregate breakdown, soil crust formation and surface runoff event, it is recommended to conduct similar experiment at a field scale level and evaluate performance of the amendment. Parameter such as impact to aggregate resistance to wind, temperature change, drying and rewetting, slope difference and rainfall intensities could be understood better in open system instead of relying on information from isolated system only. This is because those parameters can influence either soil treatment or mechanism of the treatment to induce soil aggregate stability, especially in an open system where their interactive effect can be evaluated a time period.
Chapter 8: References


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