博士論文

Effects of chicken manure and eggshell application on amelioration of low pH soils in the Mekong Delta of Viet Nam
(鶏ふん堆肥および卵殻の施用がベトナムメコンデルタの低pH土壌の改良に与える影響)

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by

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SUMMARY

Agriculture plays key roles in livelihood of farmers and economic development in the Mekong delta of Viet Nam. To grow up well, plants require many necessary elements like sunlight, water, soil, temperature, nutrients... Among them, a soil plays a crucial element as intermediate medium to provide necessary demands for plant growth. One of the problems is low pH soils, where most plants cannot develop well in low pH environment. Aggregate stability is another important issue affecting soil productivity, but it is still less concerned. To meet food security for rapid growing population, it is essential to ameliorate productivity of low pH soils for agricultural production.

The problems given were how to improve soil pH and prevent aggregate breakdown simultaneously. Before the questionnaires are answered, it is necessary to clarify how aggregate stability of low pH soils is and which conditions affect aggregate stability during aggregate stability test. Therefore, the objective of this study is (1) to evaluate aggregate stability under initial soil moisture conditions, clod sizes and breakdown process (2) to discuss the effects of chicken manure and eggshell application on changes in soil pH, aggregate stability to clarify the role of amendments on soil quality

Field work was conducted in three locations belonging to the Mekong delta of Viet Nam. Saline and sodic soil (SS) in Ca Mau province, alluvial soil (AL) in Can Tho city, and acid sulfate soil (AS) in Hau Giang province were collected at the 0-20 cm depth. Properties of soil profiles at the depth of 0-200 cm were described in the field and the laboratory. Based on diagnostic horizon, diagnostic properties and diagnostic materials, the name of soil main groups was defined.

First, aggregate stability test was conducted to evaluate the effects of initial clod sizes, initial soil moisture conditions and breakdown processes on aggregate stability. Saline and sodic soil (SS), alluvial soil (AL) and acid sulfate soil (AS) were employed. Three initial clod sizes: 1-3 mm, 2-5 mm and 5-10 mm were prepared. Two moisture levels of clods were adjusted. Fast wetting, slow wetting and mechanical breakdown were employed as breakdown processes.

The aggregate stability test suggested that mean weigh diameter (MWDs) was the

lowest for dry clods subjected to fast wetting. It implied that dry soils exposed to fast wetting like border irrigation, or furrow irrigation could deteriorate soil aggregates. MWDs suggested that saline sodic soil (SS) had the most fragile aggregates, followed by alluvial soil (AL) and acid sulfate soil (AS). The initial 2-5 mm and 5-10 mm clods were durable more than the initial 1-3 mm clods. Upon this result, 2-5 mm dry clods under fast wetting were employed for aggregate stability test after amendment application.

Soil incubation experiment was conducted with seven treatments and three replicates. Chicken manure was used as a compost and eggshell-$CaCO_3$ was substituted for lime. The eggshell application rates of lime requirement (LR) and a half lime requirement (1/2 LR) and chicken manure application rates of 25 g kg $soil^{-1}$ and 50 g kg $soil^{-1}$ were employed. Soils and either or both eggshell and chicken manure were mixed and put into a 500 ml glass bottle. Then, soil amendment mixtures were incubated for 45 days in a constant room temperature of 25 ^oC. During the incubation, CO_2 concentration of head space of the glass bottle was periodically measured. Soil pH, aggregate stability and soil organic carbon were measured after the halt of soil incubation on days of 3, 10, 20 and 45. Mean weight diameter (MWD) was used to evaluate aggregate stability. Aggregate stability was determined using the 2-5 mm dry clods exposed to fast wetting.

Eggshell application increased pH of the three soils. Chicken manure could raise pH of SS and AL, but it was less effective at raising pH of AS. The combined application of chicken manure and eggshell was the most effective at increasing soil pH. Rapid increase in CO_2 emission rate within first two days with the eggshell application suggested that the $CaCO_3$ rapidly reacted with the H^+ in the soils. SS and AL showed abundant CO_2 emission within the first five days, while AS took time to show a peak CO_2 emission rate. The combined application of chicken manure and $CaCO_3$ increased soil pH and CO_2 emission in all three soils. This suggested that microbiological activity was enhanced by an increase in soil pH caused by $CaCO_3$ in combination of chicken manure compost and eggshell-$CaCO_3$. Correlations between soil pH and CO_2 emission suggested that microbial activity increased with increasing in soil pH. The rise in soil pH induced by eggshell-$CaCO_3$ in combined application enhanced microbial activity contributing to decomposition of chicken manure. This involved in aggregate stability, where organic compounds produced from decomposition of chicken manure by micro-organisms could enhance soil particle cohesion and thus stabilized soil aggregates. Soil organic carbon was accumulated high in all the soils with the addition of chicken manure with or without eggshell. Eggshell application alone destabilized soil aggregates, whereas the chicken manure and the chicken manure-eggshell combination improved aggregate stability. From the result, the application of chicken manure and eggshell was more effective in both soil pH and aggregate stability than either chicken manure or eggshell application.

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Abbreviation

Al: Aluminium

AL: Alluvial soil

AS: Acid sulfate soil

Ca^{2+}: Calcium

CEC: Cation exchangeable capacity

Cl^{-}: Chloride

CO_2: Carbon dioxide

EC: Electric conductivity

ESP: Exchangeable sodium percentage

ESR: Exchangeable sodium ratio

Fe: Iron

FSD: Fragment size distribution

FW: Fast wetting

$KFe_3(SO_4)_2(OH)_6$: Ferric sulfate

LR: Lime requirement

LSD: Least significant difference

MB: Mechanical breakdown

Mg^{2+}: Magnesium

MWD: Mean weight diameter

Na^{+}: Sodium

OC: Organic carbon

SAR: Sodium adsorption ratio

SO_4^{2-}: Sulfate

SOM: soil organic matter

SS: Saline-sodic soil

SW: slow wetting

USDA: United State of Department of Agriculture

Chapter 1 - Introduction

1.1 General description of the Mekong delta

1.1.1 Geographic location

Mekong Delta is located in the southernmost region of Viet Nam. It is surrounded by the Gulf of Thai Lan in the West, the east-sea and the south-sea, Cambodia in the Northwest and Ho Chi Minh City in the North (Figure 1.1). The Mekong Delta is composed of 13 provinces, namely Tien Giang, Vinh Long, Can Tho, Long An, Dong Thap, Tra Vinh, Soc Trang, An Giang, Ben Tre, Bac Lieu, Kien Giang, Hau Giang and Ca Mau, with total area of about 4 million ha (General Statistic Office of Vietnam, 2015).

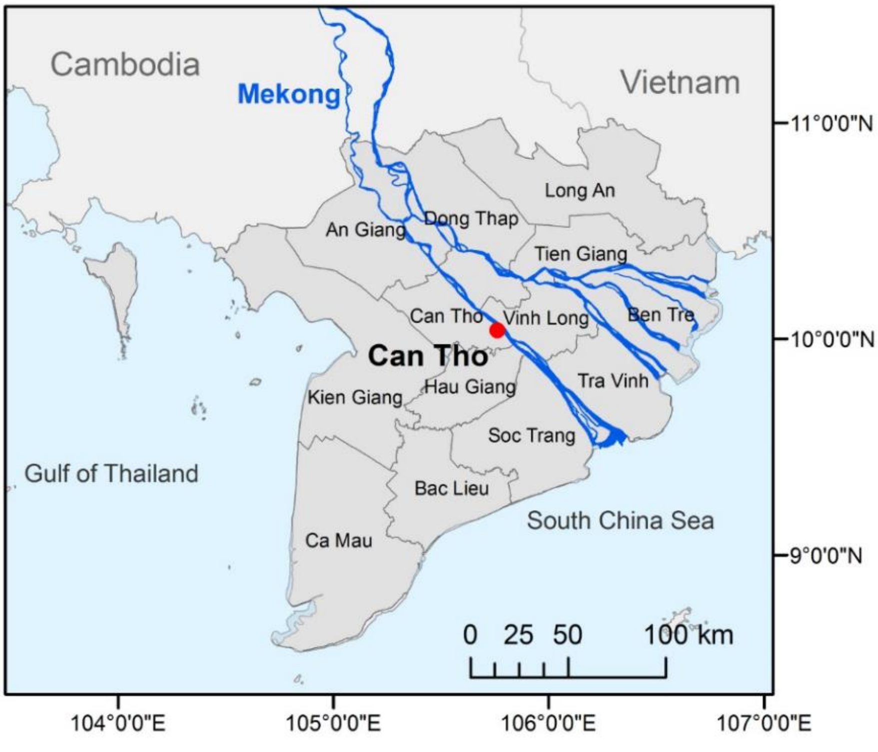


Figure 1.1 Geographic location of the Mekong delta

(https://www.vietnam-tour.biz/blog/introduction-of-mekong-delta-vietnam/)

1.1.2 Climate

Mekong Delta has a tropical climate with a seasonal distribution of dry and rainy season. The dry season lasts from December to April. The weather in this season is characterized by high temperature and less rain. Highest temperature is 40 ^{o}C (Viet Nam Institute of Meteorology, Hydrology and Climate Change (IMHEN), 2010). The lowest average rain is 1400 mm (Viet Nam – Netherlands cooperation, 2011). The rainy season lasts from May to November. The climate is characterized by high humidity and heavy rainfall in rainy season. The highest average rain mainly concentrates in rainy season being 2350 mm (Viet Nam – Netherlands cooperation, 2011). Average humidity ranges from 60 to 80%. (Viet Nam – Netherlands cooperation, 2011). The average temperature varies from 26 to 29 ^{o}C (Viet Nam Institute of Meteorology, Hydrology and Climate Change (IMHEN), 2010)).

1.2 Soil problems in Mekong Delta of Viet Nam

The Mekong delta is the most important region for agricultural production in Viet Nam. Total land area is 4 million ha, of which about 2.6 million ha is used for agriculture (General Statistic Office of Vietnam, 2015). The main agricultural products are rice, fruit, vegetables, soybean, maize, sugar cane and peanut. However, the direct and indirect impacts of climate changes will become a major challenge in the near future. The Mekong delta region surrounded by the east-sea and west-sea is favourable for salt affected soil. It increased from 706,485 ha to 884,199 ha from 1975 to 2005 (Duc and Dao, 2011) and 1.4 million ha in 2011 (Viet Nam – Netherlands cooperation, 2011). Acid sulfate soil is also one of the most burdening of agricultural production. Although area of acid sulfate soil felt down from 1.8 million ha to 1.5 million ha from 1975 to 2005 (Duc and Dao, 2011) and 1 million ha in 2011 (Viet Nam – Netherlands cooperation, 2011), damages by acid sulfate soil to crop production are enormous. Salt affected soil and acid sulfate soil are widely distributed in all the provinces belonging to the Mekong delta (Figure 1.2). Agricultural production is adversely affected by these two kinds of soils. To meet the demand of food security for rapid growing population, applying appropriate measures to increase productivity of these soils is essential.

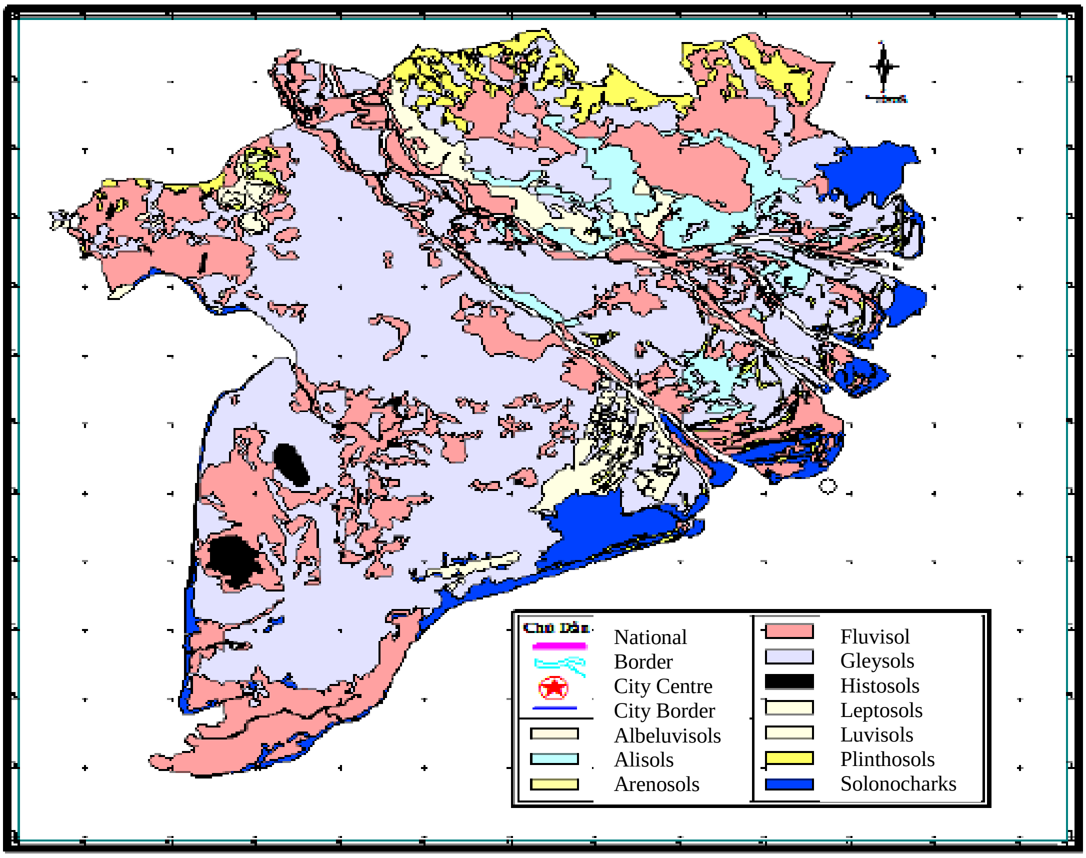


Figure 1.2 Map of soil distribution in the Mekong Delta (Vu *et al.* 2011)

1.3 Objectives of the study

In agricultural production, soil pH plays important role in plant growth. Most plants cannot develop well in extremely low pH acid sulfate soil. Therefore, improving pH is the first priority. Not only soil pH, but also soil aggregate stability is important. Both of them affect soil productivity and crop production. Breakdown of unstable aggregates may cause many serious consequences such as surface sealing, reduction in hydraulic conductivity, soil erosion, nutrient loss and inhibiting seedling emergence. However, evaluating aggregate stability and applying proper measures to improve both soil pH and aggregate stability are less concerned. Therefore, aims of this study are to investigate:

- Effects of soil moisture conditions, clod sizes and breakdown processes on aggregate stability of saline sodic soil and acid sulfate soil in the Mekong delta.

- Effects of chicken manure and eggshell on changes in soil pH and aggregate stability to clarify the role of amendments on soil quality.

The soil samples were collected in three locations belonging to the Mekong delta region. The soil profiles were described to observe soil characteristics in the field. The status of land-use was recorded to understand traditional methods of soil and water management because the land-use and management process such as tillage, irrigation, mechanical impacts may affect soil aggregate stability.

In this study, aggregate stability was evaluated by applying fast wetting, slow wetting and mechanical breakdown as breakdown processes. Prior to applying breakdown processes, the soils were adjusted with different moisture conditions, and clod sizes. Identifying aggregate behaviours under initial different conditions and breakdown processes is very important to know the key factors causing aggregate deterioration. It is helpful for soil structure management as well as applying skilful strategies to increase aggregate stability.

The application of chicken manure and eggshell were considered as one of the proposed measures in soil management. Aggregate stability after amendment application was evaluated to know effects of amendments on soil aggregate stability. The result of this study will clarify whether eggshell and chicken manure application could or could not bring positive effects on both soil pH and aggregate stability to clarify roles of amendments on soil quality.

1.4 Structure of the study

The present dissertation is composed of seven chapters (Figure 1.3). A brief description of these chapters is given as follows:

Chapter 1: This chapter presents the current problems, the necessity, the objectives and the structure of this study. Attempting to increase productivity of saline sodic and acid sulfate soil for sustainable agriculture is required to be aware of aggregate stability. Improving aggregate stability has to be considered simultaneously with soil pH alleviation, CO_2 emission and organic carbon.

Chapter 2: This chapter reviews what have done in previous studies. This information provides knowledges and supports for explanation of results in this research.

Chapter 3: This chapter describes soil characteristics at sampling sites.

Chapter 4: This chapter states the effects of initial soil moisture, clod sizes, and breakdown processes on aggregate stability. Aggregate breakdown under various conditions and breakdown processes are discussed in this chapter.

Chapter 5: This chapter is divided into two main parts of results. The first part is the effects of amendment application on aggregate stability after incubation. In the second part, the effects of amendment application on the changes in soil pH, CO_2 emission, organic carbon and aggregate stability are presented. Relationship between soil pH and aggregate stability and the relationship between organic carbon and aggregate stability are discussed in this chapter.

Chapter 6: This chapter states the main conclusions. Practical meaning and main contributions of this study to human being and society are shown.

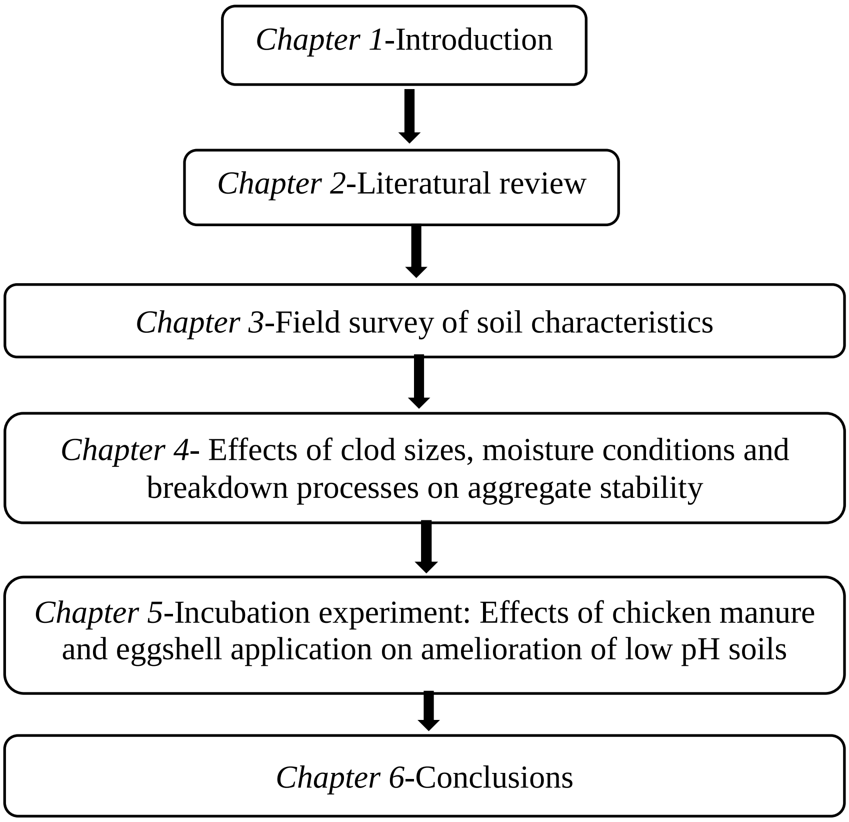


Figure 1.3 Schematic diagram of the structure of this study

Chapter 2 - Literature review

2.1 Low pH soil

The term of soil pH is a mean of expressing H^+ concentration in soil solution by using the negative logarithm of H^+ ion concentration.

$$pH = - \log [H^+]$$

Soil with pH of 7 is neutral. In acid soil, hydrogen (H^+) ions predominate or soil pH is lower than 7. The lower the soil pH, the more the acidic it is. The soil pH is an important indicator because it affects plant growth and available nutrients in soils (Goulding, 2016). Optimum pH range depends on crops. Most plants could grow well at optimum pH range of 6-6.5 (Goulding, 2016). Soils in the Mekong Delta have low pH, so improving soil pH is the first priority of agricultural purpose.

2.2 Acid sulfate soil

The presence of ferrous (Fe^{2+}), sulfate (SO_4^{2-}), abundant organic matter, and sulfate-reducing bacteria in anaerobic medium are the conditions of acid sulfate soil formation (Attanandana and Vacharotayan, 1986). In waterlogging conditions, *Desulfovibro* and *Desulfotomaculum* bacteria consume organic matter and sulfate (SO_4^{2-}) as energy sources to synthesize in their body and reduce sulfate (SO_4^{2-}) to sulphide (S^{2-}). Sulphide (S^{2-}) and Fe^{2+} could form iron pyrite (FeS_2) present in soils. Acid sulfate soils are formed from the oxidation of the iron sulphides, mainly pyrites (FeS_2), present in the soils. The oxidation occurs when water table drains out of pyrite layers. Oxygen diffusion inside the soils oxidizes pyrite. Sulfuric acid (H_2SO_4), one of the end products in pyrite oxidation processes, is a main cause of low pH. Below pH 4.0, aluminium (Al) and iron (Fe) are abundant in soluble aluminium ion (Al^{3+}) and soluble iron ion (Fe^{3+}) forms (Strawn *et al.* 2015) as the following reaction:

$$3H^+ + Al(OH)_3 \leftrightarrows Al^{3+} + 3H_2O \qquad [1]$$

The release of hydrogen (H^+) from soluble Al^{3+} hydrolysis reduces pH (Iqbal, 2012; Strawn *et al.* 2015). Soluble Fe^{3+} hydrolysis also releases protons (H^+) (Stefansson, 2007; Strawn *et al.* 2015).

In the Mekong Delta of Viet Nam, acid sulfate soil is characterized with low pH, less than 3.7, and high content of soluble Al^{3+}, ferrous (Fe^{2+}) and ferric sulfate ($KFe_3(SO_4)_2(OH)_6$) (Tho and Egashira, 1976). In the field, acid sulfate soil can be identified with straw-yellow mottles of jarosite (ferric sulfate: $KFe_3(SO_4)_2(OH)_6$) in sulfuric horizon. The straw-yellow mottles of jarosite can be seen by the naked eyes. Acid sulfate soil shows soil pH from 2 to 4 and appears within 100 cm from soil surface (Attanandana and Vacharotayan, 1986; ISSS/ISRIC/FAO, 1998; Minh and Tri, 2006). Acid sulfate soils are classified as EpiOthoThionic-Fluvisols (FLptio) based on the soil map inventory of the Mekong Delta following the World Reference Base (WRB) for Soil Resources – Food Agriculture Organization of the United Nations (FAO) at scale 1/250.000 (Minh and Tri, 2006) and WRB for soil resources classification systems (ISSS/ISRIC/FAO, 1998).

2.3 Effects of soil pH on microbial activity

Microbial activity is strongly influenced by soil pH (Rousk *et al.* 2010). Rousk *et al.* (2009) reported that microorganisms were inhibited at pH below 4.5. Kunito *et al.* (2016) also reported that pH of acid soil less than 5.5 suppressed microbial activity. The effectiveness of lime is beyond expectations of soil improvement, not only soil pH but also soil microorganisms. Lime promotes an optimum population of soil microorganisms essential for decomposition of soil organic matter (Haynes and Swift, 1988; Haynes and Naidu, 1998). At lime application rate of 35.21 mg $CaCO_3$ g $soil^{-1}$, soil pH increased from 4.2 to 6.64 and microbial activity increased simultaneously (Badalucco *et al.* 1992). In acid soils, soil respiration from combination of lime and litter application was much more than that from either lime or litter application alone during 17 weeks of incubation (Condron *et al.* 1993). The rise in pH of an acid soil due to liming increases carbon mineralization by microbial activity (Karcauskiene *et al.* 2015).

2.4 Roles of $CaCO_3$ application on soil pH

Low pH is a yield-limiting factor in acid soils. Lime is one of the most effective measures to increase soil pH to levels that are desirable for crop production. When $CaCO_3$ is applied to low pH soils, reaction between $CaCO_3$ and H^+ occurs and simplifies as following equation:

$$CaCO_3 + 2H^+ \rightleftarrows Ca^{2+} + H_2O + CO_2 \quad [2]$$

In this reaction, consumption of H^+ concentration in the low pH soils increases soil pH. Positive effects of lime on soil pH alleviation have been indicated. In a slightly acid soil, pH increased from 5.1 to 5.6, 5.9, 6.4 and 6.8, which corresponded to $CaCO_3$ application rates of 0.75, 1.5, 3.0 and 4.0 g $CaCO_3$ kg soil^{-1} (Whalen *et al.* 2002). When $CaCO_3$ application rates increased from 4.0 to 10.13 g $CaCO_3$ kg soil^{-1}, pH of an acid sulfate soil increased to be 4.51 and 6.10, respectively, from the original value of 3.19 (Khoi *et al.* 2010).

2.5 Roles of organic matter on soil pH

Compost has been used to improve soil pH. Whalen *et al.* (2002) reported that pH of an acid soil increased from 5.1 to 6.2 with the application of 40 g compost kg soil^{-1}. In an acid sulfate soil, pH rose from 3.19 to 4.16 with 62.5 g compost kg soil^{-1} application. The pH of acid sulfate soil increased to be 6.42 when 62.5 g compost kg soil^{-1} and 10.13 g $CaCO_3$ kg soil^{-1} were applied together to the soil (Khoi *et al.* 2010). The rise in soil pH caused by applying the compost could be due to the complexes of Al-organic matter (Naramabuye and Haynes, 2006, Hue and Amien, 1989). Moreover, proton (H^+) consumption in the processes of decarboxylation of organic anions may be a cause if pH rise (Yan *et al.* 1996). The pH rise may be due to alkali minerals contained in the compost.

2.6 Saline sodic soil

2.6.1 Definitions

Salt affected soils are soils containing excessive amounts of soluble salts high enough to impair soil productivity (Rengasamy, 2006; Yan *et al*. 2015). In this soil, the components of soluble salts commonly consist of sodium chloride (NaCl), sodium sulfate (Na_2SO_4), magnesium sulfate ($MgSO_4$), sodium bicarbonate ($NaHCO_3$), sodium carbonate (Na_2CO_3), calcium sulfate ($CaSO_4$), calcium carbonate ($CaCO_3$), magnesium chloride ($MgCl_2$) and potassium chloride (KCl) (Kovda *et al.* 1973; Brady and Weil, 2008; De Souza Silva and Fay, 2012). Soil classification system for salt affected soils is based on the standard of United State of Department of Agriculture (USDA) (Table 2.1). Exchangeable sodium percentage (ESP), and electrical conductivity (EC_e) are used as an indicator for estimating the influence of sodicity and salinity in soil solution. Saline sodic soils are classified based on electrical conductivity of saturation extract (EC_e) > 4 dS cm^{-1}, soil pH < 8.5, ESP > 15% (Table 2.1) (Unites States Salinity Laboratory Staff, 1954). Saline and sodic soils having high levels of both sodicity and salinity may affect soil productivity.

Table 2.1 Salt-affected soils are classified based on standard of USDA (Soil Survey Staff, 1998)

Soil classification	EC_e (dS m^{-1})	pH	SAR	ESP
Alkali soil	<4	>8.5	<13	>15
Saline soil	>4	<8.5	<13	<15
Saline-alkali soil	>4	<8.5	<13	>15
Saline-sodic soil	>4	<8.5	>13	>15
Sodic soil	<4	>8.5	>13	>15

2.6.2 The distribution of salt affected soil in the world

Salt affected soils are widely distributed in the arid and semiarid regions. According to Szabolcs (1979), about 952 million ha are salt affected soils. They are widely distributed in all the continents on over the world including Mexico and Central America (1,965 thousand ha); North America (15,755 thousand ha), South America (129,163 thousand ha), Africa (80,538 thousand ha), South Asia (84,838 thousand ha), Northern and Central Asia (211,686 thousand ha), South-east Asia (19,983 thousand ha), Australasia (357,330 thousand ha), Europe (50,804 thousand ha). Mekong delta of Viet Nam is constituted by multi-channel estuaries. Moreover, this region is surrounded by the east-sea and west-sea sea which is favourable for seawater intrusion into groundwater. Therefore, salt affected soils are commonly found along the coast belonging to Mekong delta region (Nguyen and Savenije, 2006).

2.6.3 Properties of saline sodic soil

The saline sodic soil has weak structural stability. Clay dispersion increases with increasing ESP (Abu-sharar *et al.* 1987). Clay disperses by the expansion of the diffuse double layer around the clay particles (Shainberg and Letey, 1984, Abu-Sharar *et al*. 1987). Clay dispersion is a dominant cause of aggregate breakdown of saline and sodic soil. Dispersed clay plugs soil pores and reduces soil hydraulic conductivity (Frenkel *et al.* 1978; Farahani *et al.* 2018). Ghadiri *et al.* (2004) reported that lower aggregate stability of saline and sodic soil, which corresponds to lower MWD value, and lower percentage of fragments larger than 2 mm causes soil loss by runoff and soil erosion.

The salinity and sodicity of soil affect adversely plant growth (Bernstein, 1975). Saline sodic soil is classified with high salinity and sodicity, where the soil contains much soluble salt and predominant soluble sodium. The yield of sensitive crops is restricted at the threshold of salinity of higher 4 dS m^{-1} in soil saturation extract and threshold of sodicity of exchangeable sodium percentage of more than 15% in the soils occupied by sodium (Unites States Salinity Laboratory Staff, 1954).

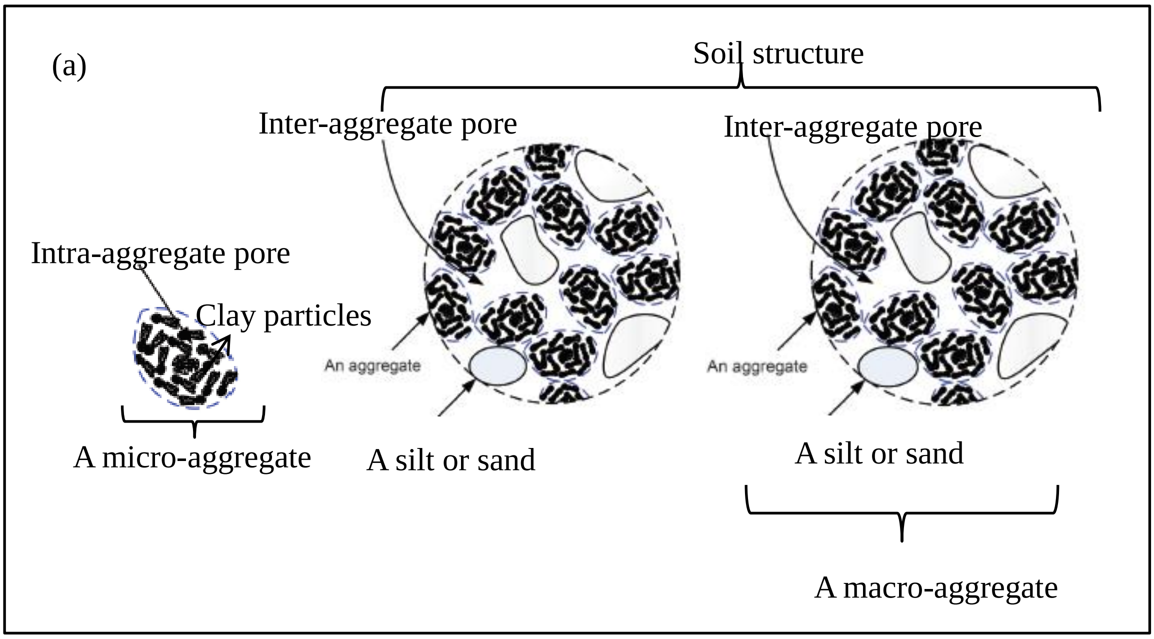
2.7 Effects of salinity and sodicity on microbial activity

Micro-organisms play important roles in decomposition of organic matter, mineralization of nutrients and stabilization of soil aggregates. Micro-organisms are considered as an indicator of soil fertility because decomposition of organic matter by microbials releases nutrients and organic components into the soil. However, microbial growth in the soil depends on environmental conditions. Saline and sodic soil is a stressful environment for soil microorganisms (Wong *et al.* 2008, Bing-Cheng *et al.* 2007). Higher salinity could inhibit the activity of micro-organisms (Shah and Shah, 2011). More CO_2 emission rate at EC < 4 dS m^{-1} than at EC >12 dS m^{-1} indicated that soil microbes worked more in lower salinity (Shah and Shah, 2011). Many other previous researches showed the effects of salinity on microbial activity (Mavi and Marschner, 2013; Wichern *et al.* 2006). Yuan et al. (2007) reported that microbial community was more stressed in the soil with higher salinity (EC = 23.05 dS m^{-1}) than lower salinity (EC = 0.32 dS m^{-1}). Wong *et al.* (2008) also reported the effects of salinity and sodicity on soil respiration rate. The results showed that soil respiration rate was lower at EC 10 dS m^{-1} SAR 30 than at EC 0.5 dS m^{-1} SAR 30. At EC 10 SAR 30, soil respiration rate was lower than at EC 10 SAR 1. Chowdhury (2016) observed that rice straw application to the soil with high salinity after 30 days increased microbial activity, which was expressed by the rise in soil respiration rate. The microbial activity increased as rice straw application rates increased as order of 0.5%, 1.0%, 1.5%, and 2.0% (Chowdhury, 2016).

2.8 Definitions of soil aggregates

Soil structure is defined as the arrangement of primary particles and secondary aggregates (Baver, 1934). According to Dexter (1988), “soil structure is defined as the spatial heterogeneity of the different components or properties of soils”. Soil aggregates are secondary structural units that are formed naturally from primary soil particles of sand, silt and clay. They are held together by inorganic cementing agents and organic compounds to form aggregates. Clods are formed by artificial means like digging, ploughing or cutting (Nimmo, 2004). Different sizes of clods are often produced during tillage operation before planting in the agricultural field.

According to Baver (1934), the composition of soil structure includes primary particles and secondary aggregate units. The aggregates in the field have irregular sizes and shapes. Macro-aggregates are composed of micro-aggregates, sand and silt, where micro-aggregates are consisted of clay particles (Figure 2.1a) (Wang and Wei, 2015). Structure of micro-aggregates was modelled by Masin and Khalili (2016) (Figure 2.1b). Clay particles consisting of clay layers tend to approach each other to become a cluster of micro-aggregate. When soils get wet or dry, the structure of aggregates may change. Clay particles can swell when wet or shrink when dry. In the field, the changes in soil structure or soil aggregates are caused by many factors related to natural phenomenon or human impacts.



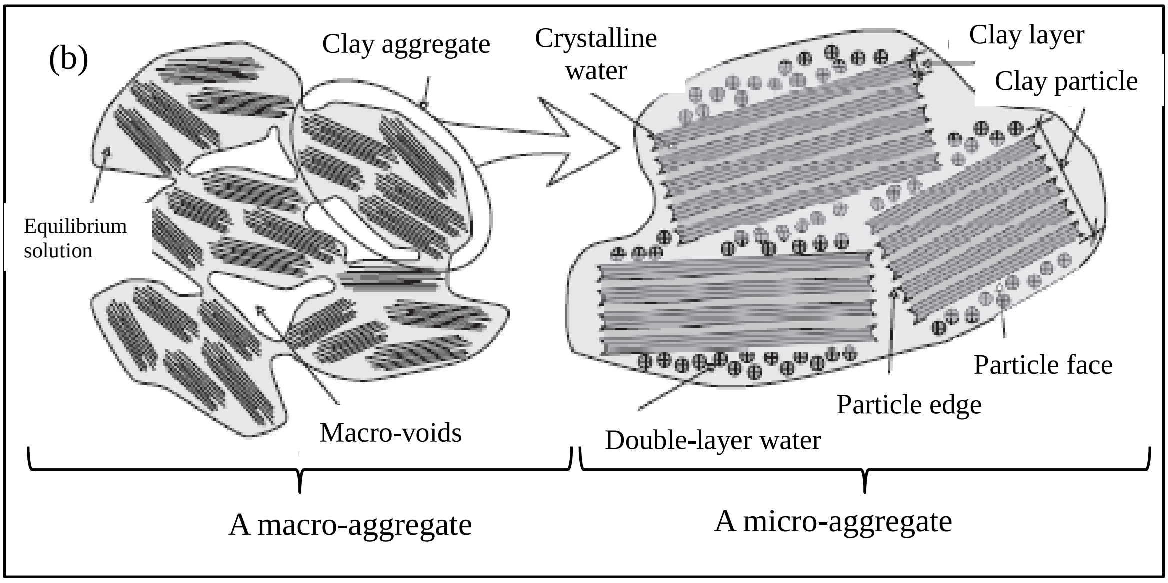


Figure 2.1 Soil structure (Wang and Wei, 2015) (a); the structure of aggregates (Masin and Khalili, 2016) (b)

2.9 Effects of dispersion and flocculation on soil aggregates

Dispersion can cause aggregate breakdown. It describes the behaviour of clay particles separating from one another. Negative charges on the clay surface attract positive charges of cations. If sodium is the dominant cation in the soil, it may attach on the clay surface. When the soil contacts with water, sodium is hydrated. The layer of positive charges gets wider until clay particles begin to repel one another and disperse (Somasundaran, 1980; Rengasamy, 1983). Dispersed clays tend to clog soil pores and reduce macro-porosity. Structure may decline and soil erosion may occur.

Positive charges of divalent calcium can depress diffuse double layers (Rimmeri and Greenland, 1976; Rengasamy, 1983). The thinner layer means the attractive forces dominate repulsive forces. Clay particles tend to gather together and flocculate. Flocculated clays encourage soil particles to aggregate. Flocculation is important because it provides more space in larger pores between aggregates for water and air movement.

2.10 Definitions of soil aggregate stability

Soil aggregate stability is the ability of soil aggregates to resist disintegration caused by disruptive forces (Saygin *et al.* 2012). The disruptive forces include slaking, clay swelling and dispersion and mechanical actions. They could be simulated in the laboratory as fast wetting, slow wetting and mechanical breakdown (Le Bissonnais, 1996). Stable aggregates refer to strong binding of primary particles in aggregates to be resistant to swelling, dispersion, slaking, and mechanical actions. Therefore, applying fast wetting, slow wetting and mechanical breakdown to the aggregates in the evaluation of aggregate stability is to measure the ability of aggregates to resist these forces. If aggregates are stable, they would be less disintegration by disruptive forces. In contrast, weak aggregates are easily broken down into smaller fragments (Nimmo and Perkins, 2002).

2.11 Roles of aggregate stability in agricultural production

Aggregate stability, an indicator of soil structural stability, is a crucial physical parameter of soil heath as well as soil productivity because of its influence on the transport of fluids, soil colloids, solutes, soil heat, root growth and microbial respiration (Nimmo, 2004). Stable aggregates offer proper medium for nutrient cycles, water and gas movement, seedling emergence and respiration of plant root in the soils. Bejat *et al.* (2000) reported that solute transport was influenced by pore size distribution of soil structure in unsaturated soils. The growth of plant root and the speed of seed germination and emergence are affected by aggregate stability, which could make it possible for water and oxygen penetration through pores (Dexter, 1988; Nasr and Selles, 1995). Aggregate stability is used to predict soil erosion, runoff (Le Bissonnais and Arrouyas, 1997; Barthes and Roose, 2002; Nimmo, 2004), infiltration, soil aeration and surface sealing (Nimmo, 2004). Closely negative relationship between aggregate stability and soil erodibility indicated that aggregate breakdown increased soil erosion (Barthes and Roose, 2002). Fine fragments from aggregate breakdown process could form surface sealing and lead to runoff (Lado *et al*. 2004). Aggregate breakdown and subsequent surface sealing formation accompanied with clogging pores depress seedling emergence (Rathore *et al*. 1983).

Owing to its importance, aggregate stability should be paid attention. Once aggregate degradation occurs, it would cause serious consequences to soil productivity. It is undeniable that aggregate stability is different from place to place according to soil types and weather conditions. In the tropical areas, especially the Mekong delta region, aggregate stability of low pH soils is less concerned.

2.12 Factors affecting aggregate stability

Soil aggregate stability is influenced by many factors: fast wetting, slow wetting and mechanical breakdown (Le Bissonnais, 1996). The fast wetting refers to the case when boarder and furrow irrigation is applied on the soil surface. In this case, air in soil is entrapped by water. It corresponded to the fast wetting test in this experiment, where clods were submerged abruptly in water. Slaking is dominant mechanism in fast wetting process. During this process, aggregates are submerged abruptly in water. At that time, aggregates are surrounded by water and the air inside aggregates is entrapped. As a result, rapid evolution of entrapped air pressure is great enough to disrupt aggregates. The aggregate breakdown occurs few seconds after rapid immersion of aggregates in water, which was modelled by Zaher *et al.* (2005). The quicker the aggregates are wetted, the greater the aggregates slake because of the rapid pressure building up in aggregates (Emerson and Greenland, 1990). According to Lado *et al.* (2004), fast wetting by abrupt immersion in water increased aggregate breakdown and sealing formation than slow wetting by mist application 1 mm h^{-1}. The slaking of aggregates decreases with increasing organic carbon (Chan and Mullins, 1994). Organic matter plays role as a barrier to slow rate of water entry and thus reduce the evolution of pressure of entrapped air in fast wetting process (Zaher and Caron, 2008).

Slow wetting may cause micro-cracking of aggregates (Le Bissonnais, 1996). It refers to the cases when water supplies slowly on the soil surface such as rainfall or irrigation sprayers or mist. In that case, no slaking by entrapped air occurs (Lado *et al.* 2004). In the experiment, slow wetting was simulated by wetting under the negative water pressure. Soils were wetted slowly by water upward movement due to capillary forces. Differential swelling and physico-chemical dispersion are considered as dominant cause of aggregate breakdown during slow wetting process (Le Bissonnais, 1996). Swelling is natural phenomenon of expansive clay. It is the ability of the soils to expand volume with free access of water (Basma *et al.*, 1996). Clay particles swell when wet and shrink when dry during wetting and drying processes. The consequences of differential swelling and shrinkage may cause micro-cracking of aggregates. Physico-chemical dispersion is a breakdown process of aggregates into primary particles. The clay swelling and dispersion causing subsequent disaggregation is promoted by low electric conductivity and high exchangeable sodium percentage (ESP) (Shainberg and Letey, 1984; Abu-sharar *et al.* 1987). In sodic soil, sodium is a dominant cause of clay swelling and dispersion (Chorom *et al.* 1994). The expansion of thickness of diffuse double layer is main driving forces which cause clay to swell. The greater repulsive forces between adjacent clay platelets than attraction forces causes soil dispersion (Czyz and Dexter, 2015). Rengasamy *et al.* (1984) reported that 20% of soil samples were dispersed at SAR above 3. It shows that soil dispersion increases with increasing sodium ion contents. Negative correlation between aggregate stability and sodium content was observed by Aziz and Karim (2016). In addition, clay dispersion can be influenced by soil pH. The rise in pH may increase negative charges on the surface of clay particles promoting repulsive forces (Zhou and Yu, 2016; Chorom *et al.* 1994).

Mechanical breakdown refers to the breakdown of aggregates caused by mechanical actions raindrop impact (Le Bissonnais, 1996). Mechanical breakdown models depositional sediments by turbulent water. Mechanical breakdown is highly influenced by the mechanical strength of the aggregates. However, the strength of aggregates depends on many factors such as water content, organic matter content, aggregate size (Causarano, 1993). The aggregate breakdown process was simulated in laboratory. The soils were applied by ethanol before mechanical breakdown treatment in order to exclude slaking, clay swelling and dispersion. Then, water was applied to them as mechanical forces.

Aggregate stability is influenced by initial clod sizes. As Farres (1978) and Kemper and Rosenau (1984) discussed smaller aggregates suffered to disintegration under rainfall events. This result was similar with Legout *et al.* (2005) who showed the most deterioration of aggregates in the initially 1-3 size clods. Aggregate stability increased as initial clod sizes increased in order of < 3 mm < 3-5 mm < 5-10 mm < 10-20 mm (Legout *et al.* 2005).

Effects of initial soil moisture on aggregate stability have been discussed earlier. The lower aggregate stability was for air-dry aggregates being immersed abruptly in water (Panabokke and Quirk, 1957). Aggregate stability increased as initial water content of aggregates prior to the immersion increased (Kemper and Rosenau, 1984). For the same aggregate size of 2-4.75 mm, initially moist aggregates were more stable than initially dry aggregates under fast wetting (Almajmaie *et al*. 2017b). It may be interpreted that smaller volume of entrapped air inside the initially moist aggregates could cause lower compression forces under fast wetting process than the initially drier aggregates (Kemper and Rosenau, 1984; Vermang *et al.* 2009).

It is highlighted that the need for evaluation of aggregate stability is prevalent slaking forces, the clay swelling and dispersion, and mechanical actions which corresponded to breakdown processes: fast wetting, slow wetting and mechanical breakdown. Slaking is dominant for fast wetting. Slow wetting is dominated by differential swelling and physico-chemical dispersion. Mechanical actions are simulated by mechanical breakdown test. The three breakdown processes would be applied to ascertain aggregate stability.

2.13 Effects of $CaCO_3$ application on soil structure

Lime application shows negative effects on soil structure. Lime caused an increase in clay dispersion, and a decrease in infiltration rate after 6 weeks from lime application to a Brazilian Oxisols (Roth and Pavan, 1991). This was because lime application increased pH, and it could increase clay dispersion. In this mechanism, as pH increases, the surface negative charge on clay colloids increases. This was demonstrated by Chorom *et al.* (1994) that net negative charge of soil increased as soil pH increased. Positively linear regressions between dispersible clay and pH of Oxisols showed that the rise in pH of Oxisols increased clay dispersion (Chorom *et al.* 1994). The consequence of clay dispersion was the reduction in stability of the aggregates of Brazilian Oxisols (Castro and Logan, 1991). Soil structure degradation is promoted by adding higher dose of lime to the Oxisols. By adding higher dose of lime to the Oxisols, the more increase in pH and electronegativity of soil could promote clay dispersion (Nunes *et al.* 2018).

2.14 Effects of organic matter on aggregate stability

Beneficial influences of compost application on soil fertility (Dikinya and Mufwanzala, 2010), soil pH (Whalen *et al.* 2002), and aggregate stability (Wortmann and Shapiro, 2008) have been reported. Building up soil organic matter in the soil may enhance soil aggregation (Wagner *et al.* 2007). Compost application could improve the structure of sodic soil. Positive effects of organic matter on aggregate stability of sodic soil have been discussed by Quirk and Murray (1991), and by Nelson and Oades (1998). Organic compounds produced from decomposition of organic matter by microbial activity may reduce clay dispersion of sodic soil (Nelson *et al.* 1998). Important roles of organic binding agents in the bridges of clay-polyvalent cations-organic matter or clay-organic matter to stabilize aggregates against slaking and clay dispersion have been shown earlier (Tisdall and Oades, 1982; Nelson and Oades, 1998). Tisdall and Oades (1982) reported that organic binding agents including transient (mainly polysaccharides), temporary (root and fungal hyphae), and persistent (aromatic components associated with polyvalent metal cations and polymer) could accelerate soil aggregation (Figure 2.2). Bonds between clay particles and polysaccharide chain in soil aggregation were modelled by Tisdall and Oades (1982) (Figure 2.2a). Bridges between organic matter-polyvalent metal cations-clay particles are a main mechanism of aggregate formation (Figure 2.2b) (Tisdall and Oades, 1982). Polyvalent metal cations could be aluminium, iron, or/and calcium which have positive trivalent or divalent charges. They could bridge with negative charges of clay particles and organic matter to form complexes of organic matter-polyvalent metal cations-clay particles through cation bridges (Oades, 1984). The aggregate cohesion is enhanced by the formation of multi-complexes of (clay-polyvalent cations-organic matter)$_x$ as linked chains in structure of aggregates (Figure 2.3) (Muneer and Oades, 1989).

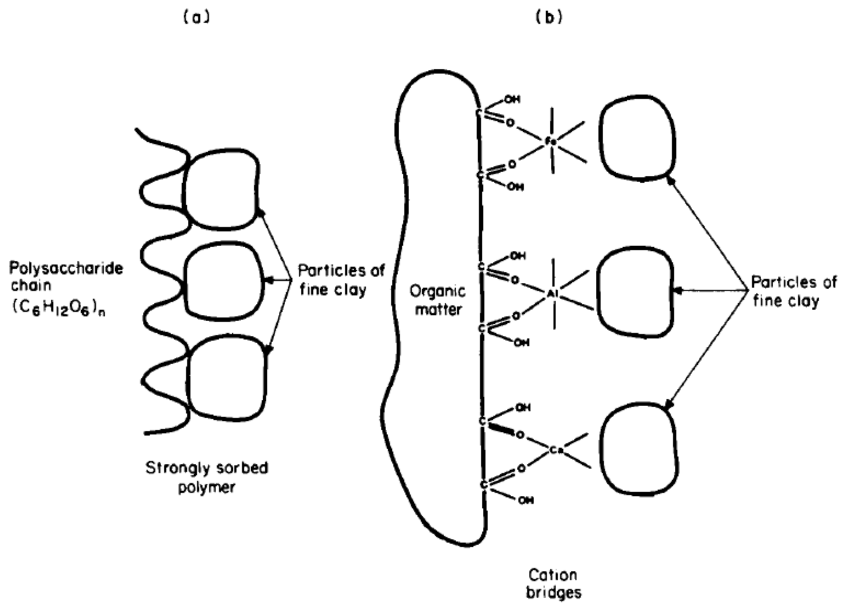


Figure 2.2 Interaction of organic binding agents and clay particles (a) and organic binding agents-polyvalent metal cations-clay particles (b) (Tisdall and Oades, 1982)

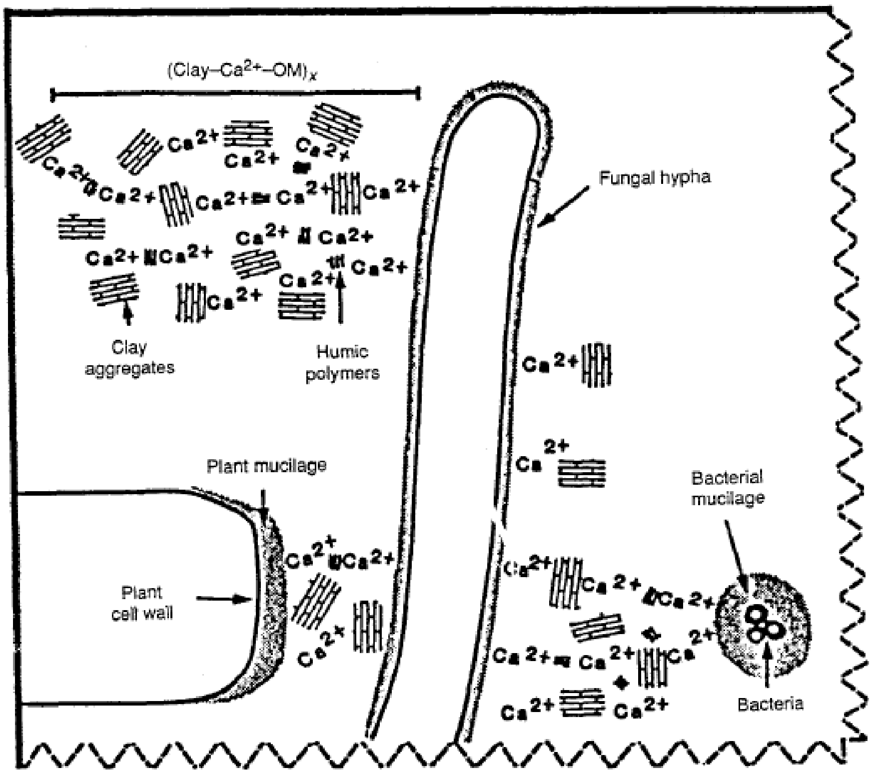


Figure 2.3 Model of soil aggregation (Muneer and Oades, 1989)

Relationship between aggregate stability and soil properties has been reported. Almajmaie *et al.* (2017b) also found negative relationship between aggregate stability and monovalent cations like Na^{+}, where monovalent cations could promote clay dispersion. Chaganti *et al.* (2015) reported that aggregate stability of saline-sodic soil was improved by adding 75 t compost ha^{-1} to the saline-sodic soil. A similar result showed the increase in aggregate stability of saline-sodic soil after 90 and 180 days from organic matter application at 3% of soil weight (Wahid *et al.* 1998). Polyvalent cations like Fe^{3+} and Al^{3+} in soils could act as bridging agents in complexes of clay-polyvalent cations-organic matter-polyvalent cations-clay to accelerate aggregate stability (Igwe *et al.* 2009). Incorporation of polyvalent cations like Ca^{2+} and organic matter together intensified aggregate stability and promoted hydraulic conductivity in soils (Wuddivira and Camps-Roach, 2007).

2.15 Roles of microbial activity on soil aggregate stability

Beneficial effects of organic amendments on aggregate stability are supported by participation of micro-organisms in the decomposition of organic matter (Griffiths and Jones, 1965). The increase in microbial activity increases decomposition of organic matter and leads to production of organic components. Carbohydrates, protein and polysaccharides produced from the decomposition of organic residues by microbial activity may act as binding agents in enhancing aggregate stability against slaking mechanisms from fast wetting (Carrizo *et al.* 2015). The result of Manjoka *et al*. (2007) showed that the rise in microbial activity accelerated decomposition of soil organic matter and production of organic binding agents during one year after applying 1.5 t lime ha^{-1} to the Oxisol. Organic binding agents produced from organic matter decompostion could increase aggregate cohesion. As a result, aggregate stability shown by mean weight diameter (MWD) increased (Manjoka *et al*. 2007). It was suggested the contribution of calcium carbonate to enhance pH of the Oxisol creating suitable environment for microbial activity in organic matter decompostion. However, the rise in pH of acid soil in response to liming increased carbon mineralization from microbial activity and reduced aggregate in long term (Karcauskiene *et al.* 2015).

2.16 Wastes of chicken manure and eggshell

Shells of chicken egg can be used an alternative source of lime because eggshell is rich in $CaCO_3$. The $CaCO_3$ occupies 96-97% of eggshell (Intharapat *et al.* 2013; Beck *et al.* 2010 and Hincke *et al*. 2012). Chicken manure is rich in organic carbon, which accounts for 35.46% of chicken manure (Aboutayeb *et al.* 2014). In addition, NO_3^- (964,32 ppm), NH_4^+ (6373,25 ppm), phosphorus (6581,25 ppm), and potassium (1419,17 ppm) in chicken manure are nutrients useful for plant growth (Aboutayeb *et al.* 2014). Therefore, chicken manure can be used as an organic source to improve soil fertility and productivity (Dikinya and Mufwanzala, 2010).

Wastes of chiken manure and eggshell are common in the Mekong delta of Viet Nam. In this region, the number of poultry was approximately 61.3 million heads in 2012 (General statistic office of Viet Nam, 2012). Of which, the number of chicken was 19.8 million heads in 2006 in this region (Desvaux *et al.* 2008). Chicken broiler farms with herd size of 2.000 – 11.000 heads are common, which accounted for 93.5 % (Desvaux *et al.* 2008). The others are chicken layers and chicken breeders. The feed sources for chicken production are rice bran, maize, or cassava. In addition, the industrial feeds like pelleted food are also supplemented. For eggshell production and consumption in 2012, the poultry egg production was about 7.3 billion pieces and egg consumption was 82.2 eggs per capita (General statistic office of Viet Nam, 2012).

Eggshell occupies approximately 11% of the total egg weight (Stadelman, 2000). If each egg weighs 60 g, weight of eggshell was estimated at about 48,180 tons in 2012.

Solving major problems related to management and disposal of wastes from chicken production is highly necessary because wastes are a source of air pollution caused by odour and threat to a quifers and surface water. Integrated agriculture – aquacuture system is the close system in sustainable agricultural practices. This system consisting of gardening, fish raising and poultry raising integration is developing in Mekong Delta of Viet Nam because it offers many benefits for society, economy and environment (Phong *et al.* 2007). In integrated system, all agricultural wastes are reused, where chicken manure and eggshell are included (Nhan *et al.* 2005).

2.17 Conclusions

Soil productivity refers to the ability of a soil to support the growth of plants. Soil pH, soil organic matter, microbial activity and aggregate stability are important indicators for soil productivity measurement. However, aggregate stability, one of important parameters, is less concerned for Mekong soils, especially saline sodic soil and acid sulfate soil. Aggregate degradation may cause many subsequent consequences: soil surface sealing, soil erosion and runoff. This leads to the loss in nutrient, and reduction in hydraulic conductivity that may seriously affect the plant growth.

Because of its importance, evaluating aggregate stability should be conducted. Prior to applying some proper measures to improve aggregate stability, it is necessary to evaluate aggregate stability in different conditions: initial soil moisture, clod sizes and breakdown processes: fast wetting, slow wetting and mechanical actions. These conditions occur commonly in the field and are considered as factors affecting aggregate stability. Stable aggregates could resist these factors and maintain stable. In contrast, unstable aggregates would be broken down. The first result would answer the questions of how aggregate behaviours under different conditions among the studied soils.

After knowing key factors of the severity of aggregate disintegration, they could be employed for evaluating aggregate stability of the soils after the incubation following to the application of eggshell and chicken manure. Aggregate stability would be evaluated during incubation periods to know its changes as the function of time. Simultaneously, soil pH, CO_2 emission and soil organic carbon were observed to discuss the effects of these parameters associated with aggregate stability.

Chapter 3 - Field survey of soil properties in Mekong delta of Viet Nam

This chapter presents major characteristics of soils on the surface and along the depths. Soil samplings were carried out in three locations of the Mekong delta of Viet Nam, namely Can Tho city, Hau Giang province and Ca Mau province. Morphological characteristics of soil profiles in the field were described in this chapter.

3.1 Introduction

Sampling sites in the Mekong delta are shown in Figure 3.1. Can Tho is regarded as a city centre of the Mekong delta. It has a total land area of 140.9 thousand ha, in which 113.4 thousand ha (80.5% of total area) is used for agriculture (General statistic office of Viet Nam, 2015). Hau Giang province has 160.2 thousand ha, in which 133.8 thousand ha (83.5% of total area) is used for agriculture (General statistic office of Viet Nam, 2015). The total area of Ca Mau is 527.5 thousand ha, in which 147.9 thousand ha (28% of total area) is used for agriculture (General statistic office of Viet Nam, 2015).

Name of the soil main groups was determined based on diagnostic horizons, properties and materials of soil profiles. It referred to the soil map inventory of the Mekong Delta following the World Reference Base for Soil Resources – Food Agriculture Organization of the United Nations at scale 1/250.000 (Minh and Tri, 2006) and World Reference Base for soil resources classification systems (ISSS/ISRIC/FAO, 1998). The diagnostic characteristics and materials of soil morphology in each soil horizon were determined in the field. Soil chemical and physical properties were determined in the laboratory. Details of soil characteristics were described as followings.

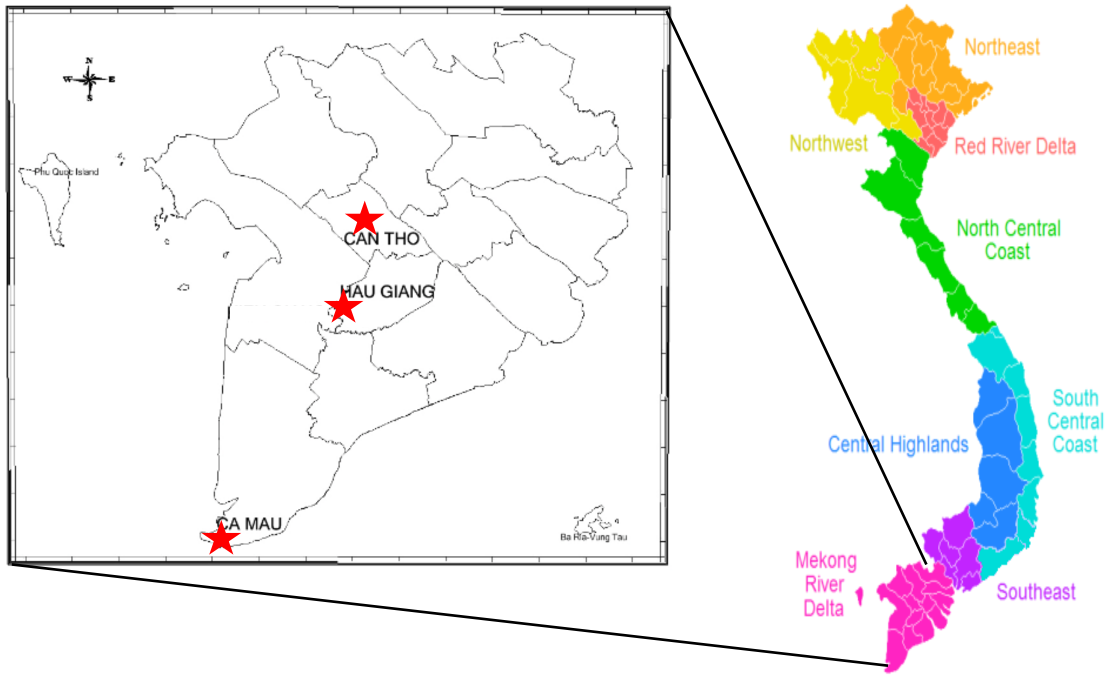


Figure 3.1 Soil sampling sites

3.2 Soil profile

3.2.1 Tools for soil profile description

Morphological properties of soils were determined in the field. The implements include an auger, a Munsell colour chart, a knife, a shovel, pH indicator papers, a ruler, soil sample rings, plastic-bags. An auger was used to dig soil profile within the 2 m depth. Different layers were defined based on soil colour, where Munsell colour chart was used. Soil pH was described using pH indicator paper. Field soil moisture and soil texture were examined by hand. Approximately 200 g samples in each soil horizon were collected and carried to the laboratory for further chemical analysis. Soil surface samples in three sites were collected at the depth of 0-20 cm to analyse soil physical properties and further experiment.

3.2.2 Soil profile description

Location 1: **Can Tho city**

Soil name: Alluvial soil (AL) (Epigleyic Fluvisols: FLglp)

Coordinates: 10°06’48.8” N; 105°30’39.5” E

Land form: Plain

Land use: Zucchini

Cultivation model: Monoculture

Table 3.1 Soil profile description in Can Tho soil (Alluvial soil)

Soil profile	Soil layers	Soil description
	0 – 117 cm	Dark grey colour (7.5 YR 3/1), clay with sticky and plasticity, moist, fresh root of plant, soil matrix with poorly incomplete organic matter, iron mottles (10 YR 4/6) of 7% with root hole shape and pH_{H2O} 7.  
	117 – 134 cm	Bright grey colour (2.5 Y 4/1), clay with sticky and plasticity, moist, less plant root, poorly complete organic matter, iron mottles (7.5 YR 3/4) of 7% with root hole shape and pH_{H2O} 7. 

	134 – 175 cm	Green grey colour (7.5 Y 5/1), clay with sticky and plasticity, wet, no plant root, no organic matter, soil matrix with iron mottles (40 – 50%) with brick colour (5 YR 4/4) and root hole shape, and pH_{H2O} 7.  

The characteristics of soil profiles in Can Tho soil were described in the field (Table 3.1). Soil was defined as alluvial soil. According to local farmers, monoculture model has been performed continuously for seven years, where Luffa Gourd has been grown. The intensive farming model of three monocrops per year with chemical fertilizers has been conducted. The investment capital for pesticides and chemical fertilizer increased recent years, while the yield decreased.

As surveyed in this area, hard soil layers appeared throughout soil profiles. Soils were surrounded by water from channels connected with the river. Furrow irrigation made water table fluctuate. During planting stage, the highest level of the water table was 15 cm from the surface. After 3 days, water table was retreated down 30 cm from the surface (according to local farmers). Then, water was allowed to move up to 15 cm from the surface. Farmers let water table move up and retreat down every 3 day interval. Grey colour on soil matrix appeared throughout the soil horizons. Grey colour represents predominant of Fe^{2+} and Mn^{2+} in anaerobic condition (ISSS/ISRIC/FAO, 1998). As a result, iron mottles appeared along the root hole with 7% in the two first layers and 40-50% for the last layer. The proportion of iron mottles was estimated using charts for estimating proportion of mottles in Munsell colour chart book (Figure 3.2)

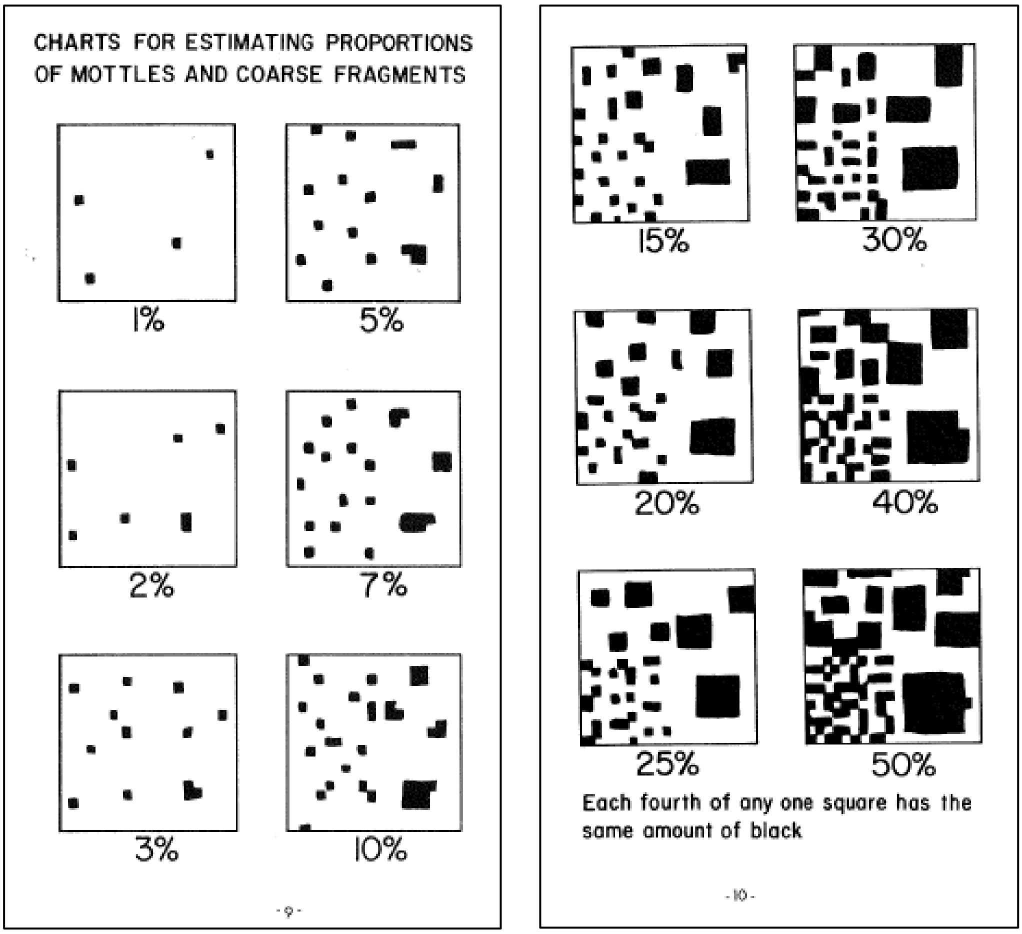


Figure 3.2. Charts for estimating proportion of mottles (Macbeth Division of Kollmorgen Instruments Corporation, 1994)

Location 2:	**Hau Giang province**
Soil name:	Acid sulphate soil (AS) (EpiOrthiThionic Fluvisols: FLtiop)
Coordinates:	09^{o}43’20.3” N; 105^{o}22’46.8” E
Land form:	Plain
Land use:	Pineapple
Cultivation model:	Monoculture

Table 3.2 Soil profile description in Hau Giang soil (acid sulfate soil)

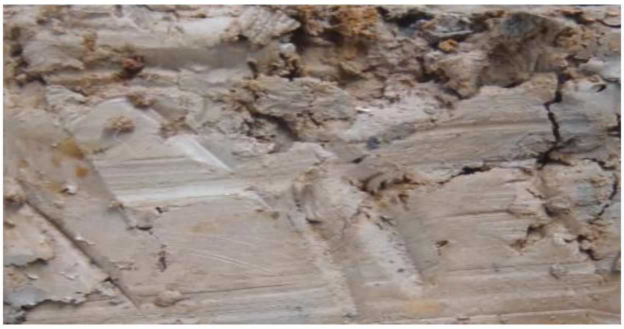
Soil profile	Soil layers	Soil description
	0 – 63 cm	Dark brown colour (10 YR 2/3), clay and silt, moist, much plant root, rich incomplete decomposed organic matter, jarosite mottles (5-7%) with cluster shape, straw yellow colour of jarosite (10 YR 7/8) and pH_{H2O} 3.
	63 – 83 cm	Black brown colour (10 YR 7/1), silt and clay, wet, much plant root, rich organic matter with incomplete decomposition, jarosite mottles (40%) with cluster shape and straw yellow colour of jarosite (2.5 Y 6/8) and pH_{H2O} 3. 

	83 – 90 cm	Brown colour (7.5 YR 3/4), silt and clay, wet, average plant roots, rich organic matter with incomplete decomposition and pH_{H2O} 4.
	90 – 97 cm	Dark brown colour (10 YR 3/2), clay, wet, much plant root, rich organic matter with incomplete decomposition and pH_{H2O} 4.
	97 – 165 cm	Grey brown colour (2.5 Y 3/2), clay, wet, average plant root, organic matter with incomplete decomposition and pH_{H2O} 4.  

The properties of soil in Hau Giang soil were described in the field (Table 3.2). Soil was defined as an acid sulfate soil. Jarosite mottles with straw yellow appear within 100 cm from the surface. The chemical formula of jarosite is $KFe_3(SO_4)_2(OH)_6$ (Tho and Egashira, 1976). The jarosite formation is a result of oxidation of pyrite (FeS_2). When oxygen enters into the soil, pyrite is oxidized. The end product of this process is sulfuric acid (H_2SO_4) which is a main cause of low pH. The soil pH measured by pH indicator paper was extremely low, 3 within 100 cm depth and 4 in deeper layers. Much organic matter with incomplete decomposition was accumulated in the acid sulfate soil because low pH may inhibit microorganisms to decompose organic matter (Rousk *et al.* 2009). Plant residues and roots remained there. This is because less micro-organism adapts this environment (low pH soil) and thus less decomposition occurs. This soil was used for monoculture with pineapple crop. The pineapple had been grown during 50 years. Because the pineapple is low pH- tolerant plant, they can adapt to grow in low pH soil. Other than pineapple, most crops could not grow to bring income for the farmers. Water-table was fluctuated by furrow irrigation. According to local farmers, they kept water table ranging from 10 cm to 20 cm from soil surface during planting stage. Water was derived from rainfall and from channels connected with the river.

Location 3:	**Ca Mau province**
Soil name:	Saline sodic soil (SS) (Episalic Solonchaks: SCszp)
Coordinates:	08^{O}34’40.5’’ N; 104^{O}49’10.8’’ E
Land form:	Plain
Land use:	Mangroves and other salt-tolerant trees
Cultivation model:	No crop

Table 3.3 Soil profile description in Ca Mau soil (saline sodic soil)

Soil profile	**Soil layers**	**Soil description**
	0 – 35 cm	Brown colour (7.5 YR 4/3), clay, moist, no plant root and poor organic matter or partly limited position with incomplete decomposition and pH_{H2O} 7. 
	35– 46 cm	Greenish brown colour (10 YR 4/2), clay, moist, much plant root and average incomplete decomposed organic matter, iron-mottle (10%) (7.5 YR 3/4) with root hole shape and pH_{H2O} 7. 

	46– 55 cm	Black green colour (N 2/0), clay, wet, rich plant root, rich organic matter with incomplete decomposition and pH_{H_2O} 7. 
	55–103cm	Greenish grey colour (10 YR 3/2), clay, moist, much plant root, organic matter with incomplete decomposition and pH_{H_2O} 7. 
	103–200 cm	Green colour (10 YR 4/1), clay with little silt, wet, much in plant root, rich in incomplete organic matter, iron mottle (40%) with cluster shape and brick colour (10 YR 4/4), and pH_{H_2O} 7. 

The properties of soil profiles in Ca Mau soil were described in the field (Table 3.3). Soil was defined as saline and sodic soil. This soil had high salinity and sodicity and pH less than 8.5. Salinity and sodicity were determined by EC_e and ESP. Details were represented in below. In the field, this sampling site was covered by seawater in historical period. Salinity of seawater is 20 per thousand. Soil may accumulate sodium, which is dominant in seawater. Because of high salinity and sodicity, no crop was planted. After 2 years accretion, the field is now not covered by sea water. The depth of 46 – 55 cm is a sign of soil accretion which is interface between old soil surface layer and new soil layer. This was clarified with accumulation of much organic matter from residues of salt-tolerant vegetation at the 46 – 55 cm depth. In the result of organic carbon analysis, organic carbon content showing later in Figure 3.9 was higher in this layer than the other layers. Saltwater surface area surrounding this site was used for aquatic agriculture such as shrimp and crab raise. Salt-tolerant trees like mangroves are suitable for their development in this area. Water table was 30 cm from the surface.

3.3 Soil properties as a function of depths

3.3.1 Analytic methods of soil properties

3.3.1.1 Soil pH

Soil $pH_{(H2O)}$ is an important indicator of hydrogen (H^+) ion concentration in soil solution. The pH expresses negative logarithmic of H^+ concentration. Soils which contained much hydrogen (H^+) have low pH.

$$pH = -\log [H^+] \quad [3]$$

Accurate 1 g air-dry soil passing 2 mm mesh sieve was added into a 50 ml centrifuge tube. Then, 5 ml distilled water was added and mixed well for 2 hours using shaking machine. The samples were centrifuged at 5600xg using centrifuge machine. The $pH_{(H2O)}$ was measured (McLean, 1982) using LAQUAtwin pH meter (Horiba, Japan).

3.3.1.2 Soil electrical conductivity (EC) (dS m^{-1})

Soil electrical conductivity (EC) is an important indicator of dissolved salts in soil solution. Dissolved salts in soil solution including soluble cations and soluble anions can dissolve in water. The high concentration of dissolved salts in soil solution shows high EC or high salinity.

Accurate 1 g air-dry soil passing 2mm mesh sieve was added into a 50 centrifuge tube. Then, 5 ml distilled water was added and mixed well for 2 hours using shaking machine. The samples were centrifuged at 5600xg using centrifuge machine. The soil EC was measured (Rhoades, 1996) using LAQUAtwin EC meter (Horiba, Japan). EC_e was determined by converting from $EC_{1:5}$ and water content at saturation extract.

3.3.1.3 Organic carbon (%) and total nitrogen (%)

Organic carbon (OC) and total nitrogen were determined by dry combustion method at 950 ^{o}C in a CN Element analyser (Vario EL cube, Elementar Analysensysteme GmbH, Germany).

3.3.1.4 Cation and anion contents (mmol$_c$/L)

Soluble Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-} and SO_4^{2-} were measured by extracts of soil / water ratio of 1: 5 using an ion chromatography. Accurate 1 g air-dry soil was added with 5 ml distilled water in a 50 ml centrifuge tube. The tubes were shaken for 30 minutes, centrifuged for 10 minutes at 5600xg and then filter the supernatant solution through 0.45 µm filter. Systems of ion chromatography consist of DGU20A, LC20A, LC20AD, SIL10Ai, SCL10A, CDD10A, CTO20A (Shimadzu corporation, Tokyo, Japan). The columns are composed of Shim-pack IC-A1 (dimensions: 100 mm x 4.6 mm i.d and particle size: 12.5 µm) (Shimadzu Corporation, Tokyo Japan) and Shim-pack IC-GA1 (10 mm x 4.6 mm i.d) (Shimadzu Corporation, Tokyo, Japan).

3.3.1.5 Exchangeable sodium percentage (ESP)(%)

Exchangeable sodium percentage (ESP) is used to estimate sodicity in soil solution. The ESP shows sodium concentration in soil solution. The ESP was determined from Gapon formula:

$$\text{ESR} = \frac{K_G}{\sqrt{1000}}\ \text{SAR} \qquad [4]$$

$$\text{ESP} = \frac{100 * ESR}{1 + ESR} \qquad [5]$$

where: ESR is exchangeable sodium ratio. Sodium adsorption ratio (SAR) is calculated by the following formula:

$$\text{SAR} = \frac{[Na^+]}{\sqrt{([Ca^{2+}]+[Mg^{2+}])/2}} \quad [6]$$

The unit of SAR is $(mmol_c/l)^{0.5}$. $[Na^+]$, $[Ca^{2+}]$ and $[Mg^{2+}]$ are the concentration of Na^+, Ca^{2+} and Mg^{2+} in soil solution and expressed as $mmol_c/L$. K_G is cation selectivity coefficient and expressed by Gapon (1933). The value of K_G was estimated about 0.5 $(mmol_c/L)^{-0.5}$ (Gapon, 1933).

3.3.1.6 Cation exchangeable capacity (CEC) (cmol$_c$ kg^{-1})

Cation exchangeable capacity (CEC) is defined as the capacity of negative charges on soil particles where exchangeable cations could be absorbed. The CEC was measured by ammonium acetate method (Sumner and Miller, 1996). Accurate 1 g soil and 5 ml CH_3COONH_4 (1 M) were added into a 50 ml centrifuge tube. They were shaken for 4 hours. The supernatant part was removed. Then, the samples were added with 5 ml CH_3COONH_4, stood overnight and shaken for 4 hours. Supernatant part was removed out of soil solution. The solid was added with 20 ml ethanol, stirred and shaken for 30 minutes. The supernatant part was removed again. A 20 ml KCl (1 M) was added into samples and shaken for 4 hours. The samples were centrifuged for 10 minutes at 5600xg filtered the supernatant solution through 0.45 µm filter. Finally, NH_4^+ in supernatant solution that could be attracted by negative charges of soil particles was measured using an ion chromatography and used for CEC determination.

3.3.1.7 Particle size distribution and soil texture

Soil samples were air-dried and passed through 2 mm mesh sieve. Then, soil organic matter was destroyed by hydrogen peroxide (H_2O_2). Sodium Hexameta phosphate ($NaPO_3$) was used to separate soil particles. The samples were stirred under ultrasonic machine. Particle size distribution was measured by Robinson pipette method (Gee and Bauder, 1986). In this method, the time for sample collection was calculated based upon Stokes Law. The particle sizes include more than 2 mm, 1-2 mm, 0.5-1 mm, 0.25-0.5 mm, 0.125-0.25 mm, 0.063-0.125 mm, 0.05-0.063 mm, 0.02-0.05 mm, 0.005-0.02 mm, 0.002-0.005 mm and less than 0.002 mm. The fractions of different particle sizes were calculated to express particle size distribution. The fractions of sand (0.05-2 mm), silt (0.002-0.05 mm) and clay (<0.002 mm) were calculated. Soil texture was determined based on the texture triangle of USDA/Soil Taxonomy (Soil Survey Staff, 1998).

3.3.1.8 Dry bulk density (ρb) (g cm^{-3})

Dry bulk density (g cm^{-3}) is a physical important indicator to evaluate soil physical fertility. Dry bulk density was measured using the undisturbed core method (Grossman and Reinsch, 2002). Samples were collected at depth of 5-10 cm by cores with volume 100 cm^3. Dry bulk density was calculated by dried soil weight (oven dried at 105°C) per bulk volume unit.

3.3.1.9 Soil particle density (ρ_p) (g cm^{-3})

Soil particle density (g cm^{-3}) is a physical important indicator to quantify mineral composition as well as organic matter in soil. Soil containing high organic matter shows lower value of particle density (2.65 g cm^{-3}). Pycnometer method was used to determine soil particle density (g cm^{-3}) (Blake and Hartge, 1986). Soils were crushed and passed through 2 mm mesh sieve. Then, soil particle density was defined by the mass soil solid per unit volume of soil solid.

3.3.1.10 Saturated hydraulic conductivity (cm s^{-1})

Saturated hydraulic conductivity (K_{sat}) (cm s^{-1}) is a physical important indicator to evaluate water permeability of soil. Saturated hydraulic conductivity was measured in saturated soil packed in 100 cm^3 columns in the laboratory using the falling-head method with tap water (Klute and Dirksen, 1986). The core samples (100 cm^3) of undisturbed soils were collected in the field at the depth of 5-10 cm. After saturated with tap water overnight, the core samples were carried out to determine K_{sat}.

3.3.1.11 Soil water characteristic curve

The water characteristic curve is the relationship between volumetric water content (cm cm^{-3}) and water suction (cmH_2O) (Brady and Weil, 2008). It was measured using hanging water table method. The range of matric pressure head was from 0 to -100 cm of water. Undisturbed soil cores were put into containers containing water to saturate them. The height of water in container equals with two-third height of soil cores. Then saturated soil cores placed on tension table at -5, -10, -20, -30, -40, -50, -60, -70, -80,

-90, -100 cmH_2O. Water drained from saturated soil was recorded every 24^h at each height. Volumetric water content was calculated at each water suction. Field capacity (FC) was determined using hanging water table at -100 cmH_2O (ψ_m = -10.1 kPa) (Klute, 1986).

3.3.2 Chemical properties as a function of depths

3.3.2.1 Soil pH

Figure 3.3 shows the variation of pH of three soils throughout the soil depths. Among the soils, pH of AS was the lowest. At the 0-63 cm depth, pH of AS was extremely low, with 3. As described in the field (Table 3.2), the sulfuric acid (H_2SO_4) is a main cause of extremely low pH. In the two next depths, soil pH increased to be 4.7 and 4.9 and decreased back to be 3.6 and 3.9 for the following depths.

Among the soils, pH of SS was the highest (Figure 3.3). The value of pH obtained 7.4 at the 0-35 cm depth. Then, pH decreased to be 6.1 at the 46-55 cm depth. This layer is the interface between the old soil surface layer and the new soil layer. Therefore, organic matter from the old soil surface layer due to soil accretion could be accumulated in this layer and release organic acid in anaerobic condition. Organic acid is a main reason of lower pH in comparison with the other layers. The soil pH in the two following depths was 6.9 and 7.4.

The pH of AL was higher than that of AS and less than that of SS (Figure 3.3). Within 100 cm from the surface, pH of AL was approximately 4.9. Below 100 cm depth, pH was higher, with 5.3 and 5.5 for the two last layers. According to farmers, in conventional cultivation of monocrop during seven years, chemical fertilizers were used such as Urea, DAP and NPK. They contained high content of available nitrogen that could provide nitrogen nutrient for plant growth. As conventional practices, the amounts of applied chemical fertilizers varied according to plant status, averagely 100 kg N ha^{-1} (according to local farmers). The nitrification of NH_4^+-N from the application of chemical fertilizer may produce H^+ and cause low pH in this soil.

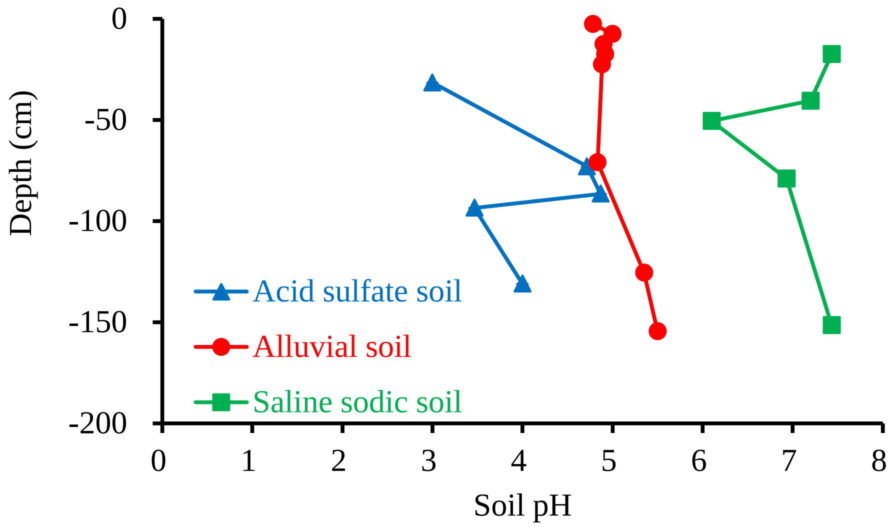


Figure 3.3 Soil pH with the depths

3.3.2.2 Soil electrical conductivity (EC_e)

Soil EC_e of three soils is depicted in Figure 3.4. Among the soils, the highest level of EC_e was shown in SS. The salinity in this soil increased as a function of depths. At the top soil, the EC_e was 15.1 dS m^{-1} and increased to be 25.4 dS m^{-1} in the next depth. In the two adjacent depths of 46-55 cm and 55-103 cm, EC_e was 44.1 and 39.1 dS m^{-1}, respectively. The highest EC_e was found in the lowest depth, with 51.8 dS m^{-1}. Soil was surrounded by seawater, where much dissolved salts was contained. During salt intrusion, dissolved salts were accumulated and thereby enhanced soil salinity. High salinity of SS is the contribution of higher contents of soluble cations: Mg^{2+}, Ca^{2+}, Na^{+} and anions: Cl^{-} and SO_4^{2-}, which were shown in below figures (Figure 3.5 ~ Figure 3.9).

As compared to SS, salinity of AS was lower (Figure 3.4). However, the salinity of AS was higher than that of AL. Within 100 cm depth, EC_e fluctuated, varying from 5.7 dS m^{-1} to 10.0 dS m^{-1} and 4.0 dS m^{-1}. Insoluble forms like ($KFe_3(SO_4)_2(OH)_6$)), a result of oxidation process of pyrite (FeS_2) (Tho and Egashira, 1976) may form more in above 100 cm depth than in below 100 cm depth. Moreover, above 100 cm depth, there was less soluble cations and anions than below 100 cm depth, which are indicated in the below result of cation and anion analysis in AS. Below 100 cm depth, EC_e of AS was higher, nearly 12 dS m^{-1}. It was interpreted less formation of insoluble $KFe_3(SO_4)_2(OH)_6$) (jarosite) in the below 100 cm depth because of less oxygen diffusion. Soluble aluminium ion (Al^{3+}) and soluble iron ion (Fe^{3+}) might be abundant in soil with pH below 4.0 (Strawn *et al.* 2015). Moreover, contents of soluble cations like Mg^{2+}, Ca^{2+}, Na^{+} and anions like Cl^{-}, SO_4^{2-} shown in below Figures (Figure 3.5 ~ Figure 3.9) increased at the last depths. Higher concentration of soluble cations and anions could contribute to higher EC_e of AS in the below 100 cm depth.

In comparison with the other soils, the lowest salinity was found in AL throughout soil layers (Figure 3.4). The EC_e of AL was less than 2 dS m^{-1} within 25 cm from the surface. The EC_e of AL increased slightly to be 3.6 dS m^{-1} at the last depth. The slight rise in EC_e in this layer may be because of presence of Fe^{2+} and Mn^{2+} in anaerobic condition (ISSS/ISRIC/FAO, 1998). The other soluble cations: Mg^{2+}, Ca^{2+}, Na^{+} and anions: Cl^{-} and SO_4^{2-} showed less content in this soil (Figure 3.5 ~Figure 3.9).

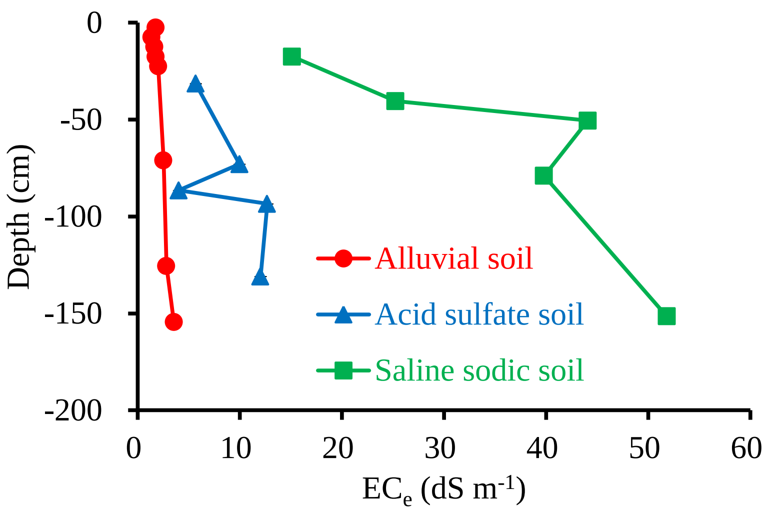


Figure 3.4 Soil electrical conductivity with the depths

3.3.2.3 Sodium (Na^{+}) contents

Figure 3.5 shows soluble sodium concentration in soil solution at saturation in the three soils. Among the soils, the highest content of sodium was shown in SS. This was followed by AS and AL, respectively. In SS, the contents of sodium increased with increasing the depth. The lowest content of sodium was 18.44 $mmol_c$ L^{-1} on the soil surface. It was about twice as much as in next depth, with 32.64 $mmol_c$ L^{-1}. The sodium concentration reached a peak at 69.51 $mmol_c$ L^{-1} at the lowest soil layer. As mentioned above, this soil is surrounded by seawater, so it could accumulate much sodium contents.

Sodium contents in AS were less than that in SS, but higher than that in AL (Figure 3.5). In AS, sodium contents were the lowest in the top soil, with 0.52 $mmol_c\ L^{-1}$. However, the contents of sodium increased as the depth increased, which was 4.20 $mmol_c\ L^{-1}$ at the 90 cm depth from the surface and 8.95 $mmol_c\ L^{-1}$ at the last layer. From this result, sodium contents were abundant in the below 90 cm depth.

Among the soils, sodium contents in AL were the lowest (Figure 3.5). The sodium contents were less than 1.12 $mmol_c\ L^{-1}$ throughout soil profile. It showed that sodium did not affect plant growth or soil problems.

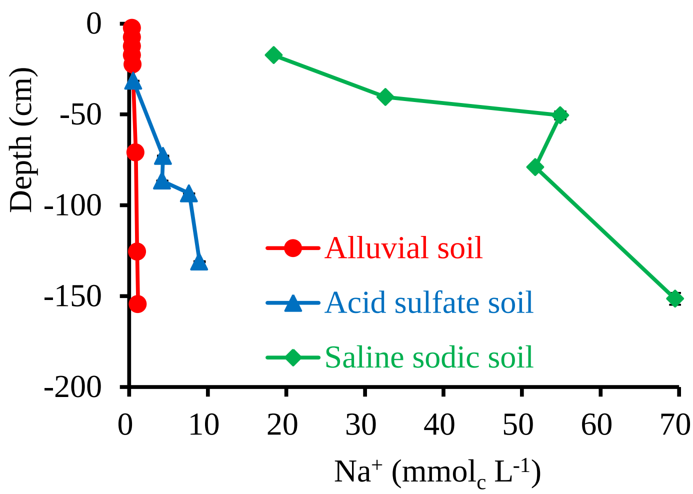


Figure 3.5 Soluble sodium concentration of soil solution at saturation with the depths

3.3.2.4 Chloride (Cl^-) contents

The chloride concentration of soil solution at saturation shown in Figure 3.6 have similar tendency with sodium contents in the three soils. Between the soils, the highest content was shown in SS, followed by AS and AL. In SS, chloride contents increased from 19.78 $mmol_c\ L^{-1}$on the top to 101.73 $mmol_c\ L^{-1}$ in the deepest layer. It showed that sodium chlorides were the main components of soluble salt in SS. The presence of sodium chlorides in soil could increase clay dispersion and adversely affect soil structure of SS.

As shown in Figure 3.6, in AS, chloride contents were low at the top, with 0.44 $mmol_c\ L^{-1}$. The contents of chlorides increased at the lower depth. Below 63 cm depth, the contents were less than 4 $mmol_c\ L^{-1}$. Compared to the soils, chloride contents in AL were the lowest. The contents were less than 0.37 $mmol_c\ L^{-1}$ throughout the soil layers.

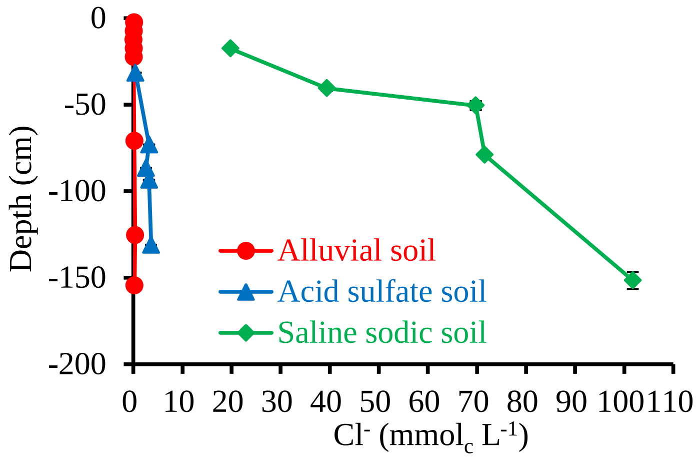


Figure 3.6 Soluble chloride concentration of soil solution at saturation with the depths

3.3.2.5 Magnesium (Mg^{2+}) and Calcium (Ca^{2+}) contents

The concentration of magnesium in soil solution at saturation in the three soils is shown in Figure 3.7. Among the soils, Mg^{2+} contents in AL were lower than that in AS and SS. It was less than 1.08 mmol$_c$ L^{-1} in whole soil layers. In SS, the maximum content of Mg^{2+} was 5.94 mmol$_c$ L^{-1} in the 46-55 cm depth. In the other layers of this soil, the Mg^{2+} contents were less than 3.0 mmol$_c$ L^{-1}. The reason for this was that higher organic matter contents at 46-55 cm depth could retain more Mg^{2+}. In AS, although contents of Mg^{2+} fluctuated along the depths, it tended to increase as the depths increased. The Mg^{2+} contents were 0.6 mmol$_c$ L^{-1} at the top soil and 5.0 mmol$_c$ L^{-1} in the last depth. This result could be used to interpret higher salinity along the depths.

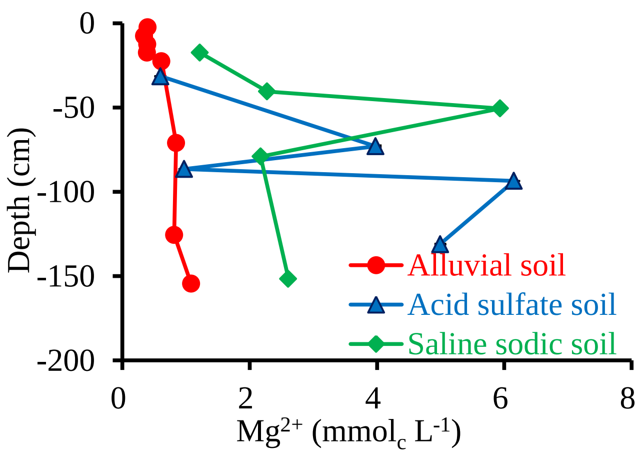


Figure 3.7 Soluble magnesium concentration of soil solution at saturation with depths

Calcium contents in three soils are depicted in Figure 3.8. Three soils showed small content of calcium, less than 2.5 $mmol_c$ L^{-1}. Among the soils, Ca^{2+} contents in AL were lower than that in AS and SS.

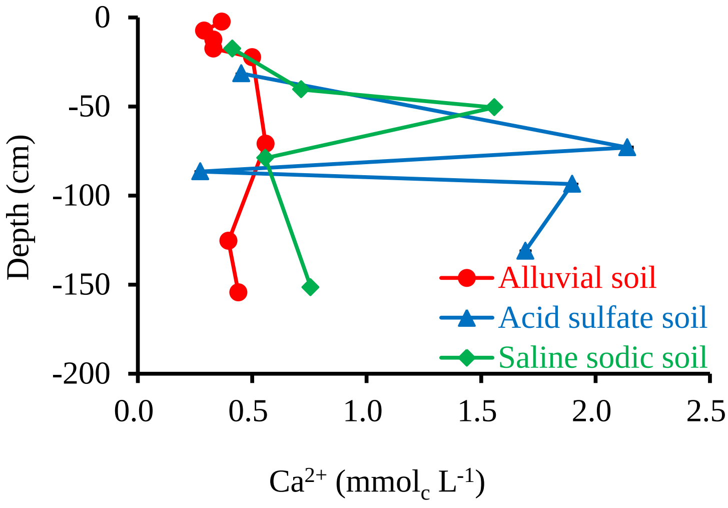


Figure 3.8 Soluble calcium concentration of soil solution at saturation with the depths

3.3.2.6 Sulfate (SO_4^{2-}) contents

Sulfate contents were different among the soils (Figure 3.9). The least content of SO_4^{2-} was shown in AL, less than 2.83 $mmol_c$ L^{-1} throughout soil layer. In SS, its content was little bit higher, around 3.0 $mmol_c$ L^{-1} throughout soil layer, but suddenly high in a 46-55 cm depth, with 8.76 $mmol_c$ L^{-1}. This was because this layer is interlayer between the old layer and the new layer due to soil accretion. Soil organic matter (SOM) (Figure 3.10) accumulated in the old soil layer could retain much SO_4^{2-}.

In AS, contents of SO_4^{2-} tended to increase upon the depths (Figure 3.9). In the first two adjacent depths, the contents were 5.2 $mmol_c$ L^{-1} and 7.1 $mmol_c$ L^{-1}. In the last two adjacent depths, the contents were 13.5 $mmol_c$ L^{-1} and 10.6 $mmol_c$ L^{-1}. Sulfate (SO_4^{2-}) is one of the main sources of pyrite formation. In anaerobic condition, sulfate would be reduced to sulphide (S^{2-}) by sulphate-reducing bacteria and thus form FeS_2. In this soil, sulfate contents were abundant. This was a main reason of jarosite formation on the surface and low pH of AS. The contents of soluble sulfate was less in the top soil than in the lower depths because sulfate was partly in insoluble forms of $KFe_3(SO_4)_2(OH)_6$ in the top soil.

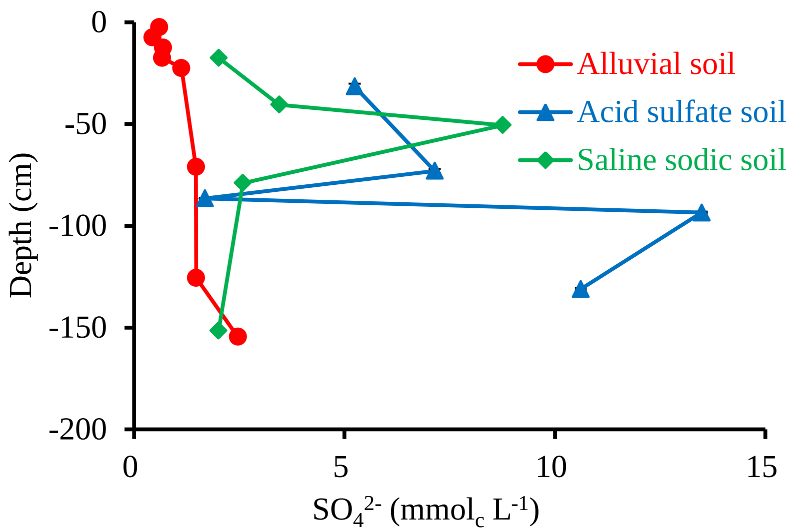


Figure 3.9 Soluble sulfate concentration of soil solution at saturation with the depths

3.3.2.7. Organic carbon (%), total nitrogen (%) and C/N ratio

Figure 3.10 shows the content of organic carbon, total nitrogen and C/N ratio. Between the soils, there was less organic carbon in AL, with less than 3.0% throughout soil layers (Figure 3.10a). SS also contained less organic carbon (3.0%) throughout soil layer (Figure 3.10b). This was except for the 46-55 cm depth, which organic carbon content was 6.06%. As mentioned above, this soil layer is interlayer between the old layer and the new layer due to soil accretion by human activity. In this layer, vegetation residues on the old soil layer were accumulated. In AS, organic carbon was rich, fluctuating from the top down, with 9.28%, 13.31%, 9.72%, 12.82% and 5.82%, respectively (Figure 3.10c). In this soil, because pH was extremely low, less micro-organism could adapt in this environment. Therefore, much organic carbon was accumulated in low pH soil. Moreover, small contents of total nitrogen presented in three soils (Figure 3.10a, b, c).

C/N ratio is an important parameter showing decomposition rate of organic matter in the soils. As indicated in Figure 3.10, C/N ratio in AS (higher than 20) throughout soil layers was higher than that in AL and SS. In AL and SS, C/N ratio was less than 20. This indicated less decomposition rate of organic matter in AS than in AL and SS. It was estimated less micro-organisms in extremely low pH soil such as AS.

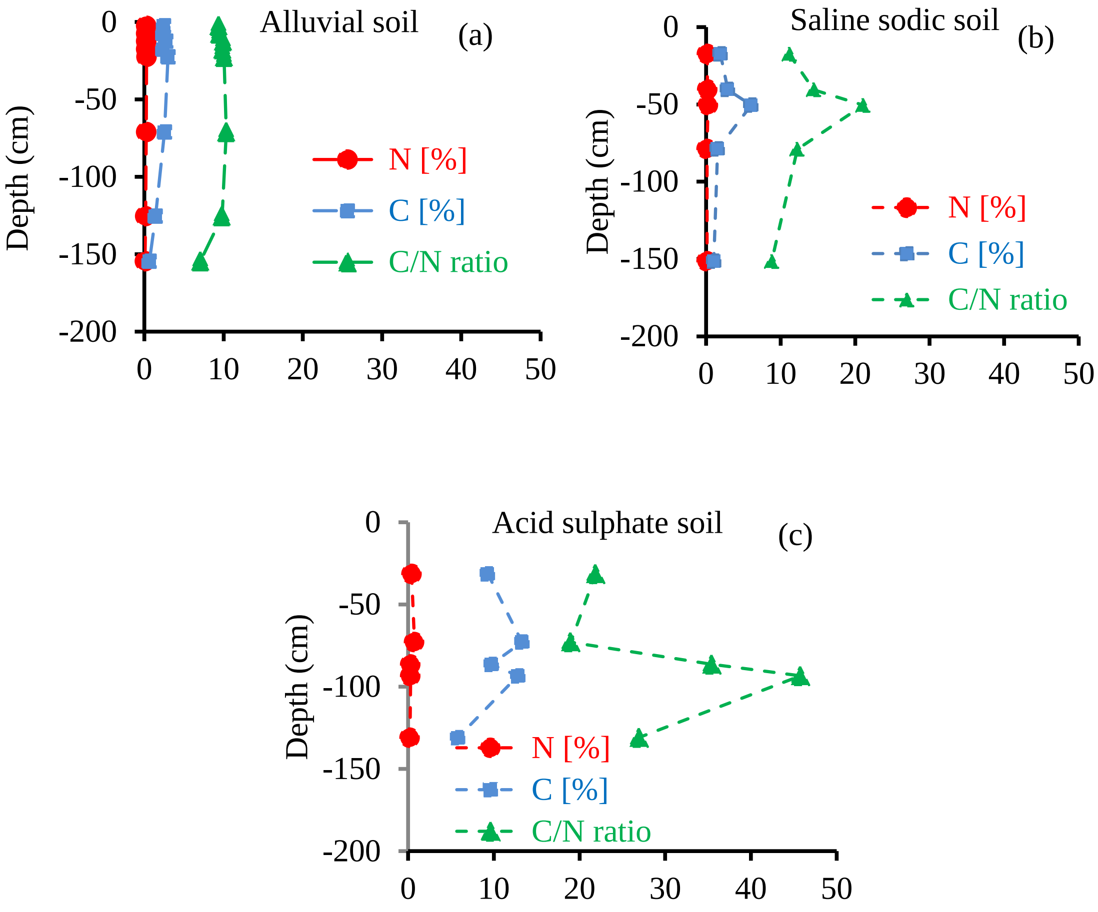


Figure 3.10 Organic carbon, total nitrogen and C/N ratio in (a) alluvial soil (b) saline sodic soil and (c) acid sulfate soil

3.3.3. Physical soil properties

3.3.3.1. Particle size distribution and soil texture

Particle size distribution in SS, AL and AS is shown Figure 3.11. Fractions of fine particles less than 0.002 mm in size were dominant, approximately 50%. Fractions of clay were 44.4% in AS, 52.5% in SS, and 55.5% in AL. Fractions of silt were 33.4% in AS, 35.2% in SS and 27.8% in AL. Sand occupied the lowest fraction, which was 22.1% in AS, 12.6% in SS and 16.7% in AL. Based on the texture triangle of USDA/Soil taxonomy, the three soils were defined as a clay texture.

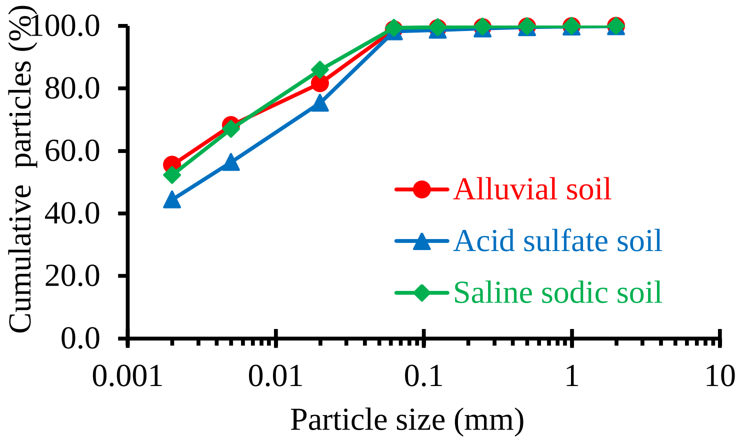


Figure 3.11 Particle size distribution curve in three soil types

3.3.3.2. Soil water characteristic curve

The ability of water retention of soil is dependent on the amount of clay. Higher fraction of clay in soils holds much more water than soils having less clay fraction. Moreover, higher soil porosity could show large pores in soil and less water retention. As can be seen in Figure 3.12, water characteristic curve showed the lowest in AS. In comparison with AL and SS, AS had the lowest fraction of clay and the highest soil porosity. The field capacity was determined using hanging table water at -100 cm H_2O. As shown in this figure, volumetric water content was the least in AS, followed by AL and SS, which were 0.24 cm cm^{-3}, 0.41 cm^3 cm^{-3}, and 0.49 cm^3 cm^{-3}, respectively.

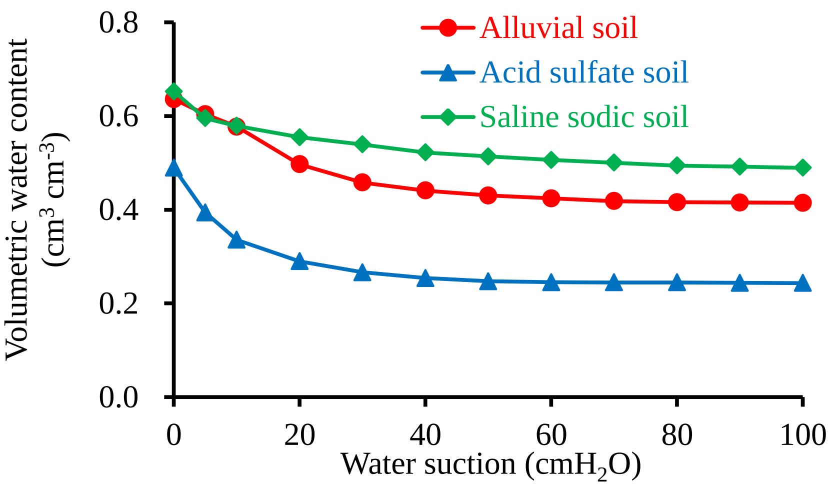


Figure 3.12 Water characteristic curves

3.3.3.3. Soil physico-chemical properties on the soil surface

Physico-chemical properties of soil surface (0-20 cm) in three sites are summarized in Table 3.4. Soils were clayey soils, ranging from the highest clay fraction of 55.5% (AL) to the lowest of 44.4 (AS). For organic content, AS illustrated the highest percentage, with 5.7%, followed by AL and SS, with 4.1% and 2.4%, respectively. Soil pH was the lowest in AS, with 2.7 while soil pH was little bit higher in AL and SS, with 4.6 and 5.5, respectively. Even SS, soil pH was not high enough to meet the optimum pH for plant growth. SS was characterised by high sodicity, with ESP (24.8%) and high salinity, with EC_e (8.2 dS m^{-1}). ESP value of AS and AL was low, with 3.0% and 2.1%, respectively. However, EC_e was high in AS while it was low in AL, with 8.1 and 1.8 dS m^{-1}, respectively. This was because AS, where its pH was extremely low, with 2.7, may contain soluble Al^{3+} (Tho and Egashira, 1976; Naramabuye and Haynes, 2006; Khoi *et al.* 2010; Strawn *et al.* 2015) and soluble Fe^{3+} (Stefansson, 2007; Strawn *et al.* 2015). In AL, since pH was 4.6, this suggested that AL had less soluble Al^{3+} and Fe^{3+} (Strawn *et al.* 2015). Saturated hydraulic conductivity was high in AS, with 0.017 cm s^{-1} because much organic carbon contained in AS and thereby resulted in high porosity. Lower saturated hydraulic conductivity in SS and AL, with $4.4x10^{-7}$ and $9.1x10^{-6}$, respectively, may predict compression status of soil, where both SS and AL had much clay fraction and lower organic carbon. Soil particle density was 2.8 g cm^{-3} in SS, 2.6 g cm^{-3} in AL and 2.5 g cm^{-3} in AS, where particle density of SS was higher than threshold of 2.65 g cm^{-3}. Dry bulk density of the three soils was lower than threshold of 1.35 g cm^{-3}. Among the soils, dry bulk density of AS was the lowest, with 0.6 g cm^{-3}, while dry bulk density of SS and AL was higher, each with 1.1 g cm^{-3}. Details of other soil properties are summarised in Table 3.4. Participants in field survey and land use in sampling sites are shown in Figure 4.13~4.16.

Table 3.4 Summary of soil physico-chemical properties on the soil surface

Parameters	**Unit**	**Saline and sodic soil**	**Alluvial soil**	**Acid sulfate soil**
Clay	%	52.2	55.5	44.4
Sand	%	12.6	16.7	22.1
Silt	%	35.2	27.8	33.4
Soil texture	-	Clay	Clay	Clay
pH_{H2O}	-	5.5	4.6	2.7
Organic carbon	%	2.4	4.1	5.7
Total nitrogen	%	0.12	0.24	0.23
C/N ratio	-	19.3	17.4	25.3
EC_e	dS m^{-1}	8.2	1.8	8.1
SAR_e	$(mmol_c/L)^{0.5}$	21.9	1.5	2.1
ESP_e	%	24.8	2.1	3.0
Bulk density	g cm^{-3}	1.1	1.1	0.6
Particle density	g cm^{-3}	2.8	2.6	2.5
Porosity	%	62.4	59.9	74.9
K_{sat}	cm s^{-1}	4.4E-7	9.1E-6	1.7 E-2
CEC	$cmol_c$ kg^{-1}	42.0	50.1	49.1
Soluble Na^+ (saturation extract)	$mmol_c/L$	69.0	5.1	5.6
Soluble Ca^{2+}(saturation extract)	$mmol_c/L$	5.1	12.0	6.6
Soluble Mg^{2+} (saturation extract)	$mmol_c/L$	14.7	12.2	8.0
Soluble K^+ (saturation extract)	$mmol_c/L$	0.45	0.06	0.23
Soluble Cl^- (saturation extract)	$mmol_c/L$	4.81	0.21	0.32
Soluble SO_4^{2-} (saturation extract)	$mmol_c/L$	3.16	0.91	5.37
Moisture at field capacity	m^3 m^{-3}	0.49	0.41	0.24
Moisture at sampling time	m^3 m^{-3}	0.56	0.51	0.62
Lime requirement (LR)	mg $CaCO_3$ g-$soil^{-1}$	3.23	4.89	32.57

Field survey

Figure 3.13 Participants in field survey

Figure 3.14 Land use in Ca Mau province

Figure 3.15 Land use in Can Tho city

Figure 3.16 Land use in Hau Giang province

Chapter 4 – Effects of clod sizes, moisture conditions and breakdown processes on aggregate stability

4.1 Summary

To intensify sustainably agricultural development in Mekong delta, especially saline and sodic soil and acid sulfate soil areas, soil reclamation is the first priority. Aggregate stability is one of the important indicators of soil health. Aggregate degradation causes many serious consequences affecting soil productivity, but it is less concerned. Proposing the strategies in strengthening aggregate stability requires basic information of aggregate behaviours under various conditions and breakdown processes. In this study, saline and sodic soil, alluvial soil and acid sulfate soil were collected at the 0-20 cm depth. Three clod sizes: 1-3 mm, 2-5 mm and 5-10 mm were prepared. All the clods were adjusted with different initial moisture conditions. Fast wetting, slow wetting and mechanism breakdown as breakdown processes were applied to the clods. Mean weight diameter (MWD) and fragment size distribution (FSD) were used to evaluate aggregate stability.

Dry clods were seriously disintegrated if they were exposed to the fast wetting, while moist clods tended to disintegrate with mechanical breakdown. Among the treatments, the greatest disintegration of aggregates corresponded to the lowest mean weight diameter (MWD) value was found in dry clods under fast wetting. The positive relationship between initial soil moisture and MWD showed that aggregate stability decreased as initial soil moisture prior to the fast wetting treatment decreased. Both moist and dry clods showed less effect of aggregate breakdown under slow wetting. The most serious deterioration of aggregates was found in SS, which was corresponded to smaller MWD. This was followed by AL and AS, which was larger MWD. The initially 2-5 mm and 5-10 mm clods were more durable than the initially 1-3 mm clods. From this result, dry clods (2-5 mm) under fast wetting were employed for evaluation of aggregate stability of the soils after the incubation following to the application of chicken manure and eggshell in chapter 5.

4.2 Introduction

Soil aggregate stability plays an important role in agriculture because it affects many processes in soils. Stable aggregates offer proper medium for nutrient cycles, water and gas movement and root respiration in the soil. In contrast, aggregate breakdown may increase soil pore clogging, reduce saturated hydraulic conductivity and increase runoff and soil erosion (Lado *et al*. 2004). Aggregate breakdown and subsequent surface seal formation accompanied with clogging pores depress seedling emergence (Rathore *et al*. 1983).

In the field, aggregate stability is affected by many factors. Different clod sizes are often created from tillage operation. According to Braunack and Dexter (1988), optimum clod sizes for seedling emergence range ranged 2-4 mm. Clod sizes are one of the factors affecting aggregate stability. The greatest disintegration of aggregates occurred in the initial smaller than 3 mm size clods (Legout *et al*. 2005). The aggregate stability increased as clod sizes increased in order of 3-5 mm < 5-10 mm < 10-20 mm (Legout *et al.* 2005). In addition, the changes in initial soil moisture could influence aggregate stability. Aggregate stability increased as initial water content of aggregates prior to immersion increased (Kemper and Rosenau, 1984). According to Le Bissonnais (1996), aggregate breakdown from fast wetting, slow wetting and mechanical breakdown were the results of four dominant mechanisms including slaking by entrapped air, differential swelling of clay and physio-chemical dispersion of clay particles and raindrop impacts. Breakdown processes, initial soil moisture and initial size clods are considered as important factors in evaluation of aggregate stability. Prior to applying proper measures for aggregate stability improvement, assessment of aggregate stability under various conditions and breakdown processes is essential. Therefore, the objective of this chapter is to evaluate aggregate stability under various conditions: initial soil moisture, initial clod sizes and breakdown processes: fast wetting, slow wetting and mechanical breakdown in the saline and sodic and acid sulfate soil in the Mekong delta of Viet Nam.

4.3 Theoretical background

As can be seen in Figure 4.1, unstable and stable aggregates behave differently. Unstable aggregates on the right hand are broken down into small fractions, which are settled down in the bottom of water column. In the water column on the left hand, stable aggregates maintained the top mesh. In this process, slaking by entrapped air is predominant for fast wetting (Le Bissonnais, 1996)

Figure 4.1 Aggregate behaviours after immersion in water
http://www.cornandsoybeandigest.com/soil-health/build-your-soil-aggregates

At the beginning of abrupt immersion of aggregates in water, the water enters rapidly into aggregates. The pressure of entrapped air is great enough to break aggregates apart into small fragments. At the same time with aggregate breakdown into small fragments, air bubbles escape (Zaher *et al.* 2005)

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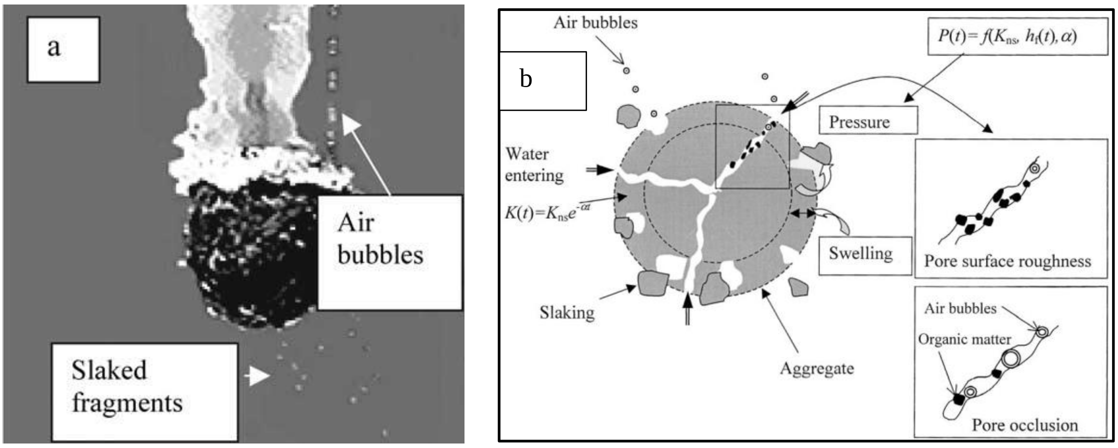


Figure 4.2 Image of aggregates after 3 second immersion in water (a) and model of aggregate breakdown after immersion in water (b) (Zaher *et al.* 2005)

The pressure evolution inside aggregates was modelled by Zaher *et al.* (2005) (Figure 4.3). Following the rapid immersion in water, the pressure of entrapped air inside aggregates with or without organic matter addition increased. However, the rate of pressure evolution of entrapped air was higher for aggregates without organic matter application than that with organic matter application. Organic matter plays an important role as a barrier to reduce the rate of water entry. The slow rate of water entry could result in less compression of entrapped air because it allows air to escape slowly outside aggregates.

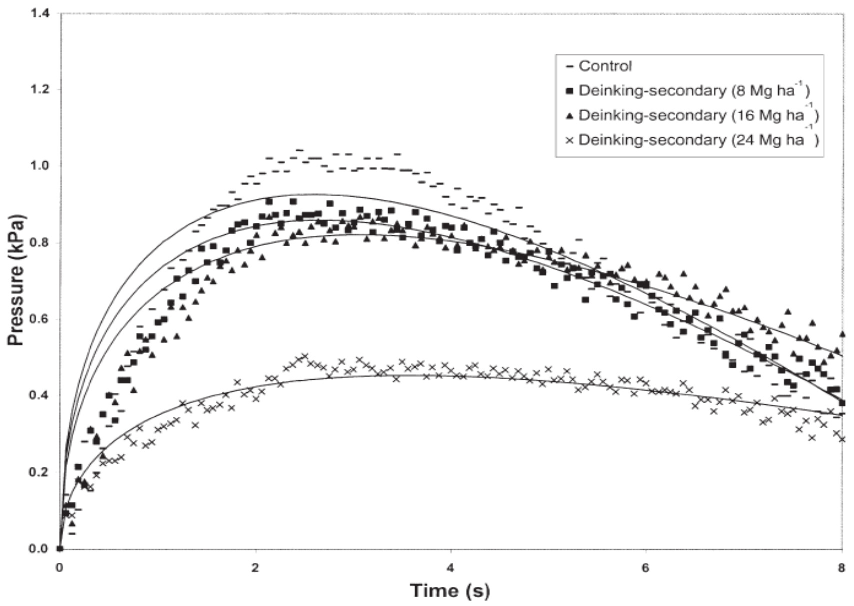


Figure 4.3 Pressure evolution with or without organic matter amendments after aggregates were suddenly immersed in water (Zaher *et al.* 2005)

Mechanism of clay swelling and dispersion is dominant for slow wetting process (Le Biossonais, 1996). In this process, water moves up slowly by capillary action. When clay particles contact with water, water molecules entering into clay layers make clay layers swell, and thus decrease inter aggregate pores. Clay swelling depends on clay properties. The 1: 1 clays like kaolinite have no expansion between the layers when wet because the 1: 1 clays do not allow water enter between clay sheets. The 2: 1 clays like smectite allow water move inside clay sheets and make them swell (Brady and Weil, 2008).

Clay dispersion depends on concentrations of cations (Figure 4.4). The increase in the concentration of polyvalent cations makes clay flocculate. In contrast, increasing concentration of monovalent cations like sodium makes clay disperse apart (Rengasamy *et al.* 1984). The repulsive forces between clay sheets increase with an increase in the concentration of monovalent cations because of the expansion of diffuse double layers.

Figure 4.4 depicts the changes in soil structure on swelling and dispersion. The phenomena of clay swelling (Figure 4.4b) and dispersion (Figure 4.4c) occur when clay particles contact with water.

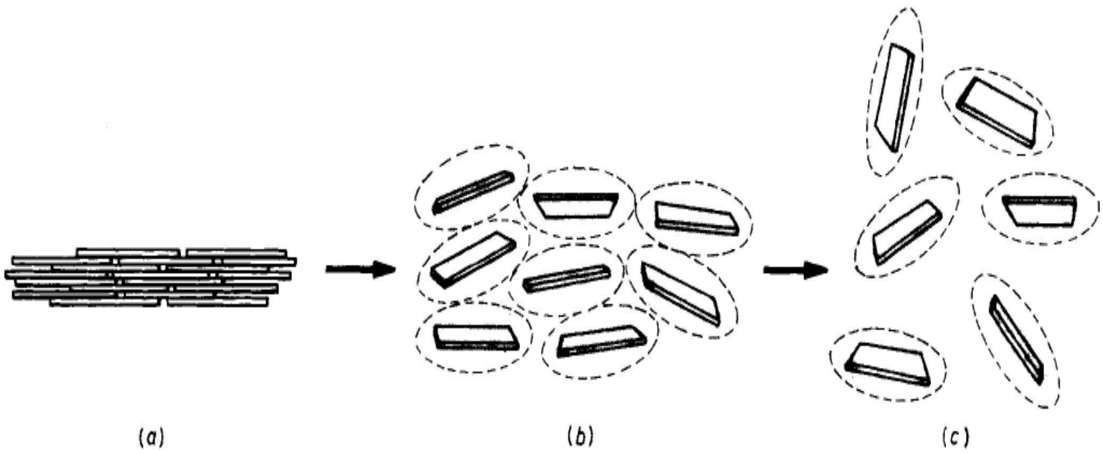


Figure 4.4 Schematic depiction of structural change on swelling (b) and dispersion (c) of smectite clay particles when they contact with water (Ramsay *et al.* 1990)

Aggregate breakdown by mechanical impacts modelled in laboratory needs to exclude slaking, clay swelling, and clay dispersion. To reduce slaking, clay swelling and clay dispersion mechanisms, the use of ethanol was proposed by Arai *et al.* (2003) and Le Bissonnais (1996). The purpose of ethanol is to remove air from aggregates before mechanical treatment is applied to the soils in order to prevent aggregate breakdown by slaking. Moreover, ethanol could help depress the thickness of diffuse double layers and prevent clay swelling and dispersion. Adjacent clay platelets are able to approach each other. According to Emerson (1957), bonds between hydroxyl (OH) of methanol (CH_3OH) and oxygen (O) on the surface of one of clay platelets and bonds between the CH_3 group of methanol (CH_3OH) and the oxygen (O) on the surface of adjacent clay platelets are mechanisms promoting Van der Waals attraction forces between adjacent clay particles (Figure 4.5). This mechanism occurs similar for ethanol (CH_3CH_2OH) when it is added to the soils. It was clarified that aggregates with addition of ethanol (96% v/v) were more stable than those with lower ethanol concentration or without the ethanol addition (Arai *et al.* 2003).

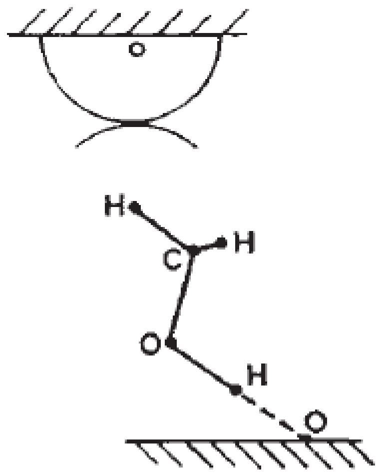


Figure 4.5 CH_3 --- O bond and OH --- O bond between methanol and the clay surface (Emerson, 1957)

4.4 Materials and Methods

4.4.1 Materials

Three soils in sampling sites were clayey, which had high stickiness and plasticity. They had structureless with massive structure. Alluvial soil was collected in the circumstance of when vegetables were planting in the growth stage. Acid sulfate soil was collected in the case of pineapple growing. Saline sodic soil was collected at the time no crop was planting. Soil was accreted after 2 years. Soil samples in three sites were collected at the 20 cm depth from the soil surface. Before collecting, themk surface litters and vegetation were removed. All of them were packed in plastic bags and carried carefully to the laboratory with minimum disturbance on natural soil structure.

4.4.2 Methods

4.4.2.1 Preparation for aggregate stability test

Natural aggregates of big blocks were collected from the field. Soil blocks were cut into smaller than 5 cm pieces as artificial clods. Then, they were left at room temperature to reduce soil moisture. Then, all of them were cut into 1-3 mm, 2-5 mm and 5-10 mm square clods. This process simulates to produce aggregates by harrowing during tillage practices. After cutting, soil moisture content was determined. Initial moisture of moist clods was 34% in AL, 40% in SS and in 63% (w/w) AS, respectively.

The clods were then modified to different levels of soil moisture content. After 5 hours, 3 days, 14 days of exposure of the air and at 40 ^{o}C in oven, moisture of clods was recorded. It was corresponded to the decline in moisture levels upon time. At the corresponding moisture levels of clods, aggregate stability was determined. The status of soil moisture in the field would affect aggregate stability. It was simulated with various levels of soil moisture in the laboratory.

4.4.2.2 Aggregate stability test

After the soil preparation, aggregate stability was examined under different breakdown processes: fast wetting, slow wetting and mechanical breakdown which was proposed by Le Bissonnais (1996). The three breakdown processes were applied to the three different size clods: 1-3 mm, 2-5 mm and 5-10 mm in size (Figure 4.6). As reported by Braunack and Dexter (1988), to make proper seedbed during tillage process, optimum clod size range for seedling emergence were 2-4 mm. So, it was essential to know aggregate stability at optimum clod sizes compared with smaller clod sizes and larger clod sizes. Therefore, the initially 1-3 mm, 2-5 mm and 5-10 mm clod sizes were employed to evaluate effects of different clod sizes on aggregate stability. Procedures of aggregate stability test modified by Le Bissonnais (1996) method are described in a below schematic diagram (Figure 4.7).

1-3 mm 2-5 mm 5-10 m

2.86 mm ± 0.15 4.53 mm ± 0.32 8.35 mm ±1.07

Figure 4.6 Preparation of initially size clods before aggregate stability test

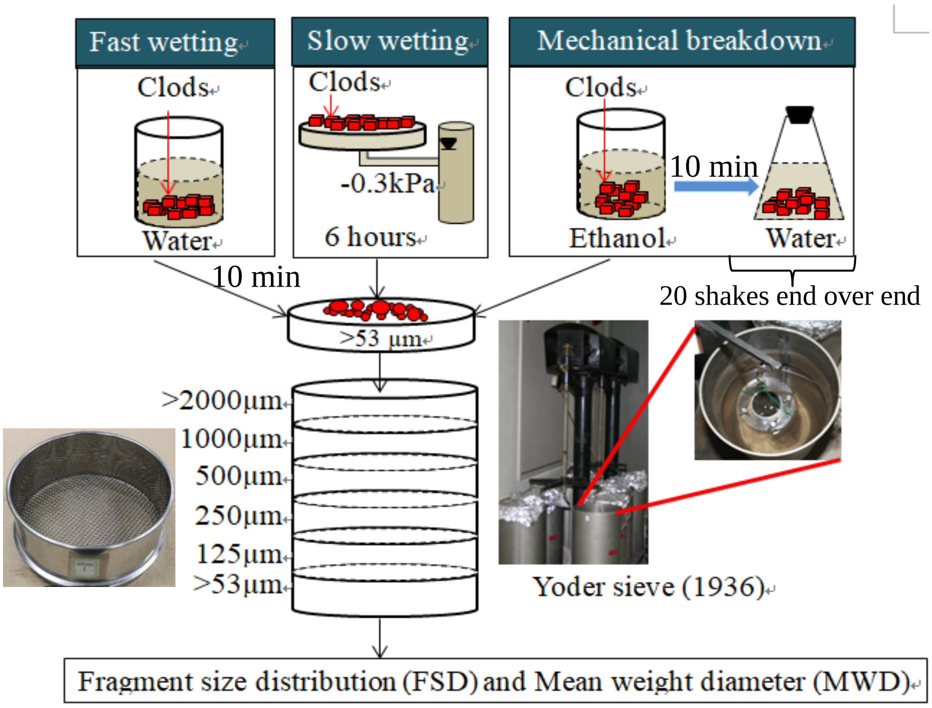


Figure 4.7 Schematic diagram procedures for aggregate test with three treatments: fast wetting, slow wetting and mechanical breakdown

The fast wetting simulates the mechanism of aggregate breakdown that is caused by sudden immersion of aggregates in water. This process is corresponded to the case of furrow or boarder irrigation in the agricultural field. In the fast wetting, 10 clods were suddenly immersed in 100 ml deionized water for 10 minutes (Figure 4.7). The water then was drawn off by a siphon. The samples were transferred to a 53 µm sieve for further calculation of fragment size distribution and mean weigh diameter (MWD). This process was repeated three replicates for each clod size and each soil moisture condition.

Slow wetting is designed in the laboratory to simulate the phenomenon of micro-cracking of aggregate. The 10 clods were left on filter paper on the tension table with the matric potential of -0.3 kPa (-3 cmH_2O) for 6 hours in order to allow water move slowly into the clods (Figure 4.8). Then, the samples were transferred to a 53 µm sieve for further calculation of fragment size distribution and mean weigh diameter (MWD).

As simulating mechanical breakdown, a 10 clod was submerged in 50 ml ethanol (99.5%) for 10 minutes (Figure 4.9). Then, ethanol was drawn off by the siphon and the samples were added in a 250 ml Erlenmeyer flask with 200 ml water. The flask was corked and shaken end-over-end for 20 times and left 30 minutes to allow particles to settle. After excess water was removed by a siphon, the samples were transferred to a 53 μm sieve for further calculation of fragment size distribution and mean weigh diameter (MWD).

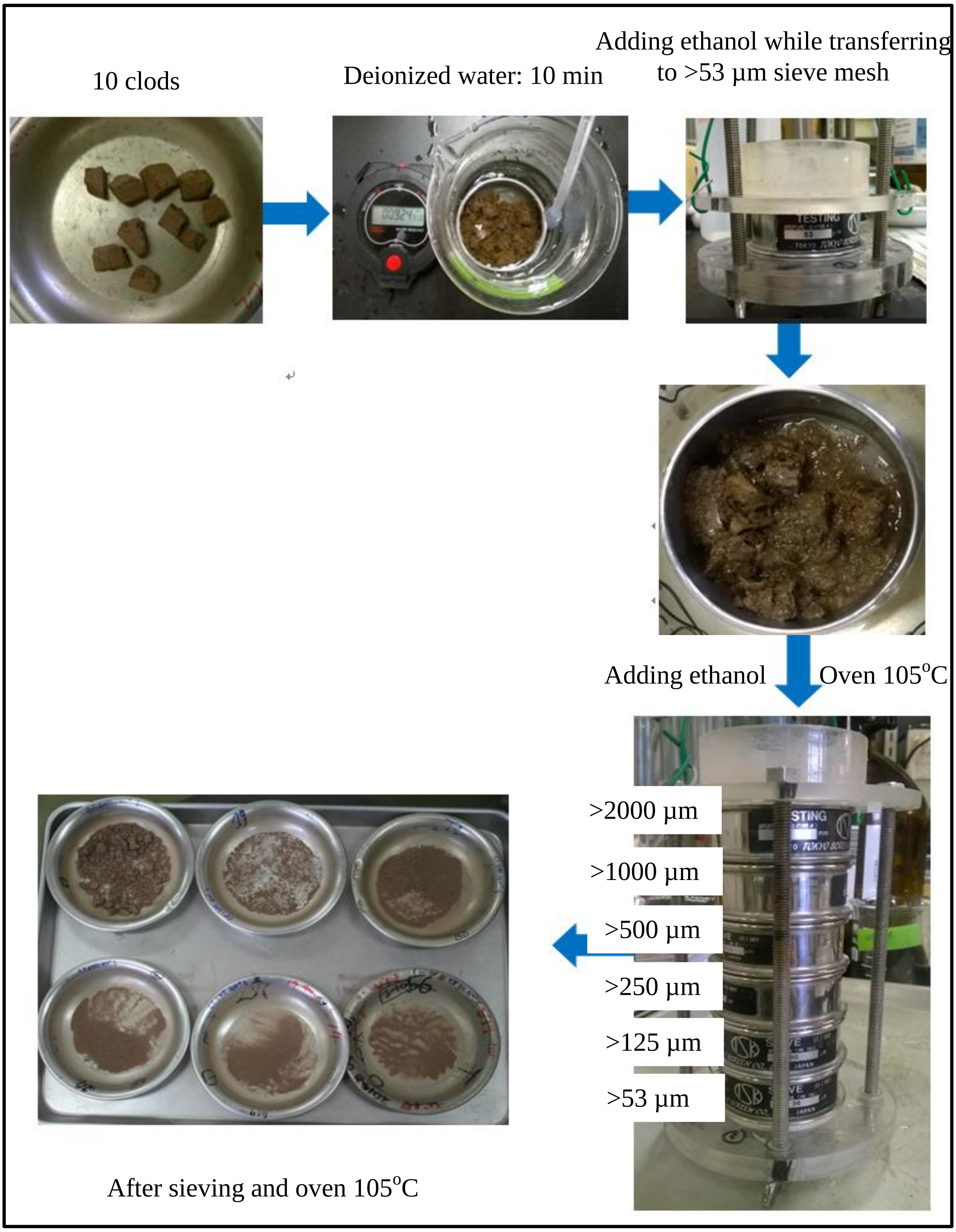


Figure 4.8 Schematic diagram of aggregate stability under fast wetting

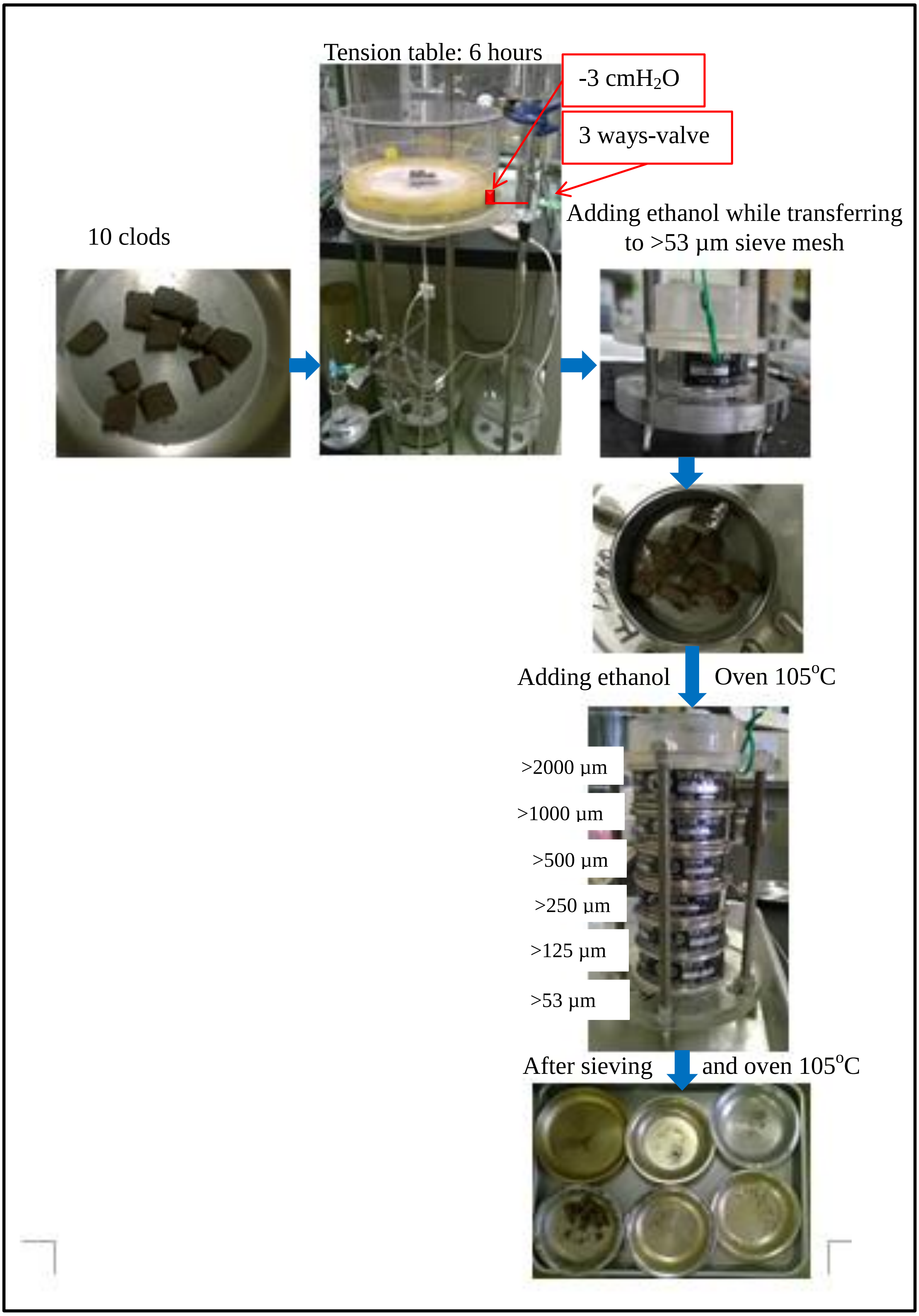


Figure 4.9 Schematic diagram of aggregate stability under slow wetting

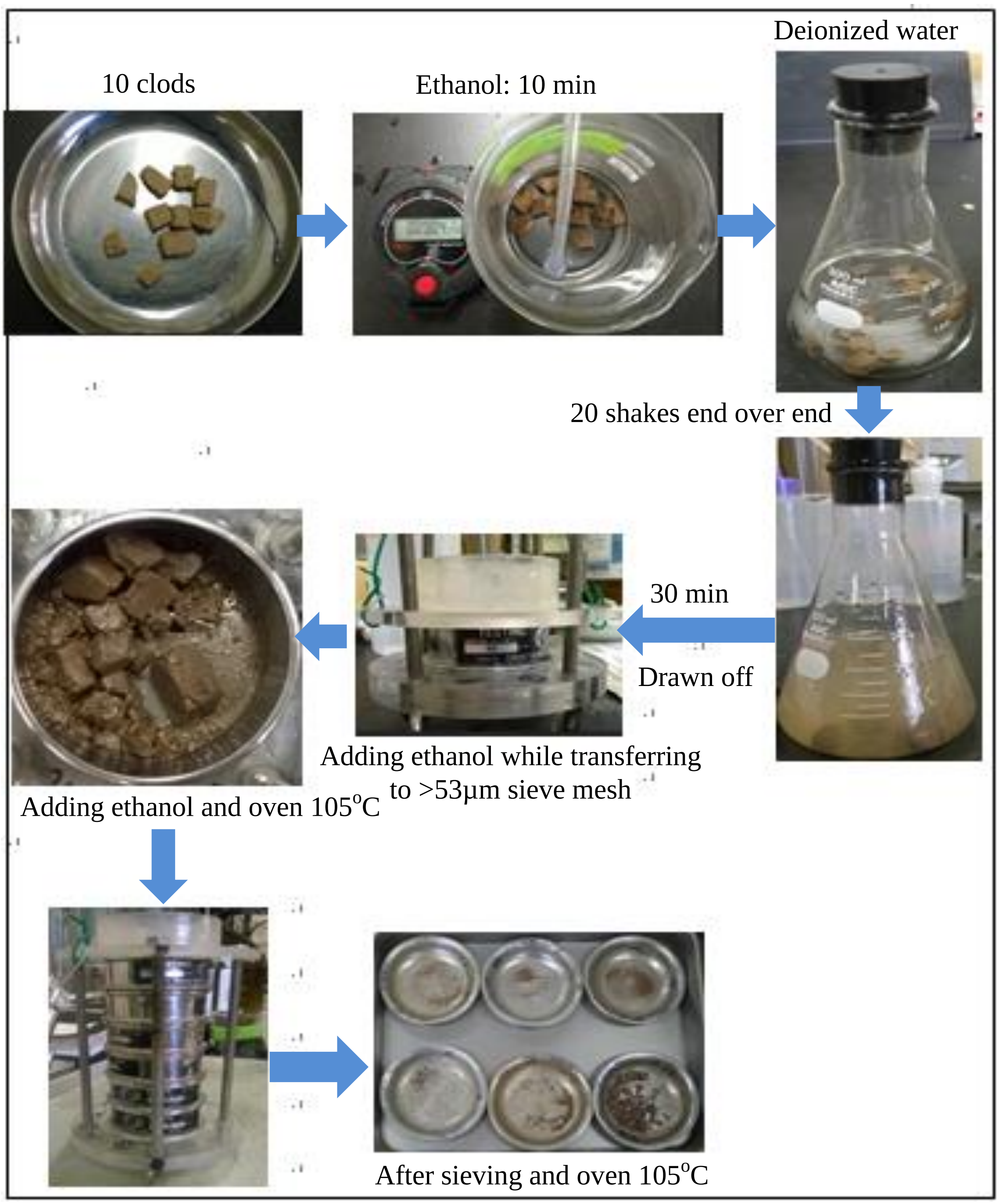


Figure 4.10 Schematic diagram of aggregate stability under mechanical breakdown

After transferred to a 53 µm mesh sieve, the samples were sieved by Yoder machine (1936) (Figure 4.10) to separate into two fractions: fragments smaller than 53 µm and fragments larger than 53 µm. The fragments larger than 53µm were then transferred to a nest of six sieves: 2000 µm, 1000 µm, 500 µm, 250 µm, 125 µm, and 53 µm and sieved by Yoder machine (1936). Fragments left on the sieves were oven-dried at 105°C. The fragments smaller 53µm were defined by the differences between initial mass and the sum of mass of the six other fragments. The aggregate stability for each treatment was expressed using the fragment size distribution in three fragment sizes: d > 2000 µm; 2000 µm > d > 250 µm; d < 250 µm. Mean weight diameter (MWD) is calculated by mass fractions of oven dry samples (g) remaining on each sieve after sieving multiplied by the mean diameter (µm) of the adjacent mesh.

$$\text{MWD} = \frac{\sum_{i=1}^{i=n} m_i d_i}{\sum m_i} \qquad [7]$$

m_i: mass of aggregate fraction "i" of soil remaining on each sieve after sieving (g).

d_i: mean diameter of the adjacent mesh (µm)

Changes in MWD indicate that the clod size has decreased as a consequence of the breakdown caused by the three treatments.

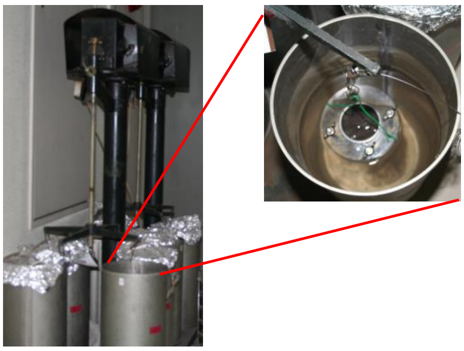


Figure 4.11 Yoder machine (1936)

4.5 Results and discussions

4.5.1 Effects of initial soil moisture content and breakdown processes on aggregate stability

Effects of initial soil moisture content and breakdown process on aggregate stability are shown in Table 4.1. The 2-5 mm clods were treated with fast wetting, slow wetting and mechanical breakdown. As recommended by Braunack and Dexter (1988), the initially 2-4 mm clod ranges were optimum size for seedling emergence. Therefore, the initially 2-5 mm clods were used to know the aggregate stability at optimum clod size under different conditions in this study. After the three treatments, the MWD value decreased compared to the original size of 2-5 mm clod size. At the same dry condition, all dry soils showed significantly smaller MWD, which corresponded to 1.91, 2.37 and 2.36 mm in SS, AL and AS, respectively, when dry clods were treated with fast wetting than dry clods were treated with slow wetting and mechanical breakdown. All moist soils mechanical breakdown showed significantly smaller MWD, which corresponded to 2.55 mm in SS, 2.50 mm in AL and 2.58 mm in AS, than those under fast wetting and slow wetting. The MWD was larger for both dry and moist clods when they were treated with slow wetting than they were treated with fast wetting and mechanical breakdown. Among the soils, MWD of SS was smaller than MWD of AL and AS when dry clods were exposed to fast wetting process.

Table 4.1 Mean weight diameter (MWD) of SS, AL and AS after the initial 2-5 mm dry and moist clods were treated with fast wetting, slow wetting and mechanical breakdown. Different lower case letters (a, b, c) with a horizontal row show the significant difference in MWD between initial soil moisture conditions. Different upper case letters (A, B, C) with a vertical column show the significant difference in MWD between breakdown processes. Different letters (a, c, bc) show the significant difference in MWD between soils at significance level of 5% using LSD test.

Soils		MWD (mm)					
		Saline sodic soil		Alluvial soil		Acid sulfate soil	
Moisture conditions		Air dry	Moist	Air dry	Moist	Air dry	Moist
Breakdown	Fast wetting	$^{a}1.91^{a\ A}$	$2.67^{b\ B}$	$^{c}2.37^{a\ A}$	$2.69^{b\ B}$	$^{bc}2.36^{a\ A}$	$2.68^{b\ B}$
	Slow wetting	$2.70^{a\ B}$	$2.68^{a\ B}$	$2.74^{b\ C}$	$2.70^{a\ B}$	$2.65^{a\ B}$	$2.71^{a\ B}$
	Mechanical breakdown	$2.57^{a\ B}$	$2.55^{a\ A}$	$2.59^{a\ B}$	$2.50^{a\ A}$	$2.65^{b\ B}$	$2.58^{a\ A}$
Breakdown*moisture		P<0.001		P<0.001		P<0.001	

There was strong interaction (P < 0.001) between two soil moisture conditions and three breakdown processes (Table 4.1). Among the factors, dry clods under fast wetting showed the smallest MWD. It can be said that fast wetting process caused the moist serious breakdown in dry soils. Slaking due to the evolution of pressure of entrapped air may be predominant mechanism causing breakdown of dry clods under fast wetting (Zaher *et al.* 2005). As compared between moisture condition at the same fast wetting treatment, dry clods showed more breakdown than moist clods, which corresponded to lower MWD of the dry clods than MWD of the moist clods (Table 4.1). Vermang *et al.* (2009) reported that fast wetting of dry soils caused the most serious breakdown of aggregates in comparison with the moist soils. This result also corresponded with Legout *et al*. (2005) who concluded that aggregates were broken down more in fast wetting than in slow wetting and mechanical breakdown.

Figure 4.11 depicts the relationship between initial soil moisture content and mean weight diameter (MWD) of clods under fast wetting. Initial clod moisture at moist condition were recorded 34% in AL, 40% in SS and 63% (w/w) in AS. After 5 hours, 3 days, 14 days of exposure to the air and at 40 ^{o}C in oven, moisture of moist clods decreased. MWD was determined at the corresponding moisture levels. Positive linear relationship between MWD and soil moisture content showed the increase in MWD with increasing initial soil moisture. It can be said that aggregate stability increased as initial soil moisture content increased. Kemper and Rosenau (1984) also reported that aggregate stability was affected by antecedent water content, where aggregate stability increased as antecedent water content rose. It may be interpreted that as antecedent water content increases, smaller volume of entrapped air inside the initially moist aggregates could cause less compression force under fast wetting process than the initially drier aggregates (Kemper and Rosenau, 1984; Vermang *et al.* 2009). As a result, soil loss and runoff may decrease with increasing antecedent moisture content (Lado *et al.* 2004).

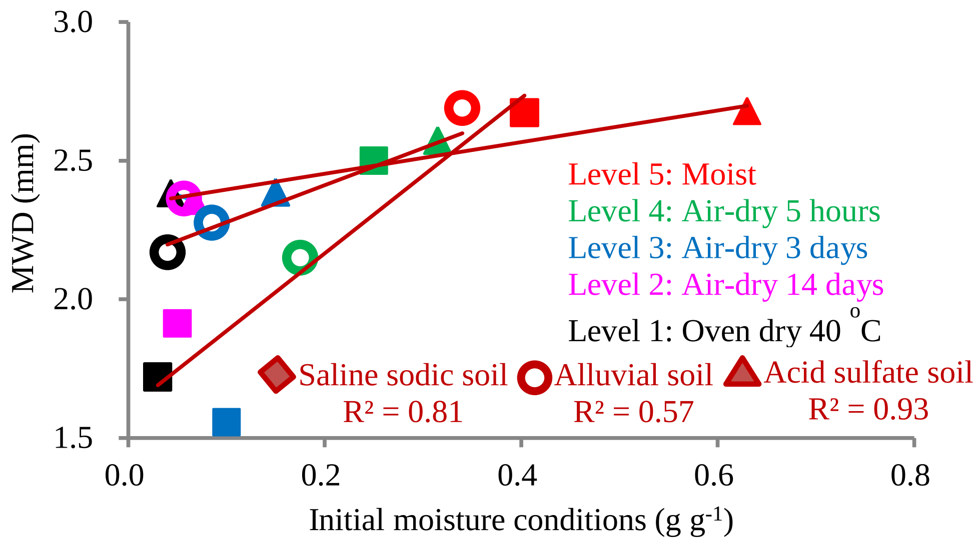


Figure 4.12 Relationship between initial soil moisture and mean weight diameter (MWD) of clods under fast wetting

As compared to dry clods with fast wetting process, dry clods under slow wetting and under mechanical breakdown indicated less disintegration, resulting larger MWD (Table 4.1). In slow wetting, dry clods got wet slowly by upward capillary action. Clay swelling and dispersion occurs and causes micro-cracking (Le Biossonais, 1996). In this process, less air was entrapped and thus leaded to less entrapped-air pressure in the aggregates. It can be said that fast wetting made dry clods break down more than slow wetting and mechanical breakdown treatment did.

At the same dry clods treated with fast wetting, among the soils, SS showed smallest MWD, followed by AL and AS (Table 4.1). It indicated more aggregate breakdown in SS than in AL and AS. The properties of three soils may affect aggregate stability. Aziz and Karim (2016) and Almajmaie *et al.* (2017b) had found that the negative correlation between aggregate stability and sodium content, where monovalent cations like sodium could promote clay dispersion. Moreover, aggregate stability and organic matter have strongly positive correlation (Aziz and Karim, 2016). The nature of soils like SS containing sodium has weak structure. Moreover, SS contained less organic matter than the remaining soils. Therefore, rapid immersion of dry SS having weak structure in water could increase the evolution of air pressure promoting aggregate breakdown. For slow wetting and mechanical breakdown, there was no slaking by entrapped air occurring in these processes. So, the breakdown of aggregates in slow wetting and mechanical breakdown was not so much more than fast wetting, even though SS have weak structure. It can be said that fast wetting caused serious breakdown of aggregates by entrapped air rather than influence of soil properties.

4.5.2 Effects of clod sizes on aggregate stability

According to the above result, dry clods under fast wetting showed the most serious breakdown of aggregates in comparison with moist and dry clods under slow wetting and mechanical breakdown. Therefore, the dry clods under fast wetting were employed to evaluate the effects of initial clod sizes on aggregate stability. In this issue, fragment size distribution (FSD) which was separated into three classes: d > 2000 µm; 250 µm < d < 2000 µm and d < 250 µm was used.

As can be seen in Table 4.2, SS and AL showed significant differences (P < 0.01) in proportion of fragments larger than 2 mm between groups of initially 2-5 mm; 5-10 mm clods and the initially 1-3 mm clods. In SS, the proportion of fragments larger than 2 mm in the initially 2-5 mm and 5-10 mm clods was twice more than that in the initially 1-3 mm clods. In contrast, the proportion of fragments < 0.25 mm in the initially 2-5 mm and 5-10 mm clods was twice less than that in the initially 1-3 mm clods. There was similar trend of fragment size distribution for AL where the proportion of fragments > 2 mm in the initially 2-5 mm and 5-10 mm clods was significantly about 1.5 times more than that in the initially 1-3 mm clods. The proportion of fragments < 0.25 mm in the initially 2-5 mm and 5-10 mm clods was twice less than that in the initially 1-3 mm clods. In AS, although there was no significant difference in proportion of fragments > 2 mm between the initial 2-5 mm and 5-10 mm clods, proportion of fragments > 2 mm increased with increasing clod sizes in the order of 1-3 mm < 2-5 mm < 5-10 mm size clods. It can be concluded that the initial 2-5 mm and 5-10 mm dry clods were more durable than the initially 1-3 mm dry clods in diameter under fast wetting process, which is common phenomenon as in Mekong delta region as well as in other tropical areas. This result corresponded with Legout *et al*. (2005) who showed the aggregate stability increased with increasing clod sizes in order < 3 mm < 3-5 mm < 5-10 mm < 10-20 mm.

Table 4.2 Effects of initially dry clod sizes on fragment size distribution under the fast wetting process. "d" expressed fragment size. Different letters show the significant difference in proportion of fragments between the treatments at significance level of 5% using LSD test.

Soils	Clod sizes	d > 2000 µm	250 µm < d < 2000 µm	d < 250 µm
Saline sodic soil	1-3 mm	21.61^{a}	58.24^{a}	20.15^{c}
	2-5 mm	43.63^{b}	46.96^{a}	9.41^{b}
	5-10 mm	48.06^{b}	47.03^{a}	4.91^{a}
$LSD_{0.05}$		14.71	16.87	3.36
P		0.01	0.25	8.53×10^{-5}
Alluvial soil	1-3 mm	48.48^{a}	41.79^{b}	11.14^{b}
	2-5 mm	77.85^{b}	20.56^{a}	2.43^{a}
	5-10 mm	68.99^{b}	26.76^{a}	4.25^{a}
$LSD_{0.05}$		12.37	11.44	6.22
P		0.003	0.01	0.03
Acid sulphate soil	1-3 mm	74.61^{a}	15.38^{ab}	10.01^{b}
	2-5 mm	79.70^{a}	16.92^{b}	4.04^{a}
	5-10 mm	87.50^{b}	9.70^{a}	2.80^{a}
$LSD_{0.05}$		7.69	6.51	2.79
P		0.04	0.08	0.002

4.5.3 Management strategies to minimize the aggregate disintegration

Through the above result, to minimize aggregate deterioration in the field, it is essential to concern aggregate sizes, soil moisture, and water supply because of their influence on aggregate stability. Tillage is implemented to create proper seedbed conditions for seedling germination and eventual plant growth. Aggregate sizes produced by the tillage would affect soil aggregate stability. Smaller aggregate sizes were less stable than larger aggregate sizes. Moreover, dry soils were seriously disintegrated when they were exposed to the fast wetting. In tropical areas, especially in Mekong delta region, the soil surface is often exposed to prolonged sunny days and heavy rainfall events. The prolonged sunny days often make soil surface become dry. The consequent heavy rain events often take place. It is inevitable that dry surface soils may be submerged abruptly with heavy rainfall events. This natural phenomenon is corresponded with the case when the dry clods were treated with fast wetting in this study. To manage soil structure in the field, using surface mulching or/and cover crops is one of the effective measures to minimize water evaporation and to reduce adverse effects of high intensity rainfall on the soil surface. Irrigation practices should be concerned to limit soil aggregate deterioration because fast water supply on dry soils might cause aggregate disintegration as fast wetting process. To reduce speed of irrigation, it had better use irrigation instruments such as irrigation sprayer. In addition, inhibiting furrow irrigation or border irrigation to avoid aggregate breakdown by fast wetting is essential. Moreover, intensive tillage to make smooth bed is not recommended because smaller size clods were stable less than larger size clods in this study. The use of chicken manure and combination of chicken manure and eggshell was one of the alternative measures strengthening aggregate stability of Mekong delta soils and shown in chapter 5.

4.7 Conclusions

Aggregate stability of SS, AL and AS was evaluated after dry and moist clods were undergone with fast wetting, slow wetting and mechanical breakdown. Among the treatments, the lowest stability of aggregates was shown in dry clods under fast wetting, which resulted in the smallest MWD. The most serious breakdown of dry aggregates exposing with fast wetting process was observed in saline-sodic soil, followed by alluvial soil and acid sulfate soil. The initially 2-5 mm and 5-10 mm clods were more durable than the initially 1-3 mm clods when dry clods were treated with fast wetting process. From the result, dry soils were unstable to fast wetting process which is considered to be a dominant cause of dry aggregate deterioration. Moreover, in our finding, the soils which had different characteristics showed different aggregate behaviors. Among the air dry soils suffering to fast wetting, saline sodic soils indicated more breakdown than alluvial soils and acid sulfate soils. Mekong delta region consists of multiple river channels. Using water from river channels for furrow or border irrigation is popular. Moreover, the soil surface often gets dry in the prolonged sunny days. Dry soils will be submerged in water abruptly if water is pumped from the river into the farm lands. This process is the same as fast wetting which is dominant cause of aggregate breakdown in this study. It would be serious problem in Mekong delta climate.

Chapter 5 - Incubation experiment: Effects of chicken manure and eggshell application on amelioration of low pH soils

5.1 Summary

Upon the results of aggregate stability test, 2-5 mm dry clods under fast wetting were employed for evaluation of aggregate stability of the soils after the incubation following to the application of chicken manure and eggshell. The smallest clods (1-3 mm) were not used for aggregate stability test because they were not proper clod size for seedling emergence. Therefore, we hypothesized 2-5 mm dry clods were stable under fast wetting after amendment application. Soil incubation experiments were designed with seven treatments and three replicates. The eggshell application rates were lime requirement (LR) and a half (1/2 LR), and chicken manure application rates of 25 and 50 g kg-soil^{-1} were employed. Soil and either or both eggshell and chicken manure were mixed and put into a 500 ml glass bottle. Then, soil amendment mixtures were incubated for 45 days in a constant room temperature at 25 ^{o}C. CO_2 concentration of headspace of the glass bottle was periodically measured. After the temporal incubations, soil pH, aggregate stability and organic carbon were determined.

Results indicated that pH of the three soils increased with the amendment application. The application of eggshell raised soil pH during incubation. Soil pH increased with increasing eggshell dose to be twice, from 1/2LR to LR. The increase in chicken manure doses could improve the pH of SS and AL, but it could not be effective at rising pH of AS. The combined application of chicken manure and eggshell was the most effective at increasing soil pH and it was considered as an effective measure for soil pH improvement.

Rapid increase in CO_2 emission rate within the first two days after the eggshell application was observed in the three soils. After chicken manure application, the increase in CO_2 emission rate of SS and AL occurred in the first five days, while the increase started from the 5th day till 20th day in AS. For the combination of eggshell and chicken manure application, CO_2 emission rate within the first five days was observed in SS and AL, whereas in AS, it behaved differently. In AS, the quick increase in CO_2 emission rate was in the first two days and the second increase started from the 5th day till 20th day. In the latter stage of incubation, CO_2 emission rate of AS with the

combined application of eggshell and chicken manure was twice than that of AS with the application of chicken manure alone. It implied that microbial activity was enhanced by the addition of the combination of chicken manure and eggshell.

The application of eggshell only deteriorated soil aggregates, while the application of either the chicken manure or the combination of chicken manure and eggshell could improve aggregate stability. Close relationships between soil pH and CO_2 emission with the addition of chicken manure and the combination of chicken manure and eggshell suggested that the rise in soil pH could enhance CO_2 emission from microbial activity in chicken manure decomposition. It implied that the rise in soil pH by eggshell-$CaCO_3$ in combined application of chicken manure and eggshell may create suitable environment for microbial growth contributing to decomposition of chicken manure. This involved in aggregate stability, where some of organic products produced from decomposition of compost may bind soil particles. It was clarified in this study that the soils having less soil organic carbon in control treatment and in only eggshell treatment showed more aggregate breakdown than the soils having more soil organic carbon in the chicken manure treatment and combination of chicken manure and eggshell treatment. From the result, the application of chicken manure and eggshell was more effective in not only soil pH, but also aggregate stability in low pH soils.

5.2 Introduction

Upon the result shown in chapter 4, dry soils were unstable when they were treated with fast wetting. Mekong delta region is located in tropical climate with two seasons: dry season and rainy season. Heavy rain events falling down on the dry soil surface often occur. This was simulated as fast wetting process, where dry soils were abruptly submerged in water. To solve this problem, the question given is how to limit aggregate breakdown and improve soil pH.

In this study, three soils have low pH. Improving soil pH is the first priority because soil pH affects plant growth. Most plants cannot develop well in low pH soils (Goulding, 2016). In extremely low pH soils like acid sulfate soil, less plant can adapt. In this study, eggshell and chicken manure were reused. Eggshell can be used as lime because it contains 97.8% $CaCO_3$. Chicken manure with low C/N ratio (10.7) was used as compost. According to Dikinya and Muwanzala (2010), the utilization of chicken manure enhanced soil fertility. Eggshell and chicken manure are common wastes in Mekong delta, where gardening-fish raising-poultry chicken raising (VAC) integrated systems are popular in this area (Nhan *et al.* 2005). Reused agricultural products may contribute to protect environment, and save the cost in sustainable agricultural production.

Aggregate stability is another important parameter of soil productivity. Upon the result of aggregate stability test shown in chapter 4, dry aggregates were disintegrated when they were submerged in water. Therefore, evaluating the aggregate stability after amendment application was conducted using 2-5 mm dry clods under fast wetting. Organic matter plays an important role in aggregate formation (Tisdall and Oades, 1982). Organic matter decomposition by microbial activity produces carbohydrates, protein, polysaccharides which act as binding agents in enhancing aggregate stability (Carrizo *et al.* 2015). Effects of organic amendments on aggregate stability and microbial activity have been investigated (Griffiths and Jones, 1965). Micro-organism activity has important roles in organic matter decomposition. Organic products from the decomposition processes may contribute to stabilize aggregates. The soil particle cohesion is enhanced by the formation of multi-complexes of (clay-polyvalent cations-organic matter)$_x$ as linked chains in structure of aggregates (Muneer and Oades, 1989). Micro-organisms are considered as an indicator of soil fertility because they decompose organic matter and release nutrients and organic compound into the soil. Manure compost increased microbial population, thus enhancing soil respiration which was be measured by CO_2 emission (Zhen *et al.* 2014). However, microbial activity is influenced by the nature of the soil and amendment input. Higher salinity could inhibit microbial activity (Shah and Shah, 2011). Not only salinity but also sodicity affect microbial activity (Wong *et al.* 2008). Soil respiration rate, which was measured by CO_2 emission, was lower at EC 10 dS m^{-1} SAR 30 than that at EC 0.5 dS m^{-1} SAR 30. At EC 10 SAR 30, soil respiration rate was lower than that at EC 10 SAR 1 (Wong *et al.* 2008). However, microbial activity could be improved by organic matter applied to the soils with high salinity (Chowdhury, 2016). The soils with pH less than 5.5 suppress microbial activity (Kunito *et al.* 2016). The rise in soil pH from 4.2 to 6.64 after $CaCO_3$ application (35.21 mg $CaCO_3$ g $soil^{-1}$) increased microbial activity (Badalucco *et al.* 1992). According to Karcauskiene *et al.* (2015), the rise in pH of acid soil due to liming increased carbon mineralization by microbial activity, and declined aggregate stability in long term period. However, little is known about the effects of chicken manure and eggshell application on both soil pH and soil aggregate stability associated with changes in soil pH and CO_2 emission in saline and sodic and acid sulfate soil. The application of combination of chicken manure and eggshell were expected to bring more beneficial effects to the soils than either the chicken manure application or the eggshell application on amelioration of acid sulfate and saline and sodic soil.

The aims of this chapter were to observe the effects of chicken manure and eggshell application on changes in soil pH and aggregate stability to clarify role of amendments on quality of saline and sodic soil and acid sulfate soil in the Mekong delta of Viet Nam.

5.3 Materials and Methods

5.3.1 Materials

5.3.1.1 Soil preparation

Soil blocks passed through 2 mm mesh sieve were mixed with amendments. This was modelled amendment application in the field, where the soils were plowed into smaller fragments in order to increase surface contact between amendments and soil particles. All the samples were air-dried at room temperature to constant mass before being mixed with amendments. A 20 g air-dry soil (~ 4% w/w) was used for each soil-incubation.

5.3.1.2 Amendment preparation

Commercial chicken manure which was produced from Tosho Company, Shizuoka Prefecture, Japan was used. The chicken manure was crushed and passed through a 1 mm mesh sieve. Eggshell was used instead of lime because eggshell contains 97.8% $CaCO_3$. Eggshell was collected from the canteen of the University of Tokyo, Japan. After washing with tap water, they were dried in a 105^{o}C oven for 24 hours. Then they crushed and passed through a 106 µm mesh sieve. Eggshell powder and chicken manure are shown in Figure 5.1. The properties of amendments were determined and summarised in Table 5.1.

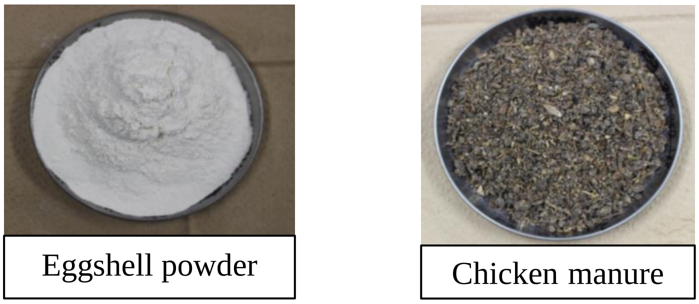


Figure 5.1 Eggshell powder and chicken manure

Table 5.1 Properties of amendments

Parameters	**Unit**	**Chicken manure**	**Eggshell**
Total carbon	%	38.7	16.4
Total nitrogen	%	3.6	1.9
C/N ratio	-	10.7	8.7
Organic carbon	%	38.1	4.7
pH	-	8.2	9.9
EC	dS m^{-1}	8.5	0.13
$CaCO_3$	%	5.0	97.8
Mass water content	%	13.3	1.7
P_2O_5	%	2.3	-
K^+	%	2.1	-
Zn^{2+}	mg kg^{-1}	200	-

Chicken manure and eggshell were employed in this study because they are common wastes in the Mekong Delta region. Since a combination of gardening, fish-raising and poultry-raising is a popular farm management in this region (Nhan *et al.* 2005). Sustainable development is required for beneficial needs of social, environmental and economic integration for long-term sustainability. Garden-pond-livestock/poultry integrated system has partly responded for the first priority of this demand, called VAC intergated system (Figure 5.2). This is close system, where all agricultural wastes are reused. Unhandled wastes would increase air and water pollution affecting human health. Therefore, effective use of wastes such as chicken dung and eggshell would contribute to solve social problems. VAC integrated system was modeled as shown in Figure 5.2.

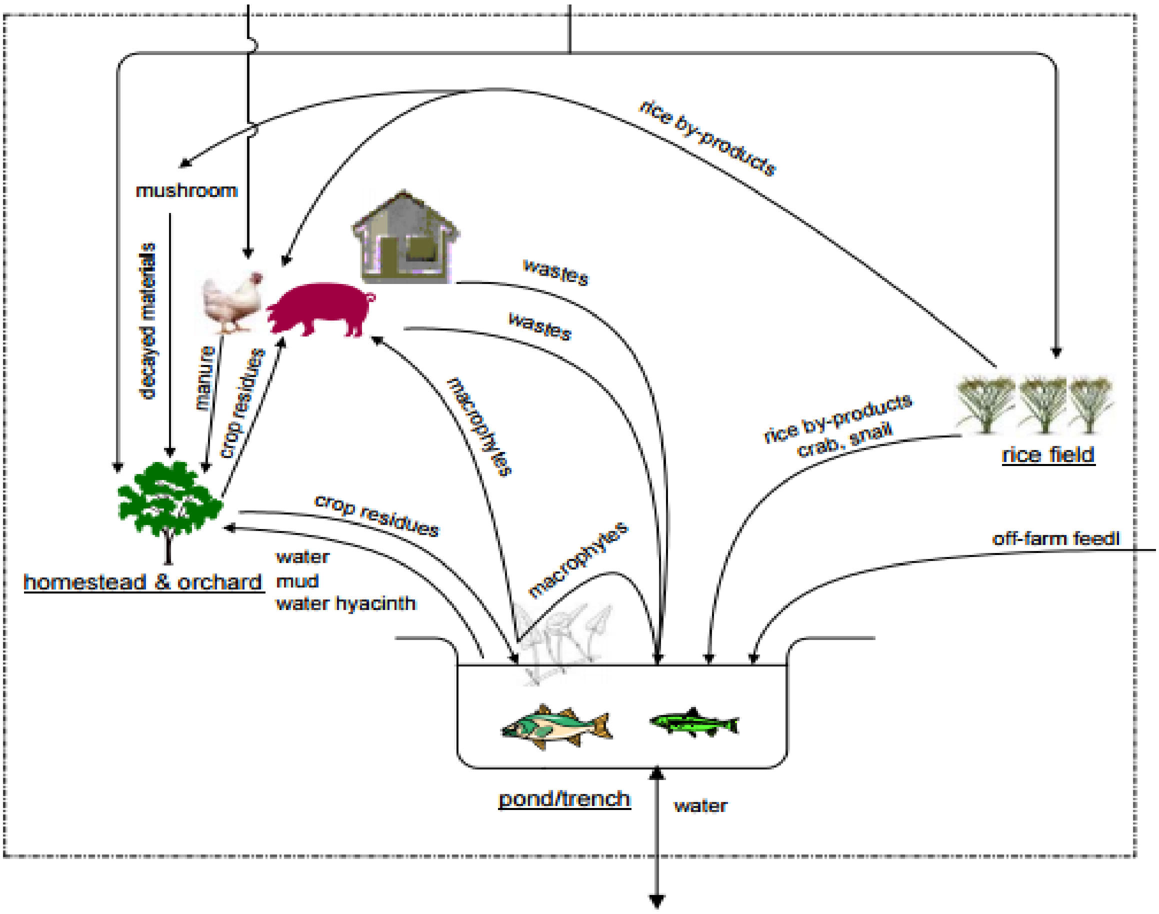


Figure 5.2 VAC integrated system in the Mekong Delta (Nhan *et al.* 2005)

5.3.2 Methods

5.3.2.1 Analytic measurement of amendment properties

EC and pH of the chicken manure were measured using a 1: 5 solid/water suspension. EC and pH of the eggshell were measured using a 1:100 solid/water suspension. The $CaCO_3$ content in the chicken manure and eggshell was determined by method of empirical standard curve (Loeppert *et al.* 1984). Weight of 5, 20, 50, 100, 200, 400, 600 mg of pure calcite containing 99.5% $CaCO_3$ was added into centrifuge tubes. Accurate 2 g of chicken manure and 100 mg eggshell were used. After addition of 30 ml acetic acid (CH_3COOH) (0.4 M), tubes were shaken intermittently for 8 hours and stood overnight with caps loosened to allow escape of CO_2. Then, the tubes were degassed, centrifuged and recorded pH. Based on the standard curve of pH versus pure calcite (mg), the percentage of $CaCO_3$ in sample was determined. Organic carbon content in the chicken manure and eggshell was determined based on total carbon and known

$CaCO_3$:

Organic carbon (%) = total carbon (%) – ($\frac{\% CaCO_3 \ x\ 12}{100}$) (Soon and Hendershot, 2006) [8]

Where: %$CaCO_3$: known percentage of $CaCO_3$

12: molar mass of carbon in $CaCO_3$ (g mol^{-1})

5.3.2.2 Soil incubation

Incubation experiment was designed with seven treatments and three replicates shown in Table 5.2.

Table 5.2 Treatments of soil incubation experiment

Treatments	Explanation
(1) Control	No amendment
(2) Eggshell-1/2LR	50% LR eggshell
(3) Eggshell-LR	100% LR eggshell
(4) CM25	25 g chicken manure kg-$soil^{-1}$
(5) CM50	50 g chicken manure kg-$soil^{-1}$
(6) CM25 + Eggshell-1/2LR	25 g chicken manure kg-$soil^{-1}$+ 50% LR eggshell
(7) CM50 + Eggshell-LR	50 g chicken manure kg-$soil^{-1}$+ 100% LR eggshell

Chicken manure application rates of 25 g kg-$soil^{-1}$ and 50 g kg-$soil^{-1}$ were used in this study. This can be converted to 25 t ha^{-1} and 50 t ha^{-1} with an assumption of incorporation into surface 10 cm thick soil layer and dry bulk density of 1 g cm^{-3}. Eggshell application rates were determined based on the results of lime requirement (LR) test (Sims, 1996) (Figure 5.3). Each 10; 25; 50 and 100 mg of eggshell was mixed with a 3 g air-dry soil in a 50 ml centrifuge tube. After the addition of 25 ml pure water, tubes left overnight and shaken over 30 minutes and then centrifuged to get supernatant to measure soil pH. The amounts of $CaCO_3$ in eggshell to attain soil pH of 6.5 were used as lime requirement (LR) (Table 3.4). The eggshell application rates of 50% and 100% of lime requirement corresponded to 1/2LR and LR were used.

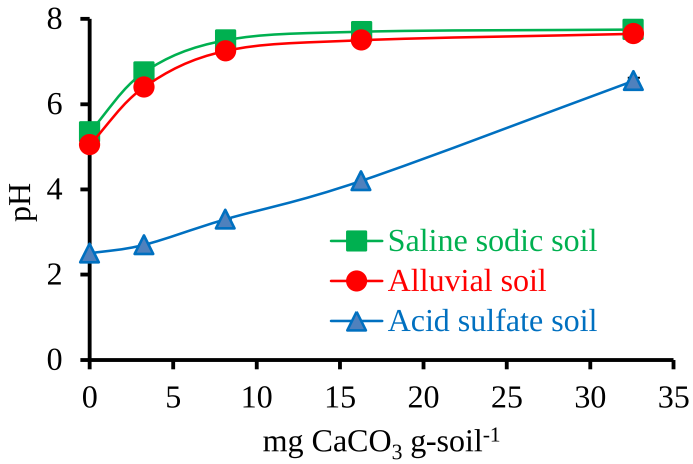


Figure 5.3 Lime requirement test

5.3.2.3 Incubation conditions

The incubation experiment was conducted for 45 days at the constant room temperature of 25 °C. A 500 ml glass bottle with two three-way-valves on its lid was used. The cap permitted gas exchange inside and outside of the bottle (Dumale *et al*. 2009). A gas sampling port with an internal septum was mounted on the lid to collect gas samples inside the bottles (Figure 5.4). Before each bottle was sealed airtight, a 20 g soil mixed with amendments was put to it. Sufficient water was added to keep soil moisture at field capacity.

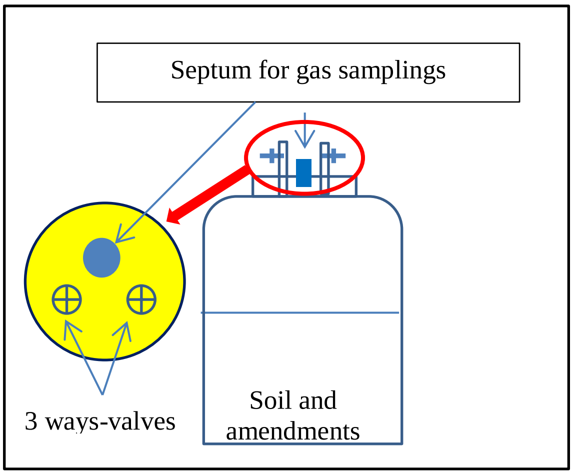


Figure 5.4 Model of glass bottle used for soil incubation

The field capacity was determined using hanging water table at -100 cm H_2O (ψ_m =

-10.1 kPa) (Klute, 1986) (Section 3.3.1.11). Volumetric water contents at field capacity were different with different soil types (Figure 5.5). The volumetric water content was the least in AS, followed by AL and SS, which were 0.24 cm^3 cm^{-3}, 0.41 cm^3 cm^{-3}, and 0.49 cm^3 cm^{-3}, respectively.

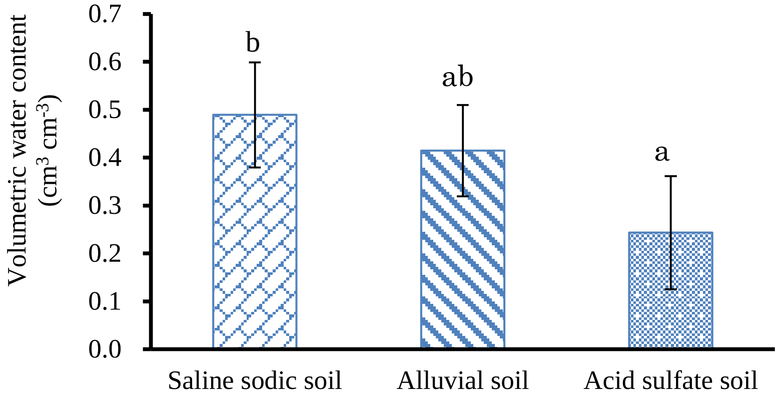


Figure 5.5 Volumetric water content at field capacity

Head space of the bottle was flushed by moist air every two days (Figure 5.6). In this way, the air in the bottle could be replaced and replenished with outside air during the incubation periods. Failure to perform this procedure would result in a rapid increase in pressure of CO_2 (p CO_2) in the bottle and inhibition of microbial activity. Moreover, soil moisture has to be kept at field capacity during main incubation. If keeping the bottles always opens during 45 days, soils will become dry due to evaporation. Therefore, pre-experiment was conducted.

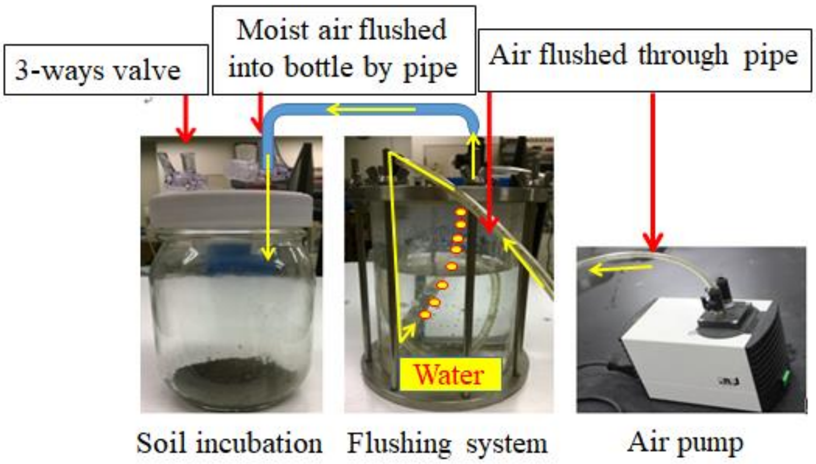


Figure 5.6 Flushing process during soil incubation experiment

In the pre-experiment, a 20 g of soils was mixed with the amendments. Soil moisture was adjusted with water at field capacity. Then, soil and amendment mixtures were incubated in constant room temperature of 25 ^{o}C. Three treatments were designed: everyday-interval flushing, every 2 days -interval flushing and non-flushing for continuous 3 days. Gas samples were collected every day to investigate the effects of flushing work on CO_2 emission. As can be seen in Figure 5.7, the lowest amount of CO_2 was shown in non-flushing of continuous 3 days. For flushing every 2 day-interval, the amount of CO_2 was highest. It showed that keeping close continuous 3 days could inhibit micro-organisms. Flushing every day (1 day interval) by moist air may decrease temperature inside the bottles compared to temperature outside the bottles. This may inhibit microbial activity and thus produce less CO_2 for 1 day interval than 2 day interval. Therefore, 2 day-interval was used for flushing work during 45 days incubation.

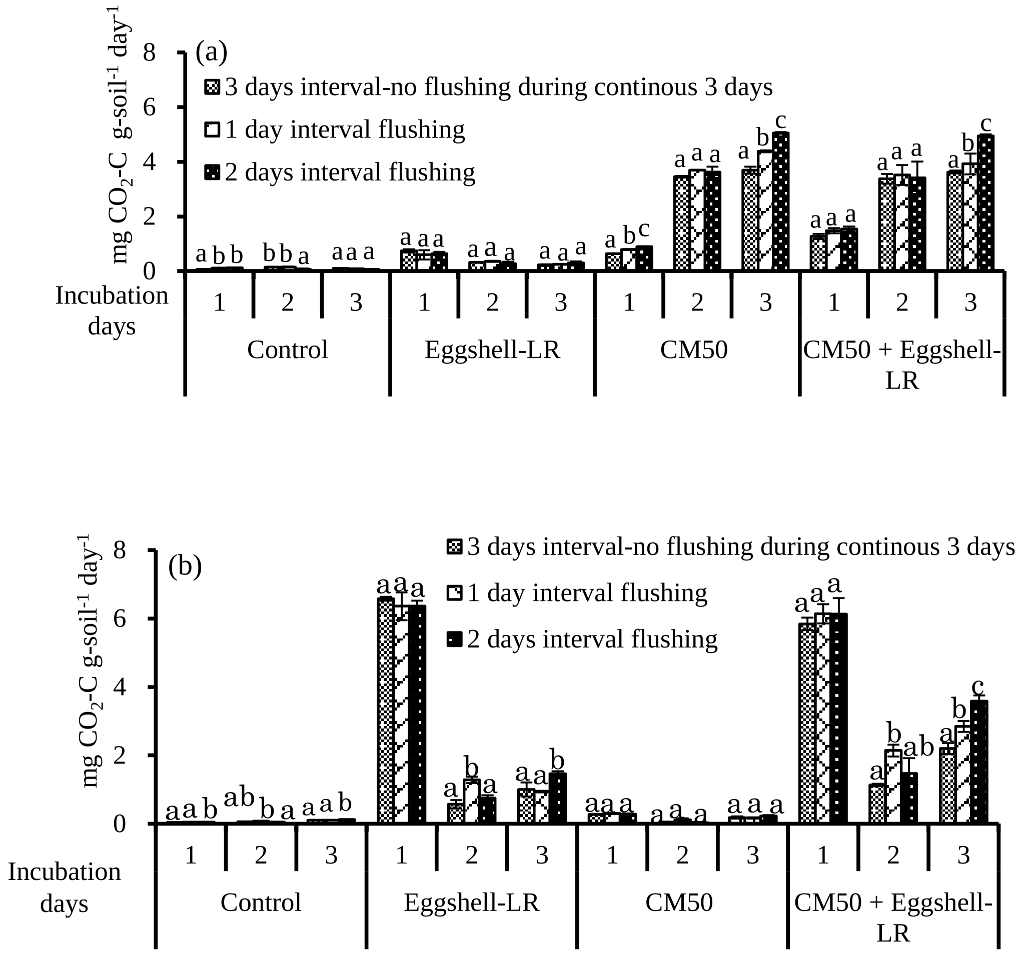


Figure 5.7 Effects of flushing work on the changes in CO_2 emission during three incubation days. The number of days-interval flushing: non-flushing continuous 3 days, 1 day-interval flushing and 2 days-interval flushing was conducted in (a) saline and sodic soil and (b) acid sulfate soil designed with four treatments: control, Eggshell-LR, chicken manure (50 g kg-soil^{-1}) and their combinations. Vertical bars showed the standard deviation. Different letters showed the significant difference between interval flushing days at significance level of 5% using least significance difference ($LSD_{0.05}$) test.

5.3.2.4 Gas sampling and gas analysis

Gas samples were drawn with a 10 ml plastic syringe (Nipro, Osaka, Japan) fitted with 0.7 x 38.0 mm needle (Nipro, Japan) to measure CO_2 concentration. First, the syringe inserted into the septum mounted on the lid of bottles to withdraw the gas. For homogenous sampling, a syringe was connected to the three-way valve to mix the air inside the bottle 4-5 times before sampling. Then, the gas samples were then transferred to a 5 ml vacuumed glass vial fitted with rubber septum. CO_2 concentration of a 2 ml gas sample was measured by a gas chromatography (GC-2014 Shimadzu, Corp., Kyoto, Japan). Gas samples were drawn at the time zero (t_o) of incubation and at sampling times (t_s) on days of 1; 2; 3; 5; 7; 10; 20; 30; 45 of incubation. Since the moist air was flushed every 2 days, the time zero (t_o) was the starting time of incubation for the first flushing during the first two days. From the first flushing till 24th flushing, gas samples at the time zero (t_o) were collected after the flush just ceased. The gas samples at the sampling time (t_s) were collected before next flush. The sampling time interval (t) is the time difference between t_s and t_o. Gas samples at t_o and t_s were collected to analyse concentration of CO_2. The CO_2 emission rate was calculated using the following equation:

$$E = \frac{V\ (\mathrm{L}) \times (C_{ts} - C_{to}) \times M\left(\frac{\mathrm{g}}{\mathrm{mol}}\right) \times P\ (\mathrm{atm})\ \times 1000}{R\ (\mathrm{L\ atm\ K^{-1}\ mol^{-1}}) \times T\ (\mathrm{K}) \times 100 \times w\ (g) \times t\ (\mathrm{day})} \qquad [9]$$

where:

E: Gas emission rate (mg CO_2 g-soil^{-1} day^{-1})
V: Volume of bottle (L)
C_{ts} and C_{to}: Concentration of CO_2 at t_s and t_o (vol.%)
t: Sampling time interval between t_s and t_o (day)
M: molar mass of CO_2 (g mol^{-1}) (44 g mol^{-1})
P: air pressure (atm) (1 atm at ideal gas)
R: gas constant (L atm K^{-1} mol^{-1}) (0.082 L atm K^{-1} mol^{-1})
T: Temperature in Kevin (K) (298K)
w: Weight of air dry soil (g)
t: day
The volume of 1 mol CO_2 at 1 atm and 25 ^oC is 24.44 (L)

5.3.2.5 Aggregate stability test

As mentioned above, amendment application at agricultural fields often needs to plow, and the plough makes soil blocks into small fragments. It is corresponded with the case of this study that soil blocks were cut into small pieces and sieved through a 2 mm mesh sieve before mixing with amendments. During soil incubation, small fragments might aggregate together to form larger aggregates with irregular shapes (Figure 5.8). To make them uniform in all the treatments in aggregate stability measurement, all the soils were cut into 2-5 mm in size after the halt of soil incubation. Upon the result of chapter 4, although fine clods (1-3 mm size) were more stable than larger clods under fast wetting, it was not recommended to create during tillage process because fine clods did not offer proper seedbed for seeding emergence. As recommended by Braunack and Dexter (1988), 2-4 mm size clod ranges were optimum for seedling emergence. From this reason, air-dry clods (2-5 mm) under fast wetting were considered as a protocol to determine aggregate stability after amendment application in incubation experiment. The purpose was to consider aggregate stability of optimum clod size range after amendment application.

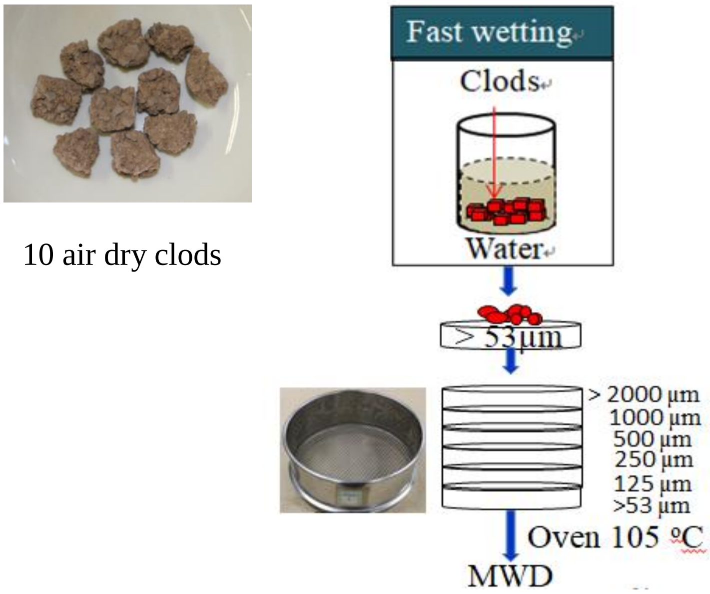


Figure 5.8 Aggregate stability test under fast wetting

From the results of aggregate stability test mentioned at 4.6 (chapter 4), air-dry clods under fast wetting process were employed for aggregate stability test after soil-amendment incubation. After the halt of incubation periods: day 3, day 10; day 20 and day 45, soil moisture was measured to know its changes compared to original soil moisture. Then, the bottles kept open for 6 hours to reduce soil wetness. All the samples were cut into 2-5 mm square clods and air-dried at room temperature of 25 ^{o}C to constant mass. The procedures of aggregate stability measurement were conducted as the same with above procedures (section 4.4.2.2) of fast wetting treatment (Le Bissonnais, 1996).

5.3.2.6 Soil pH and soil organic carbon measurement

After the halt of incubation periods of the 3th day, the 10th day, the 20th day and the 45th day, soil samples were air-dried at constant room temperature 25 ^{o}C until their mass reached constant. Then, soil pH and soil organic carbon were measured (section 3.3.1.1 and 3.3.1.3, respectively).

5.4 Results

5.4.1 Soil moisture as the function of time

Figure 5.9 shows the fluctuation of soil moisture in three soils during incubation time. As presented above, mass water content of the soil at field capacity attained for soil-amendment incubation was 47% in SS, 39% in AL and 37% in AS. After incubation periods, soil moisture had a slight tendency to increase because of the effects of moist air flushing work. Moist air was flushed into the bottles every 2 day interval. Water vapour could be absorbed by soil-amendment mixtures and thus increased slightly soil moisture.

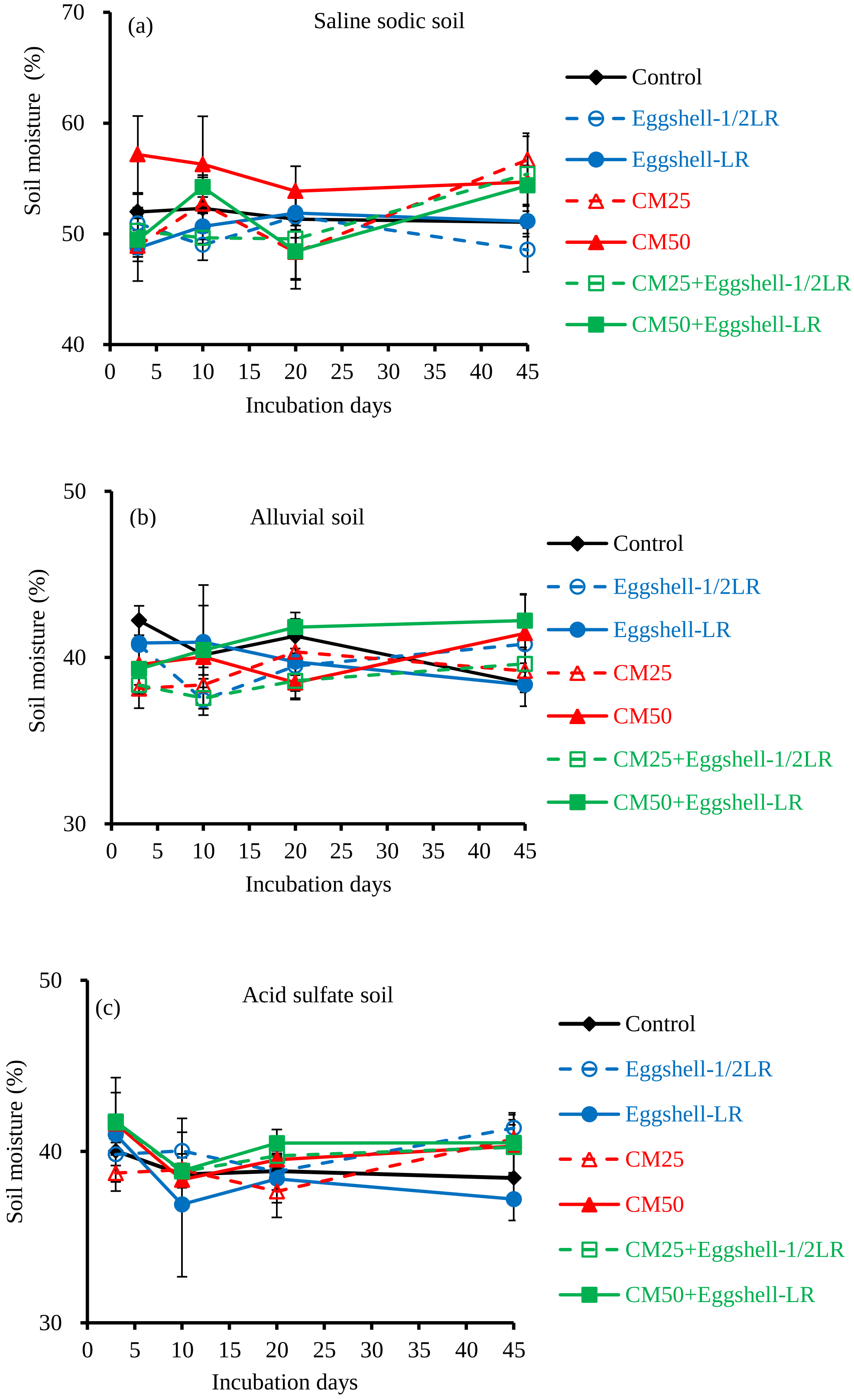


Figure 5.9 Fluctuation of soil moisture. Vertical bars show standard deviation.

5.4.2 Effects of chicken manure and eggshell application on soil amelioration

5.4.2.1 Effects of chicken manure and eggshell application on temporal changes in soil pH

Soil pH is an important parameter that affects plant growth, soil micro-organisms and available nutrients in soils (Goulding, 2016). Optimum pH range was from 6 to 6.5 (Goulding, 2016). Lower soil pH may inhibit the plant growth and microbial activity. Three soils in the Mekong delta had low pH. Therefore, improvement of soil pH is the first priority of the agricultural purpose.

The temporal changes in pH of SS after the amendment application are depicted in Figure 5.10. Among the treatments, the lowest pH level was shown in control treatment, about 4.4 during 45 day incubation. The highest pH level was obtained from the addition of a combination of CM50+Eggshell-LR, which was 6.6 on 3rd day and increased to be 7.2 on 45th day after application. When amount of each amendment in the combination of chicken manure and eggshell reduced to be a half, pH was lower. On 3rd day, the pH was 6.1, and then increased to be 6.5 on 45th day after application of the combinations of CM25+Eggshell-1/2LR. In comparison with lower dose of chicken manure (CM25) added to the SS, pH level was higher for SS with the addition of higher dose of chicken manure (CM50). Similarly, higher dose of eggshell (Eggshell-LR) was more effective in pH rise than lower dose of eggshell (Eggshell-1/2LR).

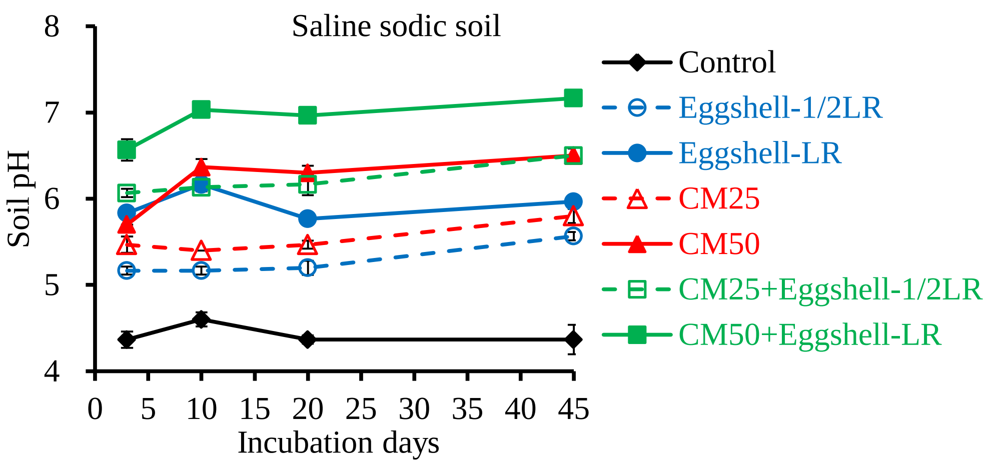


Figure 5.10 Changes in pH of SS after amendment application as a function of time. Vertical bars show standard deviation.

As can be seen in Figure 5.11, pH of AL changed after the amendment application. Among the treatments, the pH of un-amended AL was the lowest, 4.5 on 3rd day and 4.9 on 45th day after incubation. Small increase in pH of AL was found in the application of either CM25 or Eggshell-1/2LR, each with 5.8 at the end of incubation. When amendments were combined together, pH achieved higher, ranging from 5.9 on 3rd day to 6.7 on 45th day. The pH of AL attained from the combination of CM50+Eggshell-LR application was higher than that from the application of either CM50 or Eggshell-LR. With the application of combination of CM50+ Eggshell-LR, the pH was 6.6 on 3rd day and 7.1 on 45th day, while pH of AL was 6.2 for CM50 application and 6.6 for Eggshell-LR application on 45th day. The application of CM50, Eggshell-LR, combination of CM50+Eggshell-LR and combination of COM25+Eggshell-1/2LR could increase soil pH to be optimum threshold for plant growth.

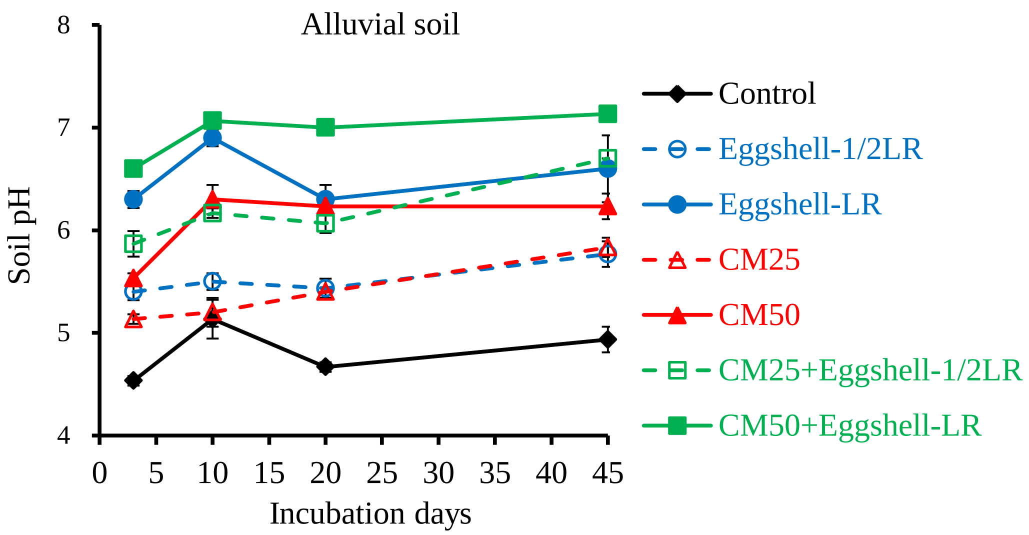


Figure 5.11 Changes in pH of AL after amendment application as a function of time. Vertical bars show standard deviation.

Figure 5.12 shows changes in pH of AS during 45 day incubation. The smallest increase in pH of AS was obtained from the application of either CM25 or CM50. This was followed by applying of either Eggshell-1/2LR or combination of CM25+Eggshell-1/2LR. For only Eggshell-LR application, pH increased to be 4.9 on 3rd day, 5.4 on 10th day and back to 4.9 on 45th day. When Eggshell-LR was combined with CM50 together and added to the AS, the pH achieved the highest. The application of combination of CM50+Eggshell-LR increased pH to be 5.4 at day 3 and 5.8 at day 45 day.

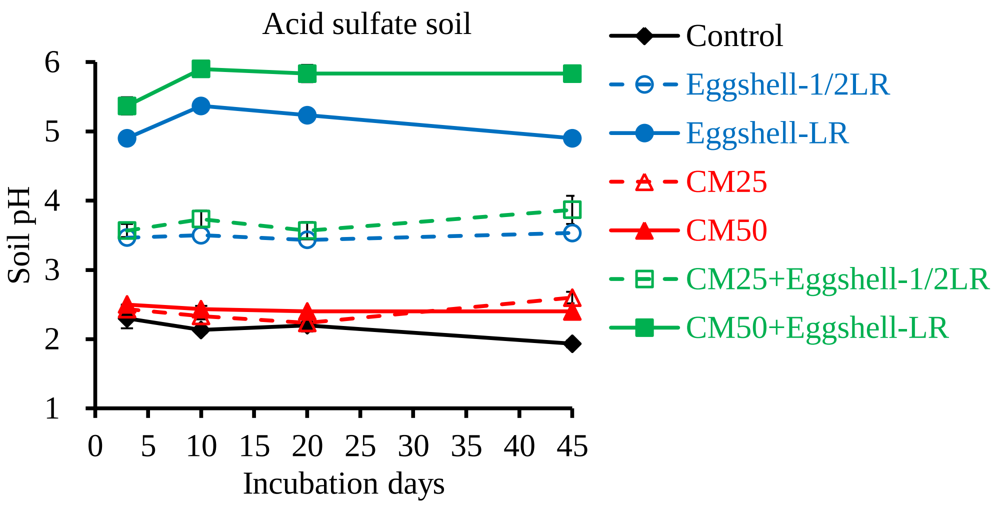


Figure 5.12 Changes in pH of AS after amendment application as a function of time. Vertical bars show standard deviation

5.4.2.2 Effects of chicken manure and eggshell application on soil pH after 45 days soil incubation

At the end of incubation, pH of amended soils was higher than that of un-amended soils (Figure 5.13). When the amount of eggshell application increased from 1/2LR to LR, soil pH increased from 5.6 to 6.0 in SS, 5.8 to 6.6 in AL and 3.5 to 4.9 in AS, respectively. Though, definition of lime requirement (LR) is the amount of calcium carbonate to raise soil pH to be 6.5, the value of pH of the AS and SS after 45-days incubation was lower than 6.5. It was obvious in AS, where pH obtained from the eggshell application rate of LR was 4.9.

The use of chicken manure could also improve soil pH (Figure 5.13). The addition of chicken manure could increase soil pH to be 5.8 and 6.5 in SS and 5.8 to 6.2 in AL when the amount of chicken manure increased from 25 g kg-soil^{-1} to 50 g kg-soil^{-1}, respectively. The pH of AS increased to be 2.6 from the initial value of pH 1.9 by applying the amount of chicken manure of 25 g kg-soil^{-1}. Shamshuddin *et al.* (2004) reported that the pH of an acid sulfate soil could increase from 3.65 to 4.35 with the addition of a combination of peat and green manure. However, the chicken manure could have less effect on the increase in pH of AS. The pH of AS remained low, with 2.4

at chicken manure application rate of 50 g kg-soil^{-1}.

Combination of eggshell and chicken manure showed greater rise in soil pH than either the eggshell or chicken manure application (Figure 5.13). There was a significant increase ($P < 0.001$) in soil pH to be 6.5, 6.7, 3.9 in SS, AL and AS, respectively by the combination of eggshell (1/2 LR) and chicken manure (25 g kg-soil^{-1}). As application rate increased to be a twice (LR), soil pH rose to be 7.2, 7.1 and 5.8 for SS, AL and AS, respectively after 45 days incubation. The spectacular increase in soil pH may be due to combined effects of eggshell and chicken manure.

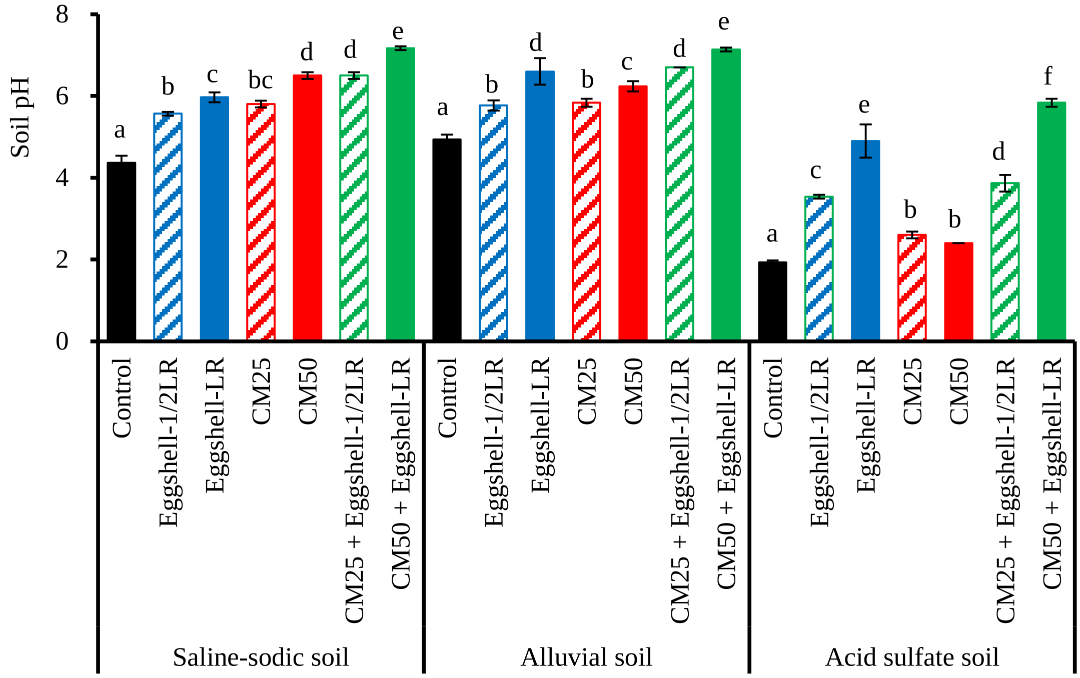


Figure 5.13 Effects of chicken manure and eggshell application on pH of the soils after 45 days soil incubation. Vertical bars show the standard deviation. Different letters show the significant differences between treatments at significance level of 5% using LSD test: saline-sodic soil ($LSD_{0.05} = 0.21$; $P = 4.3 \times 10^{-12}$); alluvial soil ($LSD_{0.05} = 0.33$; $P = 2.2 \times 10^{-8}$) and acid sulfate soil ($LSD_{0.05} = 0.39$; $P = 2.9 \times 10^{-11}$).

5.4.2.3 Effects of chicken manure and eggshell application on temporal changes in aggregate stability

Temporal changes in aggregate stability of SS, AL and AS with or without amendment application are shown in Figure 5.14~5.16. In SS, MWD values after the addition of chicken manure and combination of the chicken manure and eggshell was higher than that after the addition of the eggshell application (Figure 5.14). For the treatment of CM25 and CM25+Eggshell-1/2LR, MWD value was about 2.5 mm from 3rd day to 20th day. Till 45th day after application, it tended to decrease to be 2.32 and 2.25 mm. At the higher application rate of chicken manure and combination of chicken manure and eggshell following to CM50 and CM50+Eggshell-LR, respectively, MWD value was about 2.55 mm from 3rd day to 20th day and maintained on 45th day. It showed that aggregate stability of SS with the addition of lower rate of chicken manure and combination of chicken manure and eggshell (CM25 and CM25+Eggshell-1/2LR, respectively) could decrease over time, while aggregate stability of SS with the addition of higher rate of chicken manure and combination of chicken manure and eggshell (CM50 and CM50+Eggshell-LR, respectively,) maintain high over time. For eggshell application and no amendment (control), MWD was lower than those with the addition of chicken manure with or without eggshell. The lowest value of MWD was found in no amendment (control), followed by Eggshell-LR and Eggshell-1/2LR. On 3rd day, the MWD value following the eggshell application of LR (0.74 mm) was less than MWD value following to the eggshell application of 1/2LR (1.14 mm). Then, MWD values following to eggshell application rate of LR and 1/2LR tended to decrease over time, which was 0.59 mm for Eggshell-LR and 0.94 for Eggshell-1/2LR on 45th day.

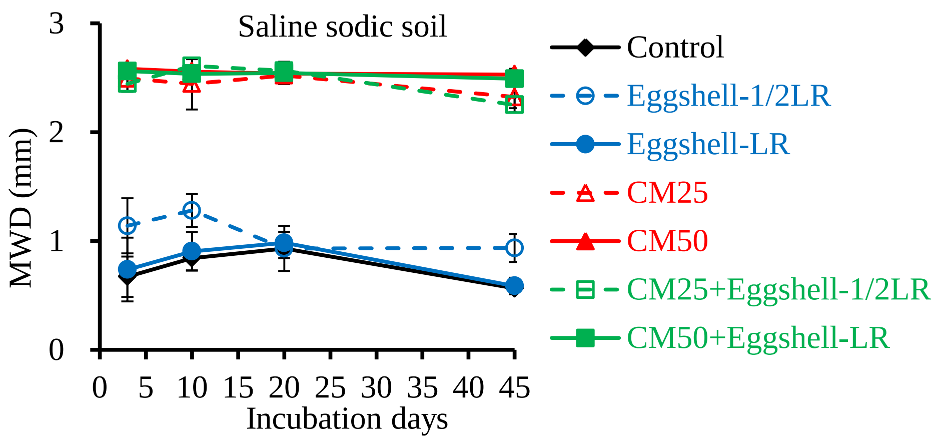


Figure 5.14 Temporal changes in aggregate stability in saline sodic soil after 45 days amendment application. Vertical bars show standard deviation.

Figure 5.15 shows the temporal changes in aggregate stability of AL after amendment application. As indicated in this figure, the application of chicken manure and combination of chicken manure and eggshell could make aggregates more stable than the application of the eggshell alone. It was obvious that higher MWD value attained by adding chicken manure and combination of chicken manure and eggshell than that by adding eggshell only or without amendment. With lower application rate of chicken manure (CM25) and combination of chicken manure and eggshell (CM25+eggshell-1/2LR), MWD was 2.70 and 2.63 mm, respectively on 3rd day and decreased slightly, each with 2.39 mm in 45th day. It showed that aggregate stability declined with the time after either the chicken manure application or the combination of chicken manure and eggshell application at lower rate. At higher application rate of chicken manure (CM50) and the combination of chicken manure and eggshell (CM50+eggshell-LR), MWD remained high, about 2.60 mm during 45 days incubation. It showed that aggregate stability maintained high over time for higher amount of chicken manure and combination of chicken manure and eggshell and tended to decrease over time for lower amount of chicken manure and combination of chicken manure and eggshell. In comparison with chicken manure with or without eggshell, aggregates with the addition of eggshell alone were disintegrated remarkably. For the eggshell application rate of 1/2LR and LR, the MWD value was less than 1.2 mm.

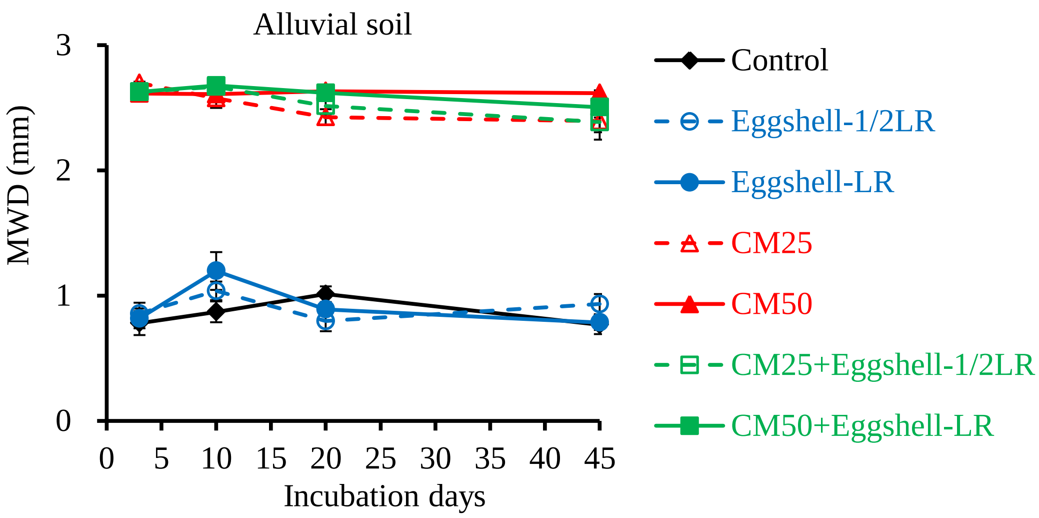


Figure 5.15 Temporal changes in aggregate stability in alluvial soil after 45 days amendment application. Vertical bars show standard deviation.

The temporal changes in aggregate stability after amendment application in AS are shown in Figure 5.16. On 3rd day after the application, chicken manure and combination of chicken manure and eggshell showed smaller MWD value than that on 10th day. The value was 2.15 mm, 1.43 mm, 2.46 mm and 1.83 mm for CM25, CM50, CM25+Eggshell-1/2LR and CM50+Eggshell-LR, respectively. It tended to increase to be 2.52, 2.51, 2.68, 2.65 mm for CM25, CM50, CM25+Eggshell-1/2LR and CM50+Eggshell-LR, respectively on 10th day. However, the value of MWD tended to decrease afterwards. The value of MWD was 2.38, 2.47, 2.54 and 2.55 mm on 20th day and 1.96 mm, 1.99 mm, 2.22 mm and 2.20 mm at 45th day for CM25, CM50, CM25+Eggshell-1/2LR and CM50+Eggshell-LR, respectively. The application of eggshell showed the smallest MWD among the treatments. Even the MWD attained by eggshell application was smaller than the control, it showed that eggshell accelerated seriously aggregate deterioration.

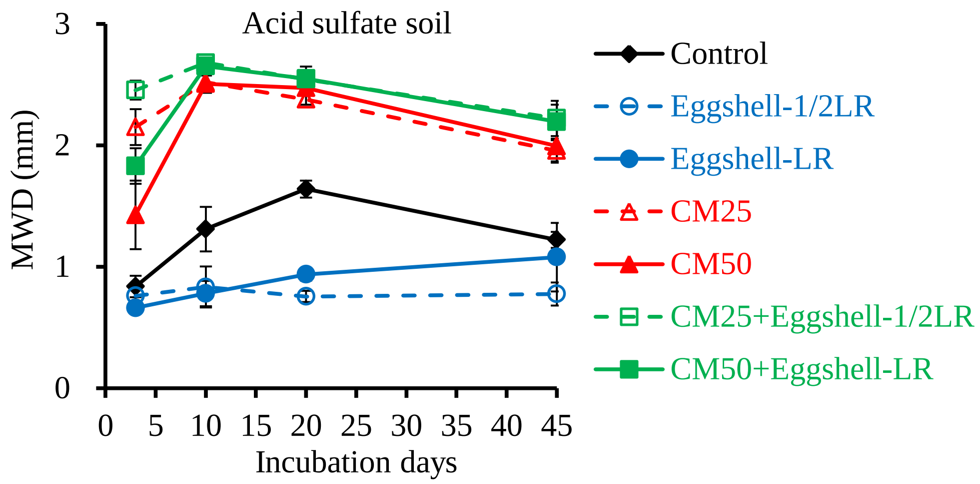


Figure 5.16 Changes in aggregate stability after amendment application in acid sulfate soil during 45 days incubation. Vertical bars show standard deviation.

5.4.2.4 Effects of chicken manure and eggshell application on aggregate stability after 45 days incubation

Figure 5.17 shows changes in MWD value of the three soils after 45 days incubation. The value of MWD was significantly ($P < 0.001$) smaller in un-amended soils and the eggshell amended soils than the soils with the addition of the chicken manure and combination of chicken manure and eggshell. In SS, aggregates could be significantly ($P < 0.001$) disintegrated for higher dose (LR) of eggshell application more than for lower dose (1/2LR) of eggshell application, which corresponded to lower MWD value for Eggshell-LR than for Eggshell-1/2LR. However, there was no significant difference in MWD between two doses of eggshell application to both the AL and AS. A drastically higher MWD was observed in the soils with the application of chicken manure and combination of chicken manure and eggshell. With application of chicken manure, MWD of all the soils increased significantly (P < 0.001). The increase in the amount of chicken manure, from 25 g kg-soil^{-1} to 50 g kg-soil^{-1}, significantly increased (P < 0.001) MWD value from 2.32 to 2.53 mm and from 2.39 to 2.62 mm for SS and AL, respectively. The aggregate stability of AS also increased significantly (P < 0.001) when the chicken manure was applied, but there was no significant difference in MWD between the two doses of chicken manure. The high stability of aggregates was shown in the soils with the application of combination of chicken manure and eggshell following to large MWD of the three soils. Decomposition of applied chicken manure could produce metabolites of micro-organisms and enforce aggregate stability (Carrizo *et al.* 2015).

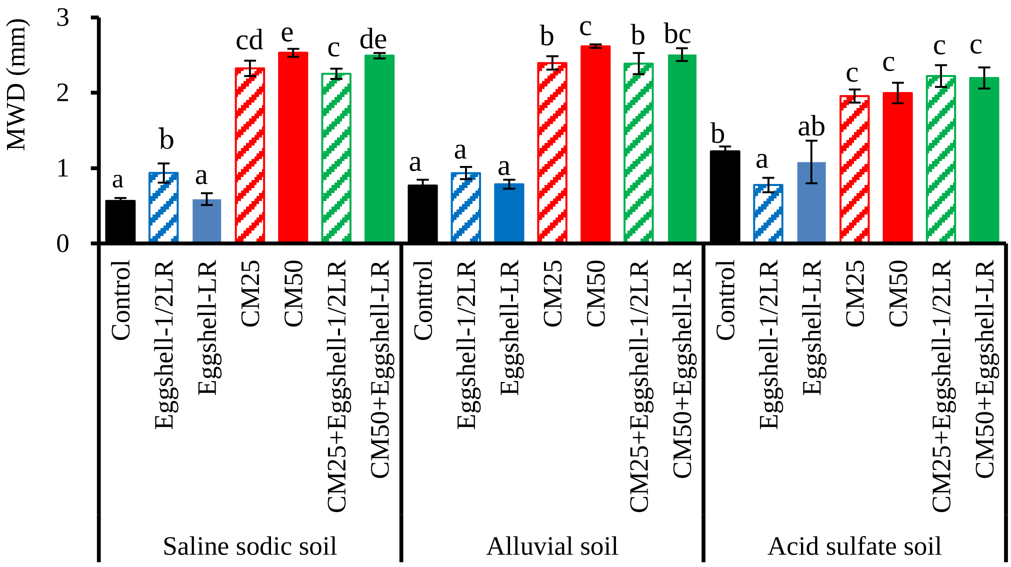


Figure 5.17 Effects of eggshell and chicken manure application on mean weight diameter (MWD) of soils after 45 days incubation. Different letters in a column show significant differences in MWD between treatments at significance level of 5% using LSD test: saline sodic soil ($LSD_{0.05}$ = 0.169; P = 1.04 x 10^{-13}), alluvial soil ($LSD_{0.05}$ = 0.183; P = 5.9 x 10^{-13}) and acid sulfate soil ($LSD_{0.05}$ = 0.324; P = 2.8 x 10^{-7}). Mean ± standard deviation is shown in the same treatment of the same soil.

5.4.2.5 Effects of chicken manure and eggshell application on total CO_2 emission

Total CO_2 emissions from the soils with or without amendments during 45 days soil incubation are shown in Figure 5.18. Without the amendments, all the soils showed a small CO_2 emission, less than 0.8 mg CO_2-C g-soil^{-1}, for all the soils. Eggshell application could increase soil pH and thus lead to increase in total CO_2-C evolution. The eggshell application resulted in a significant increase ($P < 0.001$) in CO_2 emission. In SS, total CO_2 emission was 1.42 mg CO_2-C g-soil^{-1} at lower dose (1/2LR) and 2.12 mg CO_2-C g-soil^{-1} at higher dose (LR). In AL, total CO_2 emission was 2.01 mg CO_2-C g-soil^{-1} and 2.92 mg CO_2-C g-soil^{-1} at eggshell application rate of 1/2LR and LR, respectively. Among the soils, total CO_2 emitted from eggshell application was the greatest in AS. The AS showed the total CO_2 emission of 7.47 mg CO_2-C g-soil^{-1} and 11.42 mg CO_2-C g-soil^{-1} at application rate of 1/2LR and LR, respectively.

Chicken manure application enhanced total CO_2 emission during the 45 days incubation (Figure 5.18). There was a significant difference ($P < 0.001$) in total CO_2 emission between chicken manure-applied soil and un-amended soil. The total CO_2 emission increased significantly ($P < 0.001$) with an increase in the amounts of applied chicken manure. In chicken manure-amended SS, CO_2 emission increased to 6.87 mg CO_2-C g-soil^{-1} and 12.76 mg CO_2-C g-soil^{-1} at application rate of 25 g kg-soil^{-1} and 50 g kg-soil^{-1}, respectively. In chicken manure-amended AL, the total CO_2 emission was 7.66 mg CO_2-C g-soil^{-1} and 14.66 mg CO_2-C g-soil^{-1} at application rate of 25 g kg-soil^{-1} and 50 g kg-soil^{-1}, respectively. However, the total CO_2 emission from chicken manure-amended AS was less than the other soils. The total CO_2 emissions of AS after chicken manure application at the rate of 25 g kg-soil^{-1} and 50 g kg-soil^{-1} were 3.54 mg CO_2-C g-soil^{-1} and 4.29 mg CO_2-C g-soil^{-1}, respectively. Extremely low pH of AS might be a cause of low microbial activity in chicken manure decomposition resulting in low CO_2 emission.

Application of the combination of eggshell and chicken manure could make more CO_2 emission than either the eggshell application or chicken manure application in all the soils (Figure 5.18). In SS, total CO_2 emitted from the soils with the combination of Eggshell-1/2LR+CM25, being 7.99 mg CO_2-C g-soil^{-1}, was higher than either from Eggshell-1/2LR applied soil or CM25 applied soil. The highest total emission of CO_2 for 45 days incubation was observed in the application of combination of

Eggshell-LR+CM50, with 14.11 mg CO_2-C g-soil^{-1} whilst the total CO_2 emission from either Eggshell-LR applied soil or CM50 applied soil was 2.12 and 12.76 mg CO_2-C g-soil^{-1}, respectively. This was similar with the AL, where total CO_2 emission was high by applying the combination of eggshell and chicken manure. In AS with the addition of combination of eggshell and chicken manure, the CO_2 emission was 10.94 mg CO_2-C g-soil^{-1} and 16.84 mg CO_2-C g-soil^{-1} for the treatments of Egshell-1/2LR+CM25 and Eggshell-LR+CM50, respectively. All the soils showed an increase in CO_2 emission after the addition of the chicken manure, eggshell and combination of chicken manure and eggshell. The differences in CO_2 emission between the chicken manure application and combination of chicken manure and eggshell application were not so large for SS and AL, while the differences in CO_2 emission between the eggshell application and combination of chicken manure and eggshell application were significant for AS. Rise in soil pH induced by eggshell-$CaCO_3$ in the combination of chicken manure and eggshell application (Figure 5.13) might enhance CO_2 emission (Figure 5.18).

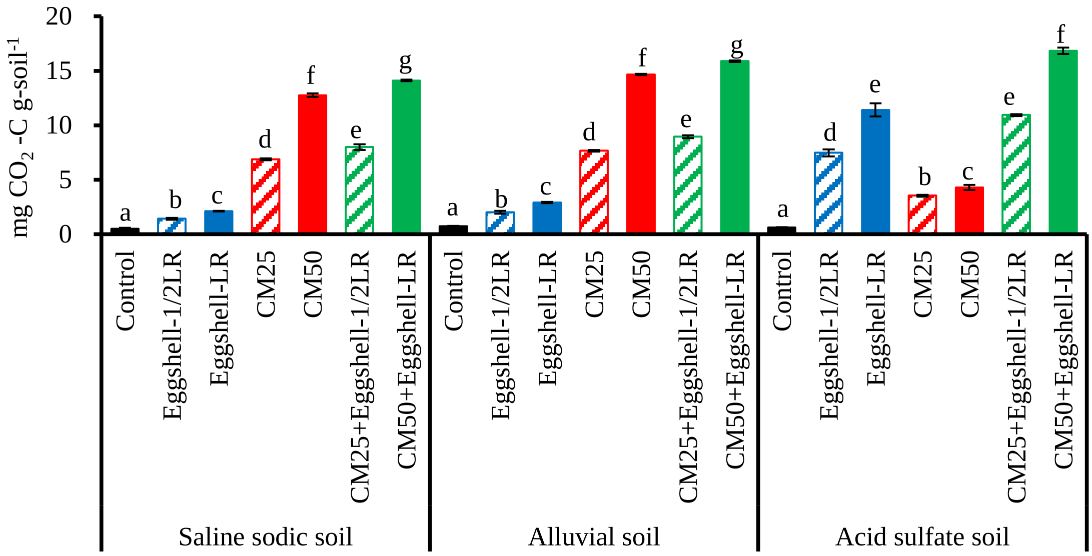


Figure 5.18 Total CO_2 emission from the soils with chicken manure and eggshell application during 45 days soil incubation. Vertical bars show standard deviation. Different letters show significant differences between treatments at the significance level of 5% using LSD test: saline sodic soil ($LSD_{0.05}$ = 0.24; P = 1.9 x 10^{-22}), alluvial soil ($LSD_{0.05}$ = 0.16; P = 1.6 x 10^{-25}) and acid sulfate soil ($LSD_{0.05}$ = 0.52; P = 9.6 x 10^{-18}).

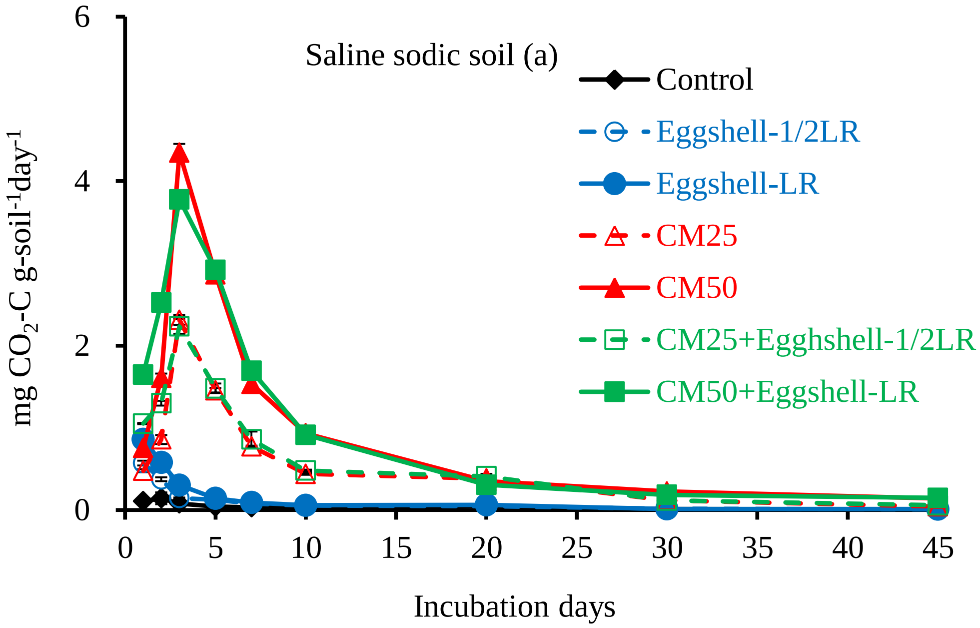
5.4.2.6 Effects of chicken manure and eggshell application on CO_2 emission rate

Temporal changes in daily emission rate of CO_2 during the 45 days soil incubation are shown in Figure 5.19. In AS, the CO_2 emission rate reached the maximum with 5.83 mg CO_2-C g-soil^{-1} day^{-1} at one day after eggshell application. In SS and AL, the CO_2 emission also rose rapidly in a day after eggshell application however this emission rate was not as high as the AS, which was 0.86 and 1.28 mg CO_2-C g-soil^{-1} day^{-1}, respectively. All the three soils showed a quick rise and an abrupt decline in CO_2 emission rate during the first two days after eggshell application. Between two doses, CO_2 emitted from lower dose of eggshell application showed less than higher dose of eggshell application. In spite of this, eggshell-$CaCO_3$ reaction in two doses occurred rapidly within two days.

After chicken manure application, daily CO_2 emission from SS and AL was similar (Figure 5.19a,b). Rapid increase in CO_2 emission rate from the chicken manure-amended SS and AL occurred in the first five days. The highest CO_2 emission rate was observed in SS and AL on 3rd day after chicken manure application, which was 4.35 and 5.04 mg CO_2-C g-soil^{-1} day^{-1} in SS and AL, respectively. At lower dose of chicken manure, CO_2 emission rate reduced by approximately a half at 3rd day. In AS, there was insignificant difference in CO_2 emission rate from chicken manure application between two doses (Figure 5.19c). Small CO_2 emission rate was observed during the first three days, which was less than 0.3 mg CO_2-C g-soil^{-1} day^{-1}. The increase in CO_2 emission rate started from the 5th day, with 0.88 mg CO_2-C g-soil^{-1} day^{-1}, to 1.09 mg CO_2-C g-soil^{-1} day^{-1} on 7th day. Then, it gradually decreased till 20th day. Among the soils, the CO_2 emission rate was lower in chicken manure-applied AS than that in chicken manure-applied SS and AL.

Daily changes in CO_2 emission rate from SS and AL with the combination of chicken manure and eggshell in during 45 days soil incubation showed similar feature of CO_2 emission obtained from chicken manure-amended SS and AL (Figure 5.19a,b). The maximum CO_2 emission was recorded on 3rd day, which was 3.78 and 3.84 mg CO_2-C g-soil^{-1} day^{-1}, respectively. At lower dose of chicken manure and eggshell combination, CO_2 emission rate reduced by approximately one third on 3rd day. In AS, there was similar trend of CO_2 emission occurring within first two days between only eggshell application and eggshell in combination of chicken manure and eggshell application

(Figure 5.19c). Then, the rate of CO_2 emission rose again to be maximum, with 1.94 mg CO_2-C g-soil^{-1} day^{-1} on 7th day at higher dose of the combined application. This second rise in CO_2 emission rate from AS at higher dose of combined application was more than lower dose of combined application and only chicken manure application in the latter stage of incubation. A rapid increase and drop in daily CO_2 emission rate within first two days after the combined application may be due to the reaction of eggshell-$CaCO_3$ in combination and H^+ in the soil. The subsequent increase starting from 5th day to the 20th day may be due to microbial activity in decomposition of chicken manure. It implied that the rise in pH induced by eggshell-$CaCO_3$ reaction could create suitable environment for micro-organisms to decompose more chicken manure and enhance more CO_2 in the latter stage of incubation.



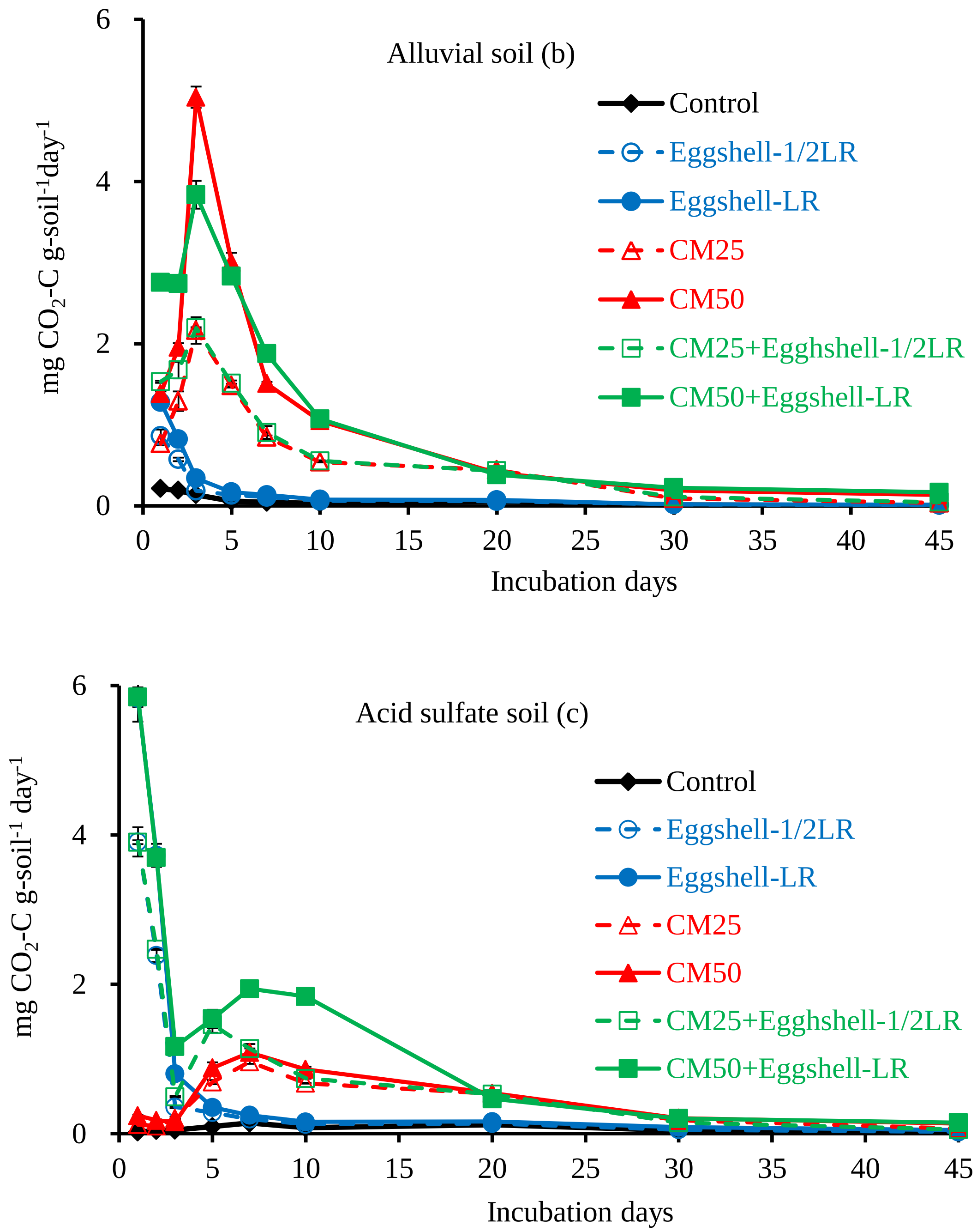


Figure 5.19 Effect of eggshell and chicken manure application on daily changes in CO_2 emission rate in saline sodic soil (a), alluvial soil (b) and acid sulfate soil (c). Vertical bars show standard deviation.

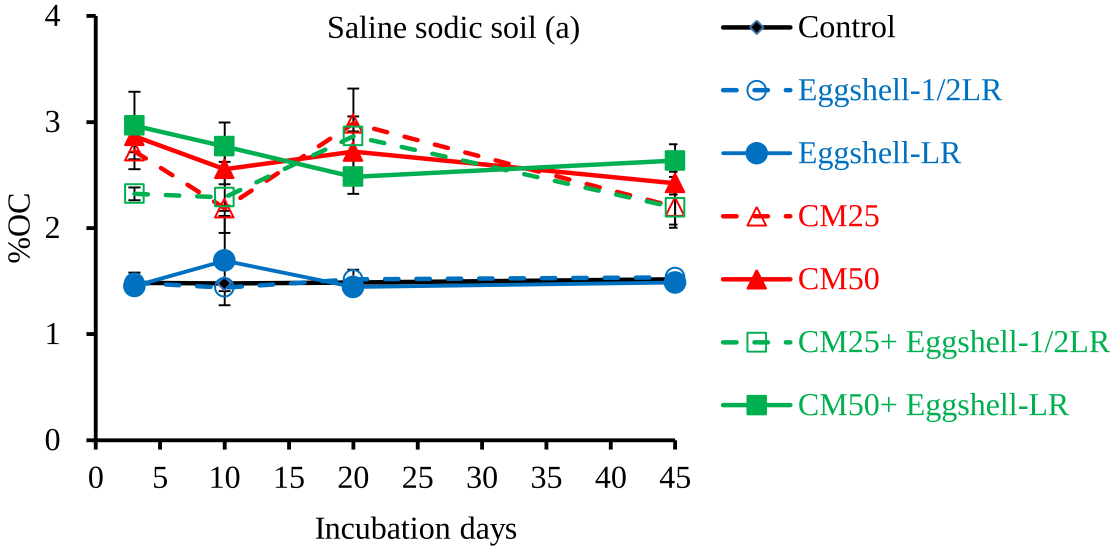
5.4.2.7 Effects of chicken manure and eggshell application on soil organic carbon

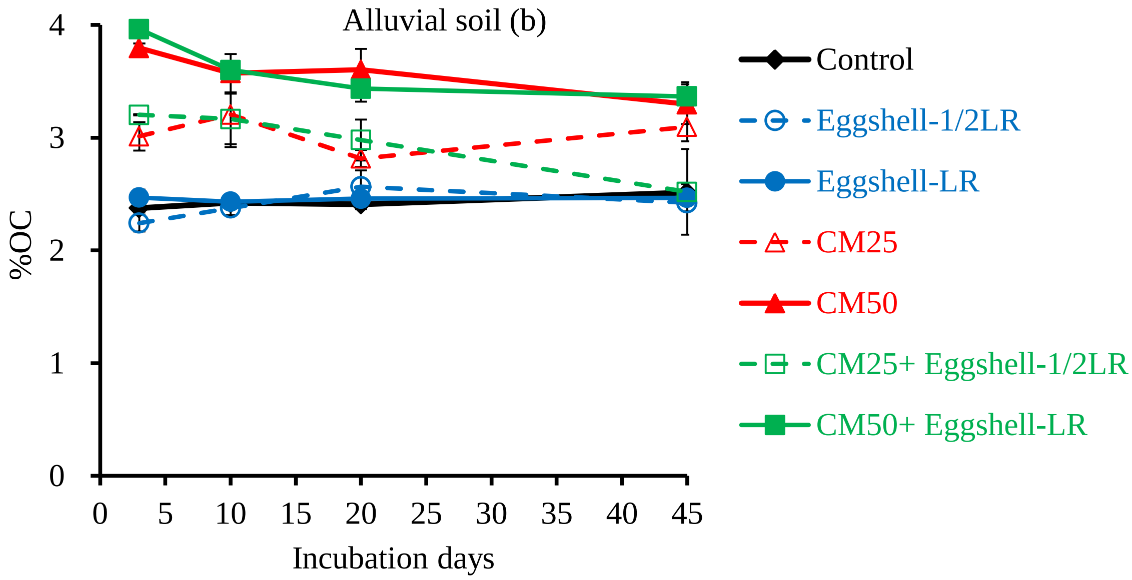
Temporal changes in organic carbon (OC) of the three soils are presented in Figure 5.20. In SS, organic carbon content of eggshell application or without application was lower than that of the application of chicken manure or chicken manure with eggshell

(Figure 5.20a). Over time, the organic carbon content for un-amended SS and eggshell-amended SS remained low, approximately 1.5%. When the chicken manure and combination of chicken manure and eggshell were applied to the SS, organic carbon content increased remarkably to be 2.9% for CM50 treatment and 3.0% for CM50+Eggshell-LR on 3rd day. Till 45th day, the organic carbon content decreased slightly to be 2.4% for the chicken manure application and 2.6% for the combination of chicken manure and eggshell application. Lower dose of chicken manure or chicken manure with eggshell showed less organic carbon than higher dose, but insignificantly.

In AL, organic carbon content of control treatment and Eggshell-1/2LR and LR treatment over 45 days incubation remained lower, each with 2.5% than the other treatments (Figure 5.20b). Applying chicken manure and combination of chicken manure and eggshell showed higher organic carbon. On 3rd day, organic carbon content was 3.8 % for CM50 and 4.0% for CM50+Eggshell-LR. It tended to decline to be 3.3 for CM50 and 3.4% for CM50+Eggshell-LR on 45th day. The lower dose of chicken manure or chicken manure with eggshell showed higher organic carbon than the higher dose.

Among the soils, organic carbon content of un-amended AS was higher than that of un-amended SS and un-amended AL, with 6.6% after 45 days incubation (Figure 5.20c). There was no significant difference in organic carbon between un-amended soils and eggshell-amended soils. This was except for AS, where organic carbon of eggshell application seemed to be lower than organic carbon for control treatment. This implied that eggshell may promote decomposition of original organic matter in AS and thus leaded to the decrease in organic carbon after eggshell application in comparison with control treatment. With the application of either chicken manure or combination of chicken manure and eggshell, organic carbon content increased to be 7.8% and 7.7%, respectively on 3rd day. It decreased to be 7.3% and 7.2%, respectively on 45th day.


Saline sodic soil (a)
%OC
Incubation days
0
1
2
3
4
0
5
10
15
20
25
30
35
40
45
Control
Eggshell-1/2LR
Eggshell-LR
CM25
CM50
CM25+ Eggshell-1/2LR
CM50+ Eggshell-LR


Alluvial soil (b)
%OC
Incubation days
0
1
2
3
4
0
5
10
15
20
25
30
35
40
45
Control
Eggshell-1/2LR
Eggshell-LR
CM25
CM50
CM25+ Eggshell-1/2LR
CM50+ Eggshell-LR

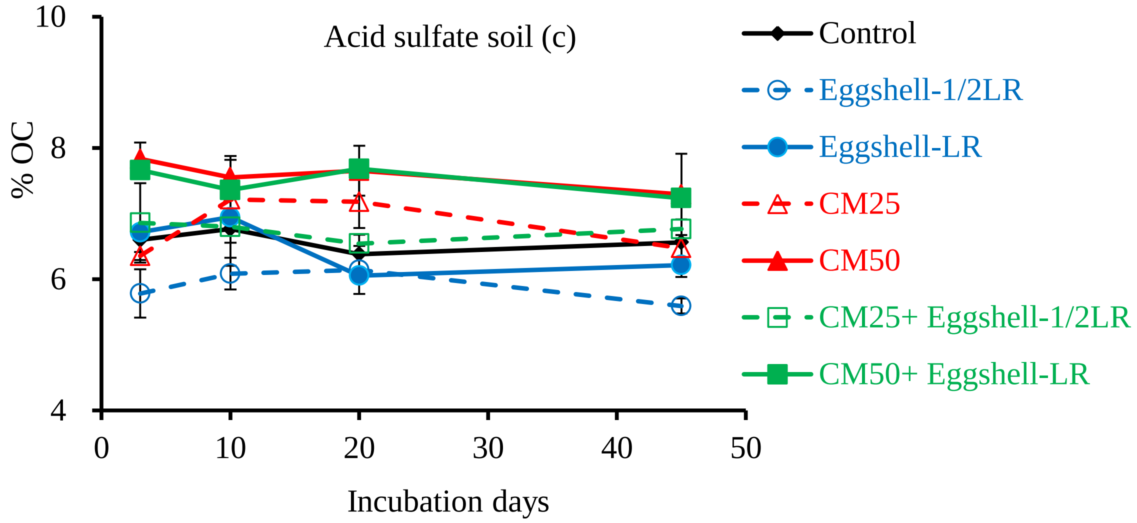


Figure 5.20 Organic carbon (OC) after amendment application (a) in saline sodic soil, (b) in alluvial soil and (c) in acid sulfate soil. Vertical bars show standard deviation

All the soils showed higher organic carbon content for the addition of chicken manure and combination of chicken manure and eggshell than that for only eggshell application at the last day of incubation (Figure 5.21). In SS, there was no significant difference in proportion of organic carbon between control treatment and Eggshell-1/2LR and Eggshell-LR treatment, each with 1.5%. The organic carbon content increased significantly ($P < 0.001$) with the application of CM25 and CM25+Eggshell-1/2LR, each with 2.2%. The rise in organic carbon was significantly ($P < 0.001$) higher for CM50 and CM50+Eggshell-LR, where the organic carbon accounted for 2.4% and 2.6%, respectively. There was similar tendency for AL, where the organic carbon from the only eggshell application was lower significantly ($P < 0.001$) than that from the only chicken manure and combination of chicken manure and eggshell. This was except for CM25+Eggshell-1/2LR treatment. In AS, the content of organic carbon in Eggshell-1/2LR treatment was significantly lower ($P < 0.01$) compared to control treatment, which occupied 5.6% for Eggshell-1/2LR treatment and 6.6% for control treatment. It showed that the eggshell application could cause the loss in organic carbon in AS. Since the rise in pH by eggshell-$CaCO_3$ reaction may promote decomposition of original organic matter by micro-organisms in the soil. This may decrease original organic carbon in AS. In comparison with SS and AL, original organic carbon of AS was much more, so the loss of original organic carbon by microbial decomposition after eggshell application can be seen clearly in AS. The lower dose of chicken manure (CM25) showed less organic carbon accumulation than the higher dose of chicken manure (CM50). There was no significant difference between control treatment and the treatments of Eggshell-LR, CM25, and CM25+Eggshell-1/2LR. The increase in organic carbon proportion in the AS was shown in CM50 and CM50+Eggshell-LR. From the result, organic carbon in AS was more for higher chicken manure dose than for lower chicken manure dose.

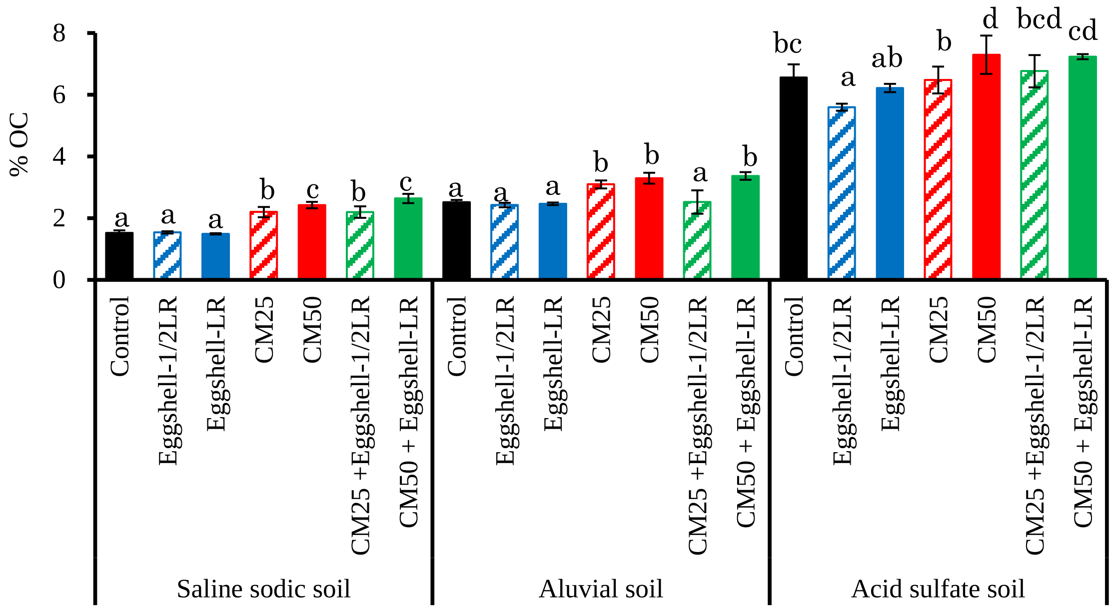


Figure 5.21 Organic carbon in the soils with chicken manure and eggshell application after 45 days soil incubation. Vertical bars show standard deviation. Different letters show significant differences between the treatments at the significance level of 5% using LSD test: saline-sodic soil ($LSD_{0.05}$ = 0.22; P = 2.5 x 10^{-8}), alluvial soil ($LSD_{0.05}$ = 0. 31; P = 1.1x 10^{-5}) and acid sulfate soil ($LSD_{0.05}$ = 0.68; P = 0.0015)

5.5 Discussions

5.5.1 Effects of eggshell and chicken manure application on soil pH

Lime is commonly used to alleviate low pH soils. Saline and sodic soil, alluvial soil and acid sulfate soil in this study had low pH, with 5.5, 4.6 and 2.7, respectively. After the application of eggshell, the pH of the three soils was significantly improved

(Figure 5.13). When the eggshell applied to the low pH soils, the reactions between H^+ and $CaCO_3$ may occur and thereby, soil pH increased. The $CaCO_3$ application at the rate of lime requirement (LR) expected to raise the soil pH to be 6.5. However, the pH of SS and AS remained < 6.5 after 45 days incubation. While the pH of SS raised to be 6.0 by the eggshell-$CaCO_3$ application at the rate of LR, pH of AS raised to be 4.9. A possible explanation for low pH of AS is gradual oxidation of pyrite, which was not considered when lime requirement test was conducted. In pyrite oxidation process, sulfuric acid (H_2SO_4) is produced and lowers pH of AS (Attanandana and Vacharotayan, 1986). As Jayalath *et al.* (2016) suggested that pyrite oxidation process might continue over 70 days incubation. Beside, in lime requirement test, pH of the soil with $CaCO_3$ was evaluated after 24 hours incubation, and the pH of the soil with eggshell-$CaCO_3$ at the rate of LR was measured after 45 days incubation.

The addition of chicken manure could also raise soil pH. There was a drastic rise in pH of SS and AL when the chicken manure application rates increased from 25 g kg-soil^{-1} to 50 g kg-soil^{-1} (Figure 5.13). On the other hand, AS showed smaller pH rise in response to the chicken manure application. The addition of 50 g chicken manure kg-soil^{-1} increased the pH of AS from 1.9 as control treatment to be 2.4. The $CaCO_3$ in the chicken manure compost might contribute to raise soil pH. In this study, the chicken manure contained 5% $CaCO_3$ (Table 5.1) and this could help to raise pH. The application of 25 and 50 g chicken manure kg-soil^{-1} equalled the 1.25 and 2.5 g $CaCO_3$ kg-soil^{-1} through chicken manure application. The eggshell-$CaCO_3$ application at the rate of 1/2 LR and LR corresponded to 1.6 and 3.2 g $CaCO_3$ kg-soil^{-1}, respectively in SS and 2.45 and 4.9 g $CaCO_3$ kg-soil^{-1}, respectively in AL. The amount of $CaCO_3$ in the applied chicken manure at the rates of 25 and 50 g kg-soil^{-1} could help to rise pH of SS. Similar pH of AL was shown between the 25 g chicken manure kg-soil^{-1} and 1/2LR $CaCO_3$ although amount of $CaCO_3$ in the application rate of 25 g chicken manure kg-soil^{-1} was less a half than the amount of $CaCO_3$ at rate of 1/2LR. This suggested alternative process other than the reaction of $CaCO_3$ was responsible for rise in pH of AL. In AS, the eggshell-$CaCO_3$ application at the 1/2 LR and LR corresponded to 16.3 and 32.6 g $CaCO_3$ kg-soil^{-1}, respectively. The amount of $CaCO_3$ in applied chicken manure was minor and negligible. Therefore, $CaCO_3$ in chicken manure could contribute less on the rise in pH of AS. Even though, pH raised after chicken manure compost application compared to control treatment.

Aluminum-organic matter complexes are also expected to raise soil pH after applying organic amendments (Naramabuye and Haynes, 2006a; Hue and Amien, 1989). Hydrolysis of soluble Al species may depress soil pH (Strawn *et al.* 2015), and Al-organic matter complexes depress soluble Al concentration. AL which had the initial pH of 4.6 may contain $Al(OH)^{2+}$ and Al^{3+} as Al species. Following to the application of organic matter, the rise in pH might be caused by Al-organic matter complexes (Naramabuye and Haynes, 2006a). In SS, since the initial pH was 5.5, it could contain an abundance of insoluble Al which could not complex with the organic matter. In contrast, AS which had an original pH of 2.7 or less may have high concentrations of Al^{3+} (Khoi *el al.* 2010). Increase in the chicken manure application did not increase the pH of AS (Figure 5.13) suggesting that Al-organic matter complexes could not affect the pH of AS after chicken manure application.

During chicken manure decomposition by micro-organisms, proton (H^+) consumption by soluble organic anions in decarboxylation processes is expected to contribute to the rise in soil pH (Yan *et al.* 1996; Naramabuye and Haynes, 2006b). Yan *et al.* (1996) used malate and citrate to discuss the role of biological decarboxylation of soluble organic anions on soil pH. They concluded that in aerobic conditions, neither denitrification nor reduction of Mn and Fe was responsible for soil pH rise. Naramabuye and Haynes (2006b) suggested that the decarboxylation of organic anions raised pH during manure decomposition. The biological decarboxylation of soluble organic anions may account for the rise in pH in addition to being a source of CO_2. In the decarboxylation process, protons (H^+) were consumed by organic anions and released CO_2 as the following equation:

$$R-CO-COO^- + H^+ \rightarrow R-CHO + CO_2 \qquad [10]$$

This process simultaneously raised soil pH and produce CO_2. Figure 5.22 shows positive relationships (R^2 = 0.83 for SS, R^2 = 0.60 for AL, and R^2 = 0.7 for AS) between soil pH and CO_2 emission for 45 days incubation with either chicken manure or chicken manure with eggshell-$CaCO_3$. In this figure, CO_2 emission was derived by subtracting CO_2 emission of the eggshell-$CaCO_3$ applied soil from the total CO_2 emissions. It represents CO_2 emission from organic matter decomposition by microbiologies. Although quantitative discussion of pH and CO_2 production relationship requires soil buffering characteristics (Yan *et al*. 1996), the rise in both pH and CO_2 emission (Figure 5.22) qualitatively suggested that the rise in soil pH following chicken manure application was caused by decomposition of chicken manure and subsequent decarboxylation (Yan *et al.* 1996). At least in the present study, both soil pH and CO_2 emission increased after adding either chicken manure or chicken manure with eggshell-$CaCO_3$ (Figure 5.22).

The combination of eggshell and chicken manure showed more effective in soil pH alleviation than either the eggshell or the chicken manure application. The soil pH was higher for the higher application rate of eggshell-LR+CM50 than that for the lower application rate of eggshell-1/2LR+CM25 (Figure 5.13). The pH rise induced by eggshell-$CaCO_3$ in the combined application of chicken manure and eggshell may create suitable environment for microbial growth contributing to decomposition of chicken manure. More soluble organic anions produced from decomposition of chicken manure may consume H^+ by decarboxylation processes of soluble organic anions. The result of this process caused more soil pH rise and more CO_2 emission. The relationship between soil pH and CO_2 would be discussed in latter part.

5.5.2 Effects of eggshell and chicken manure application on CO_2 emission

The application of eggshell to raise soil pH increased CO_2 emission. A rapid rise in CO_2 emission from eggshell-$CaCO_3$ reaction occurred in the first two days and small CO_2 emitted afterwards (Figure 5.19). It could be a reaction between $CaCO_3$ and proton (H^+) in the soil solution. Dumale *et al.* (2011) reported a rapid CO_2-C evolution within the two days after $CaCO_3$ application in an Ultisol. They suggested that the $CaCO_3$ was promptly solubilized in low pH soils like Ultisols. In this study, a maximum CO_2 emission rate was observed at the first day followed by an abrupt decline in CO_2 emission rate thereafter after eggshell application. Among the soils with the addition of eggshell, the CO_2 emission rates were high in AS and low in SS and AL. The relative differences in initial soil pH may account for the different trends of daily CO_2 emission rate among the soils following the eggshell application. In the present study, AS had the lowest pH, followed by AL and SS (Table 3.4). Much H^+ in AS may react with the eggshell-$CaCO_3$, and released CO_2 much faster than SS and AL, whose pH was comparatively higher.

The addition of chicken manure to the soils producing CO_2 suggested enhancement of microbial activity. Soils with chicken manure enhanced microbiological activity, and thus, CO_2 emission rates. However, the CO_2 emission rate varied among the different soil types in response to chicken manure application. In chicken manure-amended SS and AL, a substantial increase in CO_2 emission rate occurred within the first five days (Figure 5.19a, b). In chicken manure-amended AS, the gradual rise in CO_2 emission rate started on 5^{th} day till 20^{th} day (Figure 5.19c). The changes in CO_2 emission in the latter stage of incubation after chicken manure application relied to the activity of micro-organisms. Among the soils, the CO_2 emission rate was lower in chicken manure-applied AS than that in chicken manure-applied SS and AL. Extremely low pH of AS may inhibit micro-organism activity. The effects of soil pH on CO_2 emission rate are shown in Figure 5.22, which depicts the higher CO_2 emission in slightly low pH soils, like SS and AL than in extremely low pH soil like AS after chicken manure application. Suitable pH range for microbial growth is from 5 to 7 (Pietri and Brookes, 2008). AL and SS with chicken manure application had relatively higher initial pH and showed quick increase in CO_2 emission rate in the early stage of incubation (Figure 5.19a, b). In contrast, very acidic AS could have limited microbial activity and gradually increased CO_2 emission rate in the latter stage of soil-chicken manure incubation (Figure 5.19 c).

Soil CO_2 emission was enhanced by applying the combined application of eggshell and chicken manure in comparison with either the eggshell or the chicken manure application. The higher rise in pH of soils added with combination of eggshell and chicken manure than that of soils added with either eggshell or chicken manure (Figure 5.13) might enhance CO_2 emission (Figure 5.18). In strongly acidic AS, there were similar temporal changes in CO_2 emission rate within the first 2 days after eggshell application and the combined application of chicken manure and eggshell. The second increase in CO_2 emission rate between day 5 and day 20 in response to the application of the combination of chicken manure and eggshell was twice of that for the chicken manure alone (Figure 5.19 c). This second rise in CO_2 emission rate could be the result of the enhancement of microbial activity. It implied that the rise in pH induced by $CaCO_3$ in combination with chicken manure could produce more CO_2 by microbiological activity in chicken manure decomposition in the latter stage of incubation. It showed that the combined application of eggshell-$CaCO_3$ and chicken manure could increase soil CO_2 emission rate more than either eggshell-$CaCO_3$ or chicken manure alone. The rise in soil pH caused by the combined application of chicken manure and eggshell (Figure 5.13) could enhance soil CO_2 production (Figure

5.18). It may suggest that the rise in pH induced by eggshell-$CaCO_3$ in combination of chicken manure and eggshell may create suitable environment for microbial growth to produce more CO_2 in the latter stage of incubation in AS (Figure 5.19 c). In slightly low pH soils like SS and AL, there were similar trends of CO_2 emission rates proceeding more than 2 days and showed a peak at 3rd day in response to chicken manure application and combination of chicken manure and eggshell application (Figure 5.19 a, b). In case of the eggshell application alone, there was a small increase in CO_2 emission rate induced by $CaCO_3$ reactions within the first 2 days. Therefore, CO_2 emission rate of AL and SS proceeded more than 2 days after the combined application of chicken manure and eggshell (Figure 5.19 a, b) could be responsible for an increase in microbial decomposition activity. Slightly low pH environment suits for microbial growth (Pietri and Brookes, 2008), even though either only chicken manure or chicken manure with eggshell was applied to the SS and AL. Condron *et al.* (1993) reported that soil CO_2 respiration in acid soils (pH 4.43) with addition of lime and litter was much more than that with addition of either lime or litter for 17 weeks of incubation. However, Condron *et al.* (1993) showed weekly CO_2 emission which was from the first week to the 17th week. As Dumale *et al*. (2011) suggested that CO_2 emission following lime application occurred within a few days. Thus, weekly CO_2 emission rate cannot separate sources of CO_2, i.e. $CaCO_3$ and organic matter. In the present study, the rapid increase in daily CO_2 emission rate occurred within the first two days. It was due to eggshell-$CaCO_3$ reaction. CO_2 emission proceeded more than 2 days and later was from chicken manure compost decomposition by microbiological activity. Xue *et al.* (2010) reported an increase in soil microbiological population following the addition of $CaCO_3$ to acidic tea orchard soils. Pietri and Brookes (2008) stated that soil CO_2 evolution from microbiological activity increased with pH. The relatively higher CO_2 evolution rates from the combined application of eggshell and chicken manure suggested that $CaCO_3$ in the combination of chicken manure and eggshell could be highly effective at promoting microbiological activity in very acidic soils.

5.5.3 Effects of eggshell and chicken manure application on soil aggregate stability

The smaller MWD of the soils with the addition of eggshell than the soils with the addition of chicken manure or chicken manure with eggshell in comparison with control treatment indicated that eggshell could not enhance aggregate stability while chicken manure with or without eggshell could enhance aggregate stability (Figure 5.17). According to Roth and Pavan (1991), application of lime for 6 weeks (short term effect) increased soil pH and enhanced clay dispersion due to an increase in net negative charges. In this study, eggshell was used as alternative of lime to raise soil pH because eggshell contained 97.8% (Table 5.1). In the result, eggshell application had less effect on aggregate stability. For saline sodic soil, smaller MWD was observed for higher eggshell dose than lower eggshell dose. Nunes *et al.* (2018) also reported that higher increase in pH and electronegativity of soil caused by adding higher dose of lime could promote clay dispersion. Chorom *et al.* (1994) reported the increase in clay dispersion with pH rise. As a result, aggregate stability did not enhance with the addition of lime (Castro and Logan, 1991). Similar to this study, eggshell-$CaCO_3$ application to raise soil pH may cause clay dispersion and thus did not enhance aggregate stability. However, another study reported that lime enhanced aggregate stability after one year 1.5 t ha^{-1} lime application to the Oxisol (Manjoka, 2007). They explained that the rise in pH by lime application promoted microbial activity (Haynes and Swift, 1988). This could contribute to decompose much organic matter and produced organic binding agents enhancing aggregate stability (Manjoka, 2007). In this study, soil-eggshell incubation experiment was conducted for 45 days (short-term effect). Moreover, only eggshell application neither provided organic carbon nor decreased organic carbon in the soils. This was shown in the soils where organic carbon in eggshell treatment was not significantly different with control. Moreover, small CO_2 emission in the latter stage of incubation following eggshell application implied less micro-organism activity to decompose original organic matter in the soil. It was clear that the rise in pH by only eggshell application could not increase the decomposition of original organic matter by micro-organisms in the soil. Therefore, clay dispersion was dominant cause of making aggregates unstable after eggshell application.

A higher value of MWD was observed in the soils with the application of chicken manure and combined application of chicken manure and eggshell in comparison with control (Figure 5.17). Between the two doses of chicken manure application, aggregate stability of SS and AL was significantly greater for higher dose than that for the lower dose at the end of incubation. During 45 days incubation, aggregate stability remained high for the higher dose of chicken manure application, while aggregate stability tended to decrease for the lower dose of chicken manure application (Figure 5.14 and 5.15). In

AS, aggregate stability increased significantly with the addition of chicken manure, but there was no significant difference in MWD for the two doses of chicken manure after 45 days of incubation (Figure 5.17). There was similar trend of temporal changes in MWD of AS between the two chicken manure doses, where the MWD value was lower on 3^{rd} day and higher on 10^{th} day (Figure 5.16). This may be because of the effect of original pH of AS. Less microbial activity in decomposition of chicken manure in this soil having extremely low pH may create smaller amounts of organic compounds in the early stage of incubation. More organic compounds could be produced from decomposition of chicken manure by microbials at the following days. This may lead to an increase in aggregate stability on 10^{th} day. However, the MWD of AS after chicken manure application, then, decreased back on 45^{th} day, but it was still larger than MWD of control. The increase in MWD in response to chicken manure amendment implied that organic amendments played an important role in stabilizing soil aggregates. Organic amendments may help stabilize aggregates by inducing microbiological decomposition of organic matter (Griffiths and Jones, 1965). Carbohydrates, protein and polysaccharides produced from the decomposition of organic residues by microbial activity may act as binding agents in enhancing aggregate stability against slaking mechanisms from fast wetting (Carrizo *et al.* 2015). Earlier studies have discussed the roles of organic binding agents, clay-polyvalentcations-organic matter or clay-organic matter to stabilize aggregates against slaking and clay dispersion in the soils (Tisdall and Oades, 1982; Nelson and Oades, 1998). In this study, chicken manure was used as compost. It is an easily decomposable organic carbon source with a low C/N ratio (Table 5.1). The chicken manure was decomposed by microbials. The organic compounds released by decomposing process may bind soil particles and enhance aggregation. This contributed to strengthen soil aggregate stability. The present study showed that soil microbial activity was affected by soil pH, where CO_2 emission from chicken manure application was higher in a moderate pH like saline sodic soil and alluvial soil than in an extremely low pH such as acid sulfate soil (section 5.5.4). This could explain why aggregate stability of acid sulfate soil was lower than that of saline sodic soil and alluvial soil. Especially, aggregate stability of acid sulfate soil was lower at 3^{rd} day than at 10^{th} day. Then, it decreased significantly back to 45^{th} day. This may be because of less microbial activity to decompose chicken manure in the early stage of incubation. In the latter stage of incubation, the rise in micro-microorganism activity in acid sulfate soil may contribute to produce organic compounds. The decomposition of easily biodegradable organic sources were performed by microbial activity and produced organic compounds such as polysaccharides (Annabi, *et al.* 2014), carbohydates (Ibrahim and Shindo, 1999) contributing to enhance aggregate stability. Among the soils, although micro-organism activity at the latter stage of incubation in extremely low pH acid sulfate soil was enhanced by the application of chicken manure with eggshell, their activity was still weaker in comparison in relatively higher pH saline sodic soil and alluvial soil. This leaded to aggregates of acid sulfate soil easier broken down than saline sodic soil and alluvial soil under fast wetting in the latter stage of incubation. It was observed for short term incubation, aggregate stability of three soils tended to decrease over time series because organic compounds produced from decomposition of chicken manure may decrease over time series. It was recommended that chicken manure needs to supplement again to maintain aggregate stability in long term periods. As reported by Ibrahim and Shindo (1999), continuous application of compost in the field for long term periods increased aggregate stability because hyphae, polysaccharides and fungal produced from decomposition of compost could contribute to form soil aggregates and maintain them stable. The amendment consisting of chicken manure and eggshell was highly effective at increasing pH and stabilizing the aggregates of the three soils.

5.5.4 Relationships between soil pH and CO_2 emission associated with aggregate stability

The CO_2 emission had linear relationship with soil pH, which is shown in Figure 5.22. The linear relationships between soil pH and CO_2 emission were observed in the soils with the addition of only chicken manure and with the addition of chicken manure with eggshell (R^2 = 0.83 in SS, R^2 = 0.60 in AL and R^2 = 0.70 in AS). The data of CO_2 emission in the soils with chicken manure in combination of chicken manure and eggshell was obtained from the subtraction of CO_2 of eggshell from CO_2 of combination of chicken manure and eggshell. The changes in CO_2 emission was expected to come from the changes in chicken manure which was decomposed by microbials. The rise in soil pH and CO_2 emission in the soils with the application of chicken manure was suggested to be a cause of decarboxylation of organic anions. This process consumes proton (H^+) and release CO_2 as the equation [10]. From this equation, the proton consumption was calculated from CO_2 emission (Figure 5.23). During 45 days incubation, the proton consumption observed in chicken manure-amended AS was less than that observed in chicken manure-amended SS and AL. It may be because microbials could be inhibited by extremely low pH environment. Therefore, less microbial activity in AS having the lowest pH may lead to less decomposition of organic matter than that in SS and AL, whose pH is comparatively higher. The decomposition of chicken manure by microbials could release not only organic anions, but also other organic compounds like polysaccharides, carbohydrates that may help stabilize soil aggregates (Carrizo *et al.* 2015). When chicken manure combined with eggshell and applied to the soils, H^+ may be consumed by both eggshell-$CaCO_3$ in combination and by organic anions. After combination application, the chemical reaction of $CaCO_3$ in eggshell and H^+ in the soil occurs rapidly. Protons (H^+) were estimated by calculation through equation:

$$CaCO_3 + 2H^+ \leftrightarrows Ca^{2+} + H_2O + CO_2 \qquad [11]$$

The decomposition products such as malate, glycine, and citrate may react with H^+ in the soil and produce CO_2 (Yan *et al.* 1996) as equation [10]. From two equations, the protons (H^+) from chicken manure decomposition in combination were calculated by CO_2 emission, where CO_2 emission from eggshell-$CaCO_3$ reaction was subtracted (Figure 5.23). The rapid pH rise resulting from protons by $CaCO_3$ in combined application of chicken manure and eggshell may create suitable environment for microbial growth contributing to decomposition of chicken manure. Xue *et al.* (2010) has found the increase in the diversity of soil microbial community with the addition of $CaCO_3$ in acid tea orchard soils. Pietri and Brookes (2008) also reported that microbial activity was affected by soil pH, where soil CO_2 evolution from microbial activity increased as pH increased. The rise in microbial activity may decompose chicken manure in the combined application of chicken manure and eggshell producing organic compounds that may partly contribute to strengthen aggregate stability.

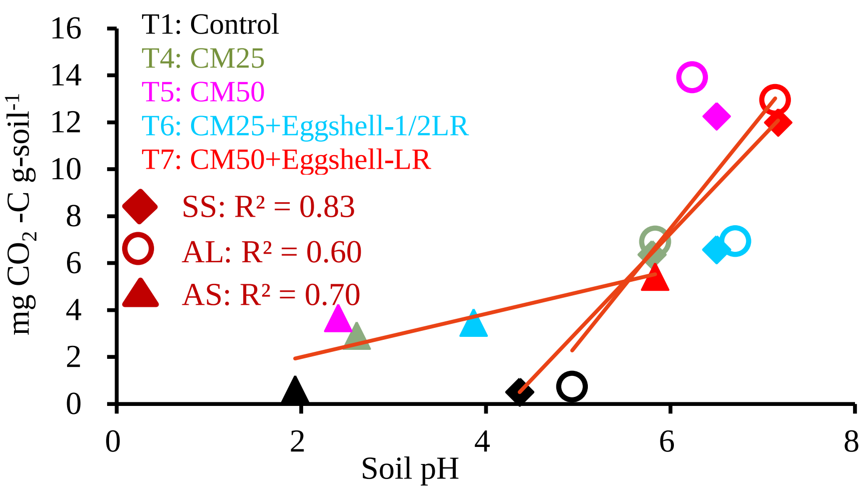
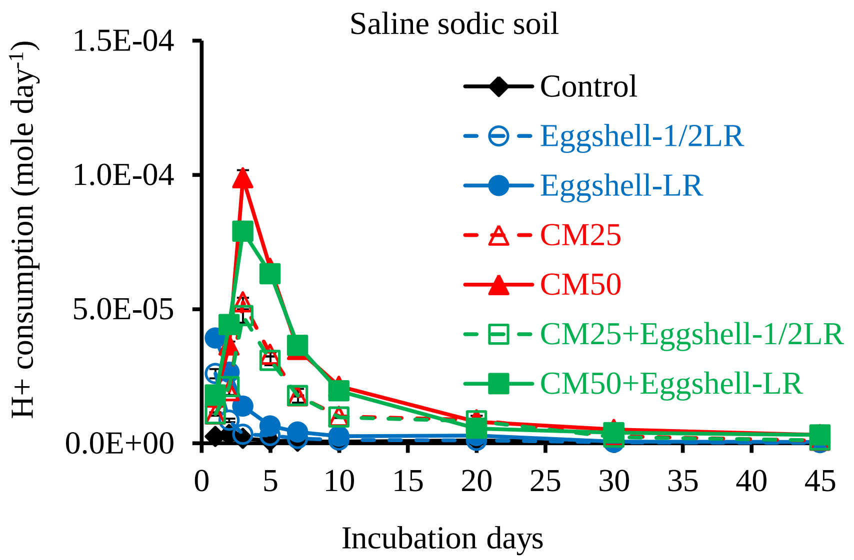


Figure 5.22 Relationships between soil pH and total CO_2 emission during 45 days incubation only chicken manure application and combinations of chicken manure and eggshell where CO_2 emission eggshell in combination was subtracted.



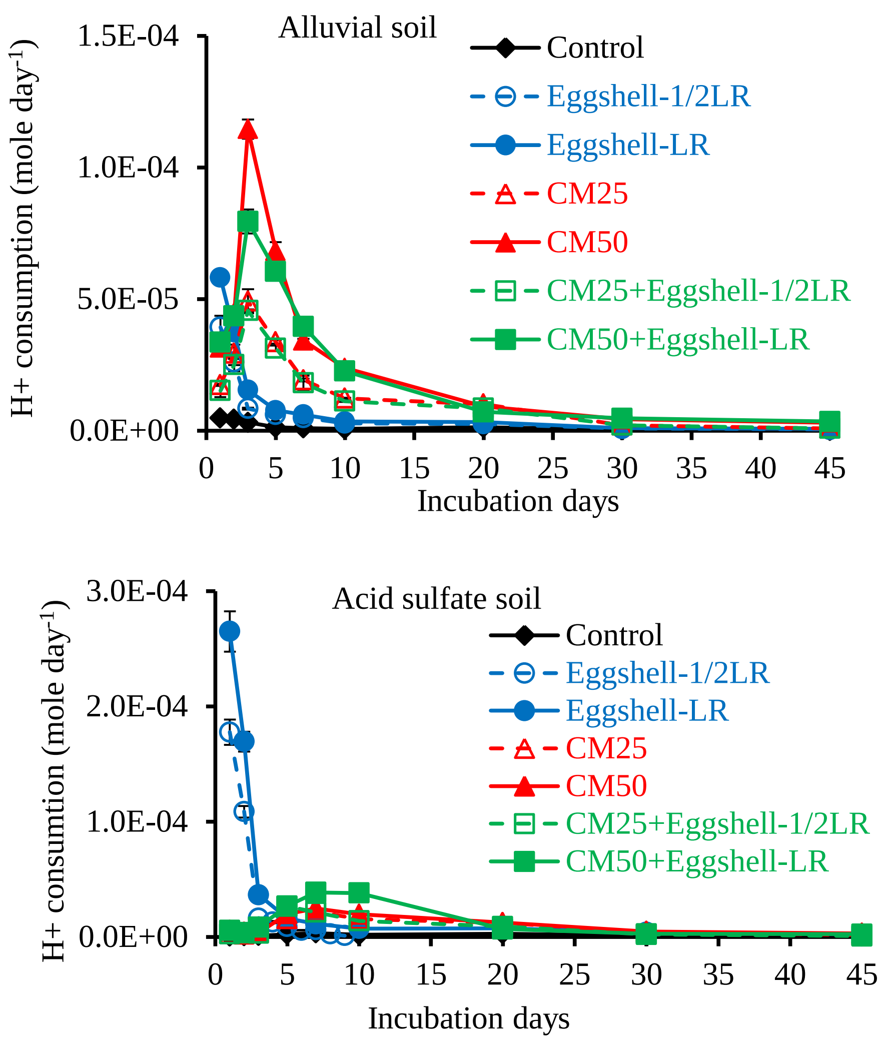


Figure 5.23 Proton (H^+) consumption from the soils with amendment application. Vertical bars show the standard deviation.

5.5.5 Relationship between soil pH on aggregate stability

Figure 5.24 shows no relationship between soil pH and aggregate stability. The rise in soil pH was found in the addition of chicken manure, eggshell or chicken manure with eggshell. However, soil aggregates behaved differently after amendment application. Smaller MWD of soils with only eggshell application and larger MWD of soils with only chicken manure or chicken manure with eggshell application are shown in below figure (Figure 5.24). This indicated that the rise in pH did not affect aggregate stability. The dominant factor affecting aggregate stability may be chicken manure application since aggregate stability was enhanced by chicken manure with or without eggshell application. As reported by Roth and Pavan (1991), they used only lime to observe clay dispersion. They found that the increase in the net negative charges with increasing soil pH was a dominant reason of clay dispersion. This may be true for only eggshell application in this study because the smaller MWD and the rise in pH were observed after eggshell application. However, larger MWD and the rise in pH were found in the soils with the application of chicken manure with or without eggshell. It was clear that pH did not affect aggregate stability in this study. Instead of this, easily decomposable organic sources like chicken manure materials may be dominant effects on aggregate stability. Smaller MWD was observed in the soils without chicken manure application, while larger MWD was shown in the soils added by chicken manure with or without eggshell. Therefore, the addition of chicken manure with or without eggshell was more outstanding for improvement of aggregate stability than only eggshell application in this study.

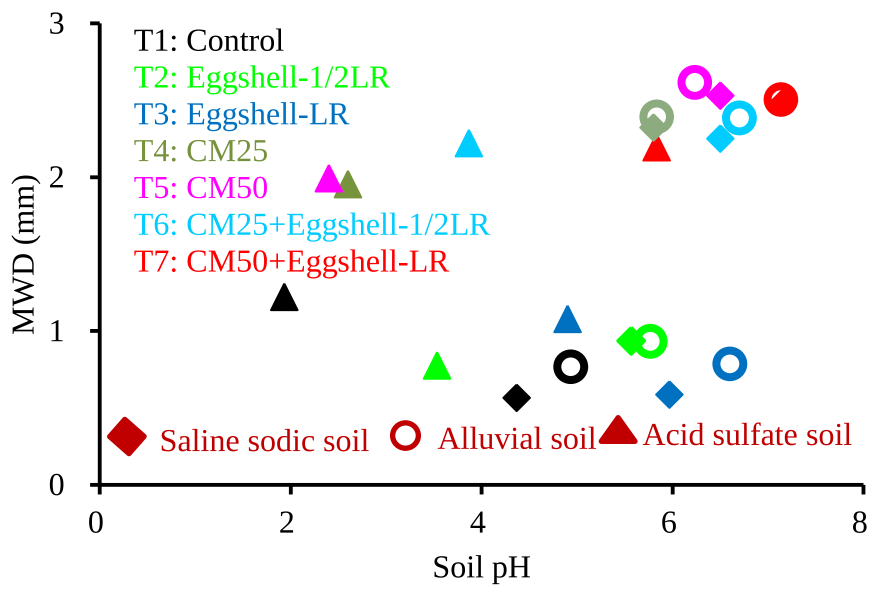


Figure 5.24 Relationships between soil pH and MWD during 45 days incubation after amendment application.

5.5.6 Effects of chicken manure and eggshell application on soil organic carbon associated with aggregate stability

Linear relationships between organic carbon and mean weight diameter (MWD) are shown in Figure 5.25. The soils with less organic carbon showed smaller MWD than the soils with more organic carbon. It showed that the rise in organic carbon content increased aggregate stability. The role of organic carbon in aggregate cohesion had been discussed by Griffiths and Jones (1965) and by Tisdall and Oades (1982). In this study, the application of chicken manure alone and combination of chicken manure and eggshell provided much more organic carbon than the eggshell application alone (Figure 5.20). The application of chicken manure with or without eggshell increased aggregate stability, while the addition of eggshell could not enhance aggregate stability. This was corresponded to larger MWD of the soils with the addition of chicken manure with or without eggshell than those with the addition of only eggshell (Figure 5.14, 5.15 and 5.16). Therefore, the application of chicken manure with or without eggshell increased organic carbon and thus aggregate stability. It may be interpreted that some of organic compounds from chicken manure decomposition could enhance cohesion between soil particles through bridging of clay-organic matter or clay – Ca^{2+}– organic matter – clay (Tisdall and Oades, 1982; Nelson and Oades, 1998, Wuddivia and Camps-Road, 2007). Because of the importance of organic carbon on aggregate stability, the use of higher dose of chicken manure (CM50) and combination of chicken manure and eggshell (CM50+Eggshell-LR) could maintain aggregates stable during 45 days incubation, while the use of lower dose of chicken manure (CM25) and combination of chicken manure and eggshell (CM25+Eggshell-1/2LR) could decrease slightly aggregate stability during 45 days incubation (Figure 5.14, 5.15 and 5.16). Chaney and Swift (1986) reported that the stability of aggregates was promoted with addition of glucose and/or extracellular polysaccharides. Polysaccharides, one of the organic compounds produced from decomposition of organic matter by micro-organisms, may act as binding agents to increase aggregate stability.

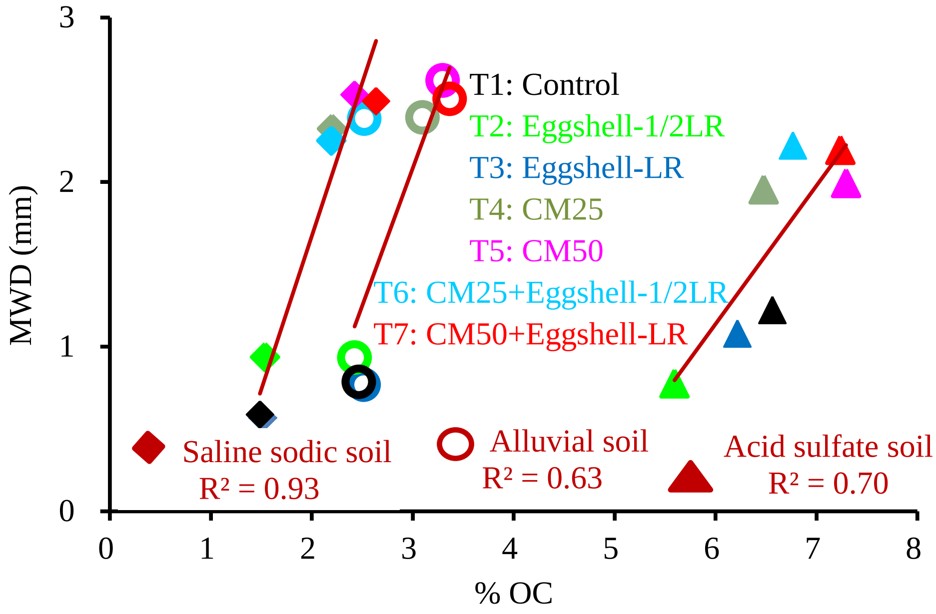


Figure 5.25 Relationship between soil organic carbon and mean weight diameter (MWD) after 45 days incubation.

5.6 Conclusions

Use of the eggshell brought effectively for the rise in pH of the three soils. The chicken manure could improve the pH of SS and AL, while pH of AS was not improved by adding the chicken manure. The rise in pH of three soils was enhanced by adding the combination of chicken manure and eggshell in comparison with the addition of either chicken manure or eggshell.

The rise in soil pH was affected by both eggshell and chicken manure application. The proton (H^+) consumed by eggshell-$CaCO_3$ may be a cause of pH rise when eggshell was applied to the soils. With the chicken manure application, the pH rise may derive from small $CaCO_3$ in chicken manure and proton consumption of organic anions. More raise in pH of three soils was obtained by adding the combination of eggshell and chicken manure. It may be due to the proton consumption from not only eggshell-$CaCO_3$ reaction, but also decarboxylation of organic anions contributing the more rise in soil pH when the combination of eggshell and chicken manure was applied to the soil.

Aggregate stability after amendment application was measured by mean weight diameter (MWD). MWD of the soils without amendments and with only eggshell application was smaller than MWD of the soils with the application of chicken manure with or without eggshell. It was obvious that the soil aggregates without amendments and with the addition of eggshell were unstable, whereas aggregates were more stable for the soils added with either the chicken manure only or the chicken manure and eggshell combination. In our finding, the rise in pH did not affect aggregate stability rather than organic amendment application.

Source of CO_2 was both $CaCO_3$ and H^+ reaction for the eggshell application and decomposition of organic matter by microbials for the chicken manure application. The CO_2 emission rate in the three soils with eggshell application or combination of eggshell and chicken manure occurred within the first two days. It was expected that rapid reaction of $CaCO_3$ in eggshell and H^+ in the soils was performed within two days. After chicken manure application, the increase in CO_2 emission rate started at the latter stage of incubation, between 5th day to 20th day in AS, whereas the rapid CO_2 emission rate increase was observed within the first 5 days in SS and AL. The changes in CO_2 emission from the soils with chicken manure application was expected to come from the changes in chicken manure decomposed by microbials. However, microbial activity in chicken manure decomposition may be affected by the original soil pH. Among the soils with the chicken manure application, AS which had the lowest pH showed lower CO_2 emission rate than SS and AL which had higher pH. It implied that microbials were inhibited in extremely low pH environment such as AS and they may work better in slightly low pH environment like SS and AL. With the addition of combination of chicken manure and eggshell, there was similar trend of CO_2 emission occurring within the first five days between the chicken manure application and the combination of chicken manure and eggshell application in SS and AL, while CO_2 emission occurred within two days and between 5th day and 20th day in AS. In the earlier stage of incubation in AS, the CO_2 emitted from the only eggshell application and the combined application overlapped. It suggested the rapid solubilization of eggshell-$CaCO_3$ in combination of eggshell and chicken manure. The second rise in CO_2 emission rate obtained from the AS with the combined application in the latter stage of incubation was more than double of that obtained from the chicken manure amended AS. It was expected more rise in decomposition of chicken manure by microbials in AS with the combined application.

Relationships between soil pH and CO_2 emission in the addition of chicken manure only implied that the microbial activity enhanced to decompose chicken manure by increasing soil pH. The more rise in soil pH and CO_2 emission was obtained by adding the combination of chicken manure and eggshell. The pH rise induced by eggshell-$CaCO_3$ in combined application of eggshell and chicken manure was expected to create suitable environment for microbial growth and promote chicken manure decomposition producing organic compounds. Some of them may act as organic binding agents that help bind soil particles and stabilize aggregates. From the results of this study, the combination of eggshell and chicken manure could alleviate not only soil pH, but also aggregate stability. They are considered as a promised measure for agricultural development in the near future.

Chapter 6 - Conclusions

One of the problems for agricultural production in the Mekong delta of Viet Nam as well as other tropical areas is low pH soils. Most plants cannot develop well in low pH environment. Therefore, improving soil pH is often attracted the most interest. One of the effective measures to raise pH is lime application. Use of lime could improve pH of soils that brings suitable environment for crop growth.

Aggregate stability is another important issue affecting soil productivity. It was reported that use of lime for low pH soil amelioration has a side effect of promoting clay dispersion of Oxisols. Aggregate stability could be improved by adding organic matter. Clarifying how compost and lime affects not only soil pH but also aggregate stability of low pH soils in Mekong delta region is important for sustainable agricultural production.

In this study, eggshell was used instead of lime because it contains 97.8% $CaCO_3$. Chicken manure was used as a compost and considered as a decomposable organic source with low C/N ratio (10.7). Those are common wastes in the Mekong region, where integrated-farming systems (gardening-fish raising-poultry raising-Biofgas systems called VACB system) are recommended to apply in each household. Because unhandled wastes would increase air and water pollution affecting human health. In this model, pig dung and chicken dung are applied to create biogas to use as biofuel. This cannot only help them save cost of living but also handle wastes in a friendly environmental way. Besides, this study provides information about efficiency of those wastes from chicken farms on soil amelioration. This can contribute to create diversity of waste handling in each household not only used for biogas production but also for soil amelioration in cultivation. Therefore, effective use of wastes such as chicken dung and eggshell would contribute to solve environmental and social problems.

Prior to aggregate stability test for incubation experiment, aggregate stability of undisturbed soils were examined under different treatments: initial moisture conditions, initial clod sizes and breakdown processes. The purpose of this experiment was to know which treatments affecting seriously aggregate stability. By the way, aggregate stability of three soil types was evaluated. Each undisturbed soil type was cut into three clod size range (1-3 mm; 2-5 mm and 5-10 mm). Moisture was recorded at two levels: moist and air dry. Fast wetting, slow wetting and mechanical breakdown were employed as three breakdown processes.

The aggregate stability test suggested that mean weigh diameter (MWDs) was the lowest for dry clods subjected to fast wetting. Among the breakdown processes proposed by Le Bissonais (1996), fast wetting in dry soils was suggested as the most serious problem that caused aggregate breakdown in Mekong delta region. When fast wetting applied to the three size clods, larger clods (2-5 mm and 5-10 mm size) showed less breakdown than fine clods (1-3 mm). Although fine clods (1-3 mm size) were more stable than larger clods under fast wetting, it was not recommended to create during tillage process because fine clods did not offer proper seedbed for seeding emergence as recommended from previous researches. From this reason, air-dry clods (2-5 mm) under fast wetting were considered as a protocol to determine aggregate stability after amendment application in incubation experiment. The purpose was to consider effects of amendments on aggregate stability. Moreover, in our finding, the soils which had different characteristics showed different aggregate behaviors. MWDs suggested that saline sodic soil (SS) had the most fragile aggregates, followed by alluvial soil (AL) and acid sulfate soil (AS).

The main objective of this study was to investigate the effects of chicken manure and eggshell application on amelioration of low pH soils in the Mekong delta of Viet Nam (chapter 5). Soil pH and aggregate stability of soil samples and CO_2 concentration of the headspace air in incubation bottles were periodically measured during 45 days incubation. Aggregate stability is affected by many conditions before and during aggregate stability. Upon the results of aggregate analysis on three different kinds of soil from Mekong delta region before soil incubation, 2-5 mm dry clods suffering to fast wetting were employed as the protocol to evaluate aggregate stability after chicken manure and/or eggshell application. The purpose of observing the CO_2 emission rate is to elucidate the changes in chicken manure by microbial activity when chicken manure with or without eggshell was applied to the soils.

In the Mekong Delta region, there is a great deal of interest in soil pH amelioration. Lime is commonly used to raise soil pH. In this study, eggshell could be used effectively to alleviate pH of three soils as an alternative of lime. Reaction of $CaCO_3$ in eggshell with H^+ in low pH soils may be a cause of pH rise after eggshell application. The pH of SS and AL was improved by adding either eggshell or chicken manure or both. The only exception was for chicken manure-amended AS, where chicken manure application could not raise pH. $CaCO_3$ in chicken manure (1.25 and 2.5 g $CaCO_3$

kg-chicken manure^{-1} was converted from 5% $CaCO_3$ in 2.5 and 50 g chicken manure kg^{-1}) may partly contribute the pH rise in three soils. In SS and AL, the amount of $CaCO_3$ in applied chicken manure occupied approximately a half compared with 1/2 LR and LR $CaCO_3$ application rates. This suggested that $CaCO_3$ in chicken manure was responsible for the rise in pH of SS and AL. However, the amount of $CaCO_3$ in applied chicken manure applied to AS was minor and negligible. Therefore, $CaCO_3$ in chicken manure could contribute less on the rise in pH of AS. Even though, pH of AS raised after chicken manure application compared to control treatment. Moreover, decarboxylation of organic anions was expected to be a source of CO_2 and pH rise. Slightly low pH of SS and AL may be appropriate for decomposition of organic matter by microbiology, while extremely low pH of AS may inhibit decomposition of organic matter by micro-organisms. As aided by microbials in organic matter decomposition, the much more proton (H^+) consumption in SS and AL and small proton (H^+) consumption in AS were a cause of pH rise. The combined application of eggshell and chicken manure was the most effective measure of pH rise in three soils in comparison with the application of either eggshell or chicken manure. For the combined application, the proton consumption was from the reaction of $CaCO_3$ in eggshell with H^+ in soils, so decarboxylation of organic anions could be a main contributor of more pH rise when the eggshell combined with chicken manure and applied to the soils.

Improving soil pH as well as aggregate stability is desirable to intensify soil productivity. Mean weight diameter (MWD) was measured to evaluate aggregate stability after 45 days incubation. The presenting study showed that although the physicochemical properties of the three soils differed, eggshell application could not enhance aggregate stability which showed similar MWD with control. The rise in pH induced by eggshell application may enhance clay dispersion and thus disintegrate soil aggregates. The addition of chicken manure with or without eggshell indicated greater aggregate stability which corresponded to larger MWD in comparison to control. It implied that organic matter played an important role in aggregate stability. The decomposition of organic matter could produce organic compounds. Some of them acted as organic binding agents to bind soil particles and thus enhance aggregate stability.

CO_2 emission rate from the SS and AL with chicken manure application occurred in the first five days, while CO_2 emission rate from the AS with chicken manure application occurred between 5th day and 20th day. The changes in CO_2 emission rate after chicken manure application were expected by microbial activity for decomposition of chicken manure. In soil respiration process, micro-organisms decomposed chicken manure and released CO_2. AS which had the lowest pH showed lower CO_2 emission rate than SS and AL whose pH was comparatively higher. It suggested that the decomposition of chicken manure by microbials may be affected by the original pH. Slightly low pH medium may be more appropriate for microbial development in decomposition of chicken manure than extremely low pH environment. CO_2 emission rate from the three soils with eggshell application occurred within the first two days. It can be expected that the rapid reaction between $CaCO_3$ in eggshell and H^+ in the soils was performed within the two days. CO_2 emitted from eggshell-amended AS was more than that from eggshell-amended SS and AL. Plenty of H^+ in AS may react with much more $CaCO_3$ in eggshell and release much more CO_2. For the addition of combination of chicken manure and eggshell, CO_2 emission from SS and AL occurred within the first five days, while CO_2 emission from AS occurred within two days and between 5th day and 20th day. In the early stage of soil incubation, the CO_2 emission from AS with only eggshell application and with the combined application overlapped. This suggested that eggshell-$CaCO_3$ in combination of eggshell and chicken manure solubilized rapidly. The second rise in CO_2 emission rate in the latter stage of incubation obtained from combined application of chicken manure and eggshell was more than double of that obtained from chicken manure application alone in AS. The second rise in CO_2 emission rate in the latter stage of soil incubation was expected to be caused by the rise in decomposition of chicken manure by microbials after the combined application of chicken manure and eggshell. The rise in pH induced by eggshell-$CaCO_3$ in combined application of chicken manure and eggshell was expected to create suitable environment for microbial growth and promote chicken manure decomposition in the latter stage of incubation. In slightly low pH soils like SS and AL, there was similar trend of CO_2 emission occurring within the first five days both in chicken manure application and in combined application of chicken manure and eggshell. Because CO_2 emission from $CaCO_3$ and H^+ reaction in eggshell applied soils occurred the first two days, the CO_2 emission proceeding more than two days and latter from the combined application of eggshell and chicken manure was suggested by microbial activity in chicken manure decomposition. Slightly low pH environment suited for microbial development, even though either only chicken manure or chicken manure with eggshell was applied to SS and AL. The organic by-products of microbial chicken decomposition may enhance aggregate stability. The results of this study indicated that the combined application of eggshell and chicken manure improved both soil pH and aggregate stability. From the results, the combined application of eggshell and chicken manure are considered as a promised measure for agricultural production in the near future.

In Mekong delta regions, chicken farms are widely developing because chicken production contributes to promote economic development and improving livelihood of farmers. Large amounts of chicken dung were discharged. Uncountable amount of eggshell was left after egg consumption. Instead of throwing away wastes of materials such as chicken manure and eggshell to the river threating to air pollution and water pollution, recycling those wastes as fertilizer to ameliorate soil quality are essential. Moreover, instead of investing money to buy commercial fertilizers, recycling those wastes may contribute to reduce production expense. Therefore, combination of chicken manure and eggshell can solve social and environmental problems. Moreover, this study provided useful information about efficiency of those wastes on soil amelioration. From the result of this study, combination of chicken manure and eggshell are recommended to apply in VAC integrated-close system of agriculture, where all agricultural wastes are required to reuse to meet the demand of sustainable development of economy, environment and society.

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APPENDICES

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Appendix 1: Result of the study

Appendix 1.1: Relationship between MWD and moisture conditions

SS		AL		AS	
MWD (mm)	Moisture (%)	MWD (mm)	Moisture (%)	MWD (mm)	Moisture (%)
1.72±0.10	0.03±0.00	2.17±0.06	0.04±0.00	2.38±0.17	0.04±0.01
1.91±0.28	0.05±0.00	2.36±0.04	0.06±0.01	2.36±0.13	0.07±0.01
1.56±0.07	0.09±0.01	2.28±0.07	0.08±0.01	2.39±0.06	0.13±0.05
2.50±0.12	0.25±0.02	2.15±0.07	0.18±0.01	2.57±0.05	0.32±0.02
2.67±0.04	0.40±0.01	2.69±0.01	0.34±0.00	2.68±0.02	0.63±0.05

Appendix 1.2: Soil pH after amendment application as a function of time

Soil types	Treatments	Incubation days				Stdev			
		3	10	20	45	3	10	20	45
	Control	4.4	4.6	4.4	4.4	0.09	0.08	0.05	0.17
	Eggshell-1/2LR	5.2	5.2	5.2	5.6	0.05	0.05	0.08	0.05
	Eggshell-LR	5.8	6.2	5.8	6.0	0.05	0.17	0.09	0.12
SS	CM25	5.5	5.4	5.5	5.8	0.09	0.00	0.05	0.08
	CM50	5.7	6.4	6.3	6.5	0.00	0.09	0.08	0.08
	CM25+Eggshell-1/2LR	6.1	6.1	6.2	6.5	0.05	0.05	0.12	0.08
	CM50+Eggshell-LR	6.6	7.0	7.0	7.2	0.12	0.05	0.05	0.05
	Control	4.5	5.1	4.7	4.9	0.05	0.19	0.05	0.12
	Eggshell-1/2LR	5.4	5.5	5.4	5.8	0.08	0.08	0.09	0.12
	Eggshell-LR	6.3	6.9	6.3	6.6	0.08	0.08	0.14	0.33
AL	CM25	5.1	5.2	5.4	5.8	0.05	0.14	0.00	0.09
	CM50	5.5	6.3	6.2	6.2	0.05	0.14	0.05	0.12
	CM25+Eggshell-1/2LR	5.9	6.2	6.1	6.7	0.12	0.05	0.09	0.00
	CM50+Eggshell-LR	6.6	7.1	7.0	7.1	0.00	0.05	0.00	0.05
	Control	2.3	2.1	2.2	1.9	0.14	0.05	0.00	0.05
	Eggshell-1/2LR	3.5	3.5	3.4	3.5	0.05	0.08	0.12	0.05
	Eggshell-LR	4.9	5.4	5.2	4.9	0.22	0.09	0.05	0.41
AS	CM25	2.4	2.3	2.2	2.6	0.05	0.05	0.12	0.08
	CM50	2.5	2.4	2.4	2.4	0.00	0.05	0.00	0.00
	CM25+Eggshell-1/2LR	3.6	3.7	3.6	3.9	0.09	0.12	0.12	0.21
	CM50+Eggshell-LR	5.4	5.9	5.8	5.8	0.12	0.08	0.12	0.09

Appendix 1.3: CO_2 emission rate after amendment application as a function of time

Soils	Treatments	CO_2 emission rate (mg CO_2 g-soil^{-1} day^{-1}) Incubation days									Stdev								
		1	2	3	5	7	10	20	30	45	1	2	3	5	7	10	20	30	45
	Control	0.11	0.14	0.08	0.04	0.03	0.03	0.05	0.01	0.01	0.00	0.07	0.01	0.01	0.016	0.00	0.01	0.002	0.002
	Eggshell-1/2LR	0.57	0.37	0.15	0.13	0.08	0.05	0.05	0.02	0.01	0.03	0.02	0.01	0.00	0.01	0.00	0.00	0.00	0.00
	Eggshell-LR	0.86	0.58	0.30	0.14	0.09	0.06	0.06	0.01	0.01	0.02	0.01	0.01	0.00	0.009	0.00	0.00	0.002	0.003
SS	CM25	0.48	0.86	2.31	1.46	0.78	0.44	0.38	0.12	0.05	0.02	0.05	0.06	0.03	0.01	0.01	0.06	0.00	0.00
	CM50	0.76	1.61	4.35	2.87	1.53	0.93	0.35	0.23	0.14	0.02	0.05	0.11	0.02	0.067	0.03	0.01	0.002	0.005
	CM25+Eggshell-1/2LR	1.05	1.30	2.23	1.48	0.86	0.48	0.41	0.12	0.06	0.01	0.03	0.09	0.06	0.10	0.01	0.00	0.00	0.01
	CM50+Eggshell-LR	1.65	2.52	3.78	2.92	1.69	0.91	0.31	0.19	0.15	0.05	0.04	0.03	0.01	0.047	0.03	0.01	0.002	0.003
	Control	0.21	0.19	0.14	0.06	0.04	0.03	0.06	0.01	0.00	0.01	0.00	0.00	0.00	0.006	0.00	0.00	0.000	0.001
	Eggshell-1/2LR	0.86	0.57	0.18	0.13	0.11	0.06	0.06	0.02	0.01	0.08	0.02	0.01	0.00	0.02	0.01	0.00	0.00	0.00
	Eggshell-LR	1.28	0.82	0.34	0.17	0.13	0.08	0.07	0.02	0.01	0.02	0.02	0.01	0.00	0.018	0.00	0.00	0.001	0.002
AL	CM25	0.77	1.29	2.16	1.48	0.85	0.54	0.44	0.09	0.04	0.01	0.12	0.17	0.02	0.02	0.01	0.01	0.02	0.01
	CM50	1.39	1.95	5.04	3.00	1.51	1.05	0.40	0.19	0.13	0.03	0.05	0.13	0.12	0.022	0.01	0.01	0.007	0.005
	CM25+Eggshell-1/2LR	1.53	1.67	2.19	1.51	0.90	0.55	0.43	0.11	0.04	0.01	0.10	0.01	0.04	0.08	0.01	0.02	0.01	0.00
	CM50+Eggshell-LR	2.75	2.74	3.84	2.83	1.88	1.07	0.38	0.22	0.17	0.06	0.02	0.17	0.01	0.035	0.02	0.00	0.007	0.003
	Control	0.02	0.04	0.05	0.10	0.14	0.08	0.12	0.04	0.03	0.00	0.01	0.00	0.01	0.012	0.00	0.00	0.002	0.001
	Eggshell-1/2LR	3.91	2.39	0.36	0.28	0.20	0.13	0.14	0.05	0.02	0.20	0.09	0.01	0.02	0.00	0.00	0.01	0.00	0.00
	Eggshell-LR	5.83	3.73	0.80	0.35	0.25	0.16	0.16	0.09	0.05	0.31	0.15	0.01	0.01	0.027	0.01	0.01	0.004	0.002
AS	CM25	0.12	0.10	0.20	0.69	0.96	0.68	0.54	0.18	0.07	0.00	0.01	0.02	0.03	0.03	0.01	0.01	0.01	0.00
	CM50	0.24	0.18	0.16	0.88	1.09	0.86	0.54	0.21	0.14	0.01	0.01	0.04	0.08	0.053	0.04	0.02	0.004	0.002
	CM25+Eggshell-1/2LR	3.90	2.47	0.50	1.46	1.14	0.74	0.53	0.15	0.06	0.03	0.01	0.01	0.11	0.06	0.00	0.04	0.01	0.00
	CM50+Eggshell-LR	5.84	3.70	1.17	1.54	1.94	1.84	0.47	0.21	0.15	0.13	0.08	0.02	0.12	0.027	0.06	0.01	0.005	0.011

Appendix 1.4: Aggregate stability after amendment application as a function of time

Soils	Treatments	MWD (mm)				Stdev			
		Incubation days							
		3	10	20	45	3	10	20	45
SS	Control	0.67	0.84	0.93	0.57	0.19	0.11	0.21	0.04
	Eggshell-1/2LR	1.14	1.28	0.93	0.94	0.25	0.15	0.09	0.13
	Eggshell-LR	0.74	0.91	0.98	0.59	0.29	0.18	0.10	0.08
	CM25	2.49	2.44	2.52	2.32	0.11	0.24	0.02	0.10
	CM50	2.58	2.56	2.54	2.53	0.01	0.01	0.07	0.05
	CM25+Eggshell-1/2LR	2.45	2.61	2.56	2.25	0.08	0.06	0.02	0.07
	CM50+Eggshell-LR	2.56	2.54	2.55	2.49	0.05	0.04	0.10	0.04
AL	Control	0.78	0.87	1.01	0.77	0.10	0.08	0.06	0.08
	Eggshell-1/2LR	0.86	1.04	0.80	0.93	0.09	0.07	0.08	0.08
	Eggshell-LR	0.82	1.20	0.89	0.79	0.08	0.15	0.05	0.06
	CM25	2.70	2.58	2.43	2.39	0.01	0.08	0.06	0.09
	CM50	2.61	2.61	2.63	2.62	0.05	0.05	0.04	0.02
	CM25+Eggshell-1/2LR	2.63	2.67	2.52	2.39	0.05	0.02	0.07	0.14
	CM50+Eggshell-LR	2.63	2.68	2.62	2.51	0.04	0.02	0.05	0.08
AS	Control	0.84	1.31	1.64	1.22	0.09	0.18	0.07	0.07
	Eggshell-1/2LR	0.76	0.83	0.76	0.78	0.05	0.17	0.05	0.10
	Eggshell-LR	0.66	0.78	0.94	1.08	0.04	0.10	0.05	0.28
	CM25	2.15	2.52	2.38	1.96	0.15	0.09	0.04	0.09
	CM50	1.43	2.51	2.47	1.99	0.28	0.07	0.02	0.14
	CM25+Eggshell-1/2LR	2.46	2.68	2.54	2.22	0.08	0.01	0.11	0.14
	CM50+Eggshell-LR	1.83	2.65	2.55	2.20	0.15	0.04	0.03	0.14

Appendix 1.5: Soil organic carbon amendment application as a function of time

Soils	Treatments	Organic carbon (%)				Stdev			
		Incubation days							
		3	10	20	45	3	10	20	45
SS	Control	2.55	2.54	2.56	2.61	0.17	0.02	0.17	0.15
	Eggshell-1/2LR	1.48	1.44	1.52	1.54	0.10	0.03	0.09	0.04
	Eggshell-LR	2.50	2.91	2.48	2.56	0.13	0.72	0.05	0.04
	CM25	2.72	2.19	2.99	2.20	0.17	0.02	0.33	0.17
	CM50	4.93	4.40	4.68	4.17	0.26	0.25	0.33	0.19
	CM25+Eggshell-1/2LR	2.32	2.29	2.87	2.19	0.06	0.33	0.19	0.19
	CM50+Eggshell-LR	5.10	4.76	4.27	4.54	0.55	0.39	0.28	0.26
AL	Control	4.09	4.17	4.15	4.32	0.06	0.06	0.07	0.13
	Eggshell-1/2LR	2.24	2.38	2.57	2.42	0.08	0.06	0.14	0.08
	Eggshell-LR	4.25	4.19	4.23	4.24	0.12	0.06	0.06	0.07
	CM25	3.01	3.21	2.82	3.10	0.13	0.29	0.08	0.13
	CM50	6.53	6.15	6.20	5.67	0.07	0.29	0.32	0.30
	CM25+Eggshell-1/2LR	3.20	3.17	2.98	2.52	0.01	0.22	0.18	0.38
	CM50+Eggshell-LR	6.82	6.19	5.91	5.79	0.08	0.06	0.20	0.22
AS	Control	11.35	11.64	10.98	11.29	0.52	1.09	0.11	0.72
	Eggshell-1/2LR	5.78	6.09	6.14	5.59	0.37	0.24	0.37	0.12
	Eggshell-LR	11.55	11.95	10.42	10.69	0.75	2.21	0.10	0.23
	CM25	6.36	7.22	7.18	6.48	0.06	0.66	0.40	0.44
	CM50	13.47	12.99	13.16	12.54	0.43	0.46	0.65	1.07
	CM25+Eggshell-1/2LR	6.86	6.80	6.54	6.77	0.61	0.60	0.14	0.52
	CM50+Eggshell-LR	13.18	12.66	13.22	12.45	0.28	0.54	0.76	0.15

Appendix 2: Result of ANOVA analysis

Appendix 2.1: Effects of initial soil moisture and breakdown processes on aggregate stability

Table 2.1.1 Between soil moisture conditions under fast wetting in saline sodic soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	1	0.86	0.86	22.13	0.0093
Within Groups	4	0.16	0.039		
Total	5	1.02			

Table 2.1.2. Between soil moisture conditions under slow wetting in saline sodic soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	1	0.00054	0.00054	0.33	0.60
Within Groups	4	0.0066	0.0016		
Total	5	0.0071			

Table 2.1.3 Between soil moisture conditions under mechanical breakdown in saline sodic soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	1	0.00057	0.00057	2.15	0.22
Within Groups	4	0.0011	0.00026		
Total	5	0.0016			

Table 2.1.4 Interaction between soil moisture conditions and treatments in saline sodic soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Sample	2	0.48	0.24	17.74	0.00026
Columns	1	0.26	0.26	19.02	0.00093
Interaction	2	0.61	0.30	22.18	9.31E-05
Within	12	0.16	0.014		
Total	17	1.51			

Table 2.1.5 Between soil moisture conditions under fast wetting in alluvial soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	1	0.15	0.15	179.21	0.00018
Within Groups	4	0.0034	0.00086		
Total	5	0.16			

Table 2.1.6 Between soil moisture conditions under slow wetting in alluvial soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	1	0.0029	0.0029	8.63	0.043
Within Groups	4	0.0013	0.00034		
Total	5	0.0042			

Table 2.1.7 Between soil moisture conditions under mechanical breakdown in alluvial soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	1	0.010	0.010	3.72	0.12619
Within Groups	4	0.011	0.0028		
Total	5	0.022			

Table 2.1.8 Interaction between soil moisture conditions and treatments in alluvial soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Sample	2	0.14	0.07	52.12	1.21E-06
Columns	1	0.019	0.019	13.86	0.0029
Interaction	2	0.15	0.074	55.50	8.6E-07
Within	12	0.016	0.0013		
Total	17	0.32			

Table 2.1.9 Between soil moisture conditions under fast wetting in acid sulfate soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	1	0.16	0.16	18.88	0.012
Within Groups	4	0.03	0.0083		
Total	5	0.19			

Table 2.1.10 Between soil moisture conditions under slow wetting in acid sulfate soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	1	0.0059	0.0059	2.17	0.21
Within Groups	4	0.011	0.0027		
Total	5	0.017			

Table 2.1.11 Between soil moisture conditions under mechanical breakdown in acid sulfate soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	1	0.0077	0.0077	16.58	0.015
Within Groups	4	0.0018	0.00046		
Total	5	0.0095			

Table 2.1.12 Interaction between soil moisture conditions and treatments in acid sulfate soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Sample	2	0.079	0.04	10.39	0.0024
Columns	1	0.049	0.05	12.93	0.0037
Interaction	2	0.12	0.06	15.81	0.00043
Within	12	0.046	0.0038		
Total	17	0.30			

Table 2.1.13 Between fast wetting, slow wetting and mechanical breakdown in dry condition in saline sodic soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	1.06	0.53	19.93	0.0022
Within Groups	6	0.16	0.027		
Total	8	1.22			

Table 2.1.14 Between fast wetting, slow wetting and mechanical breakdown in dry condition in alluvial soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	0.22	0.11	44.25	0.00026
Within Groups	6	0.015	0.0024		
Total	8	0.23			

Table 2.1.15 Between fast wetting, slow wetting and mechanical breakdown in dry condition in acid sulfate soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	0.17	0.086	12.36	0.0075
Within Groups	6	0.042	0.0069		
Total	8	0.21			

Table 2.1.16 Between fast wetting, slow wetting and mechanical breakdown in moist condition in saline sodic soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	0.03	0.015	20.91	0.002
Within Groups	6	0.0043	0.00072		
Total	8	0.034			

Table 2.1.17 Between fast wetting, slow wetting and mechanical breakdown in moist condition in alluvial soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	0.072	0.036	153.86	7.0E-06
Within Groups	6	0.0014	0.00023		
Total	8	0.073			

Table 2.1.18 Between fast wetting, slow wetting and mechanical breakdown in moist condition in acid sulfate soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	0.029	0.014	20.45	0.0021
Within Groups	6	0.0042	0.0007		
Total	8	0.033			

Appendix 2.2: ANOVA statistics in the effects of clod sizes on fragment size distribution

Table 2.2.1 Between clod sizes for fragment sizes > 2 mm in saline sodic soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	1204.18	602.09	11.10	0.01
Within Groups	6	325.45	54.24		
Total	8	1529.63			

Table 2.2.2 Between clod sizes for 0.25 mm < fragment sizes < 2 mm in saline sodic soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	252.96	126.48	1.77	0.25
Within Groups	6	427.74	71.29		
Total	8	680.70			

Table 2.2.3 Between clod sizes for fragment sizes < 0.25 mm in saline sodic soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	367.86	183.93	65.15	8.53E-05
Within Groups	6	16.94	2.82		
Total	8	384.81			

Table 2.2.4 Between clod sizes for fragment sizes > 2 mm in alluvial soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	1361.45	680.73	17.75	0.003
Within Groups	6	230.08	38.35		
Total	8	1591.53			

Table 2.2.5 Between clod sizes for 0.25 mm < fragment sizes < 2 mm in alluvial soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	714.98	357.49	10.91	0.01
Within Groups	6	196.61	32.77		
Total	8	911.59			

Table 2.2.6 Between clod sizes for fragment sizes < 0.25 mm in alluvial soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	126.6	63.3	6.5	0.03
Within Groups	6	58.2	9.7		
Total	8	184.8			

Table 2.2.7 Between clod sizes for fragment sizes > 2 mm in acid sulfate soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	253.23	126.61	5.69	0.04
Within Groups	6	133.51	22.25		
Total	8	386.74			

Table 2.2.8 Between clod sizes for 0.25 mm < fragment sizes < 2 mm in acid sulfate soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	86.87	43.43	4.09	0.08
Within Groups	6	63.78	10.63		
Total	8	150.65			

Table 2.2.9 Between clod sizes for fragment sizes < 0.25 mm in acid sulfate soil

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	2	89.26	44.63	22.95	0.002
Within Groups	6	11.67	1.945		
Total	8	100.93			

Appendix 2.3: ANOVA statistics in the effects of chicken manure and eggshell on soil pH after 45 days incubation

Table 2.3.1 Effects of chicken manure and eggshell on pH of saline sodic soil after 45 days incubation

Source of variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	14.3	2.38	161.06	4.3E-12
Within Groups	14	0.21	0.015		
Total	20	14.17			

Table 2.3.2 Effects of chicken manure and eggshell on pH of alluvial soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	9.61	1.61	45.45	2.2E-08
Within Groups	14	0.49	0.035		
Total	20	10.10			

Table 2.3.3 Effects of chicken manure and eggshell on pH of acid sulfate soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	35.91	5.98	122.01	2.9E-11
Within Groups	14	0.69	0.049		
Total	20	36.59			

Appendix 2.4: ANOVA statistics in the effects of chicken manure and eggshell total CO_2 emission after 45 day incubation

Table 2.4.1 Effects of chicken manure and eggshell on total CO_2 emission in saline sodic soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	541.26	90.21	4948	1.9E-22
Within Groups	14	0.26	0.018		
Total	20	541.52			

Table 2.4.2 Effects of chicken manure and eggshell on total CO_2 emission in alluvial soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	661.58	110.26	13561	1.6E-25
Within Groups	14	0.11	0.0081		
Total	20	661.69			

Table 2.4.3 The effects of chicken manure and eggshell on total CO_2 emission in acid sulfate soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	560.03	93.34	1048.1	9.6E-18
Within Groups	14	1.25	0.089		
Total	20	561.27			

Appendix 2.5: ANOVA statistics in the effects of chicken manure and eggshell on aggregate stability after 45 day incubation

Table 2.5.1 Effects of chicken manure and eggshell on aggregate stability in saline sodic soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	15.33	2.56	275.85	1.04E-13
Within Groups	14	0.13	0.0093		
Total	20	15.46			

Table 2.5.2 Effects of chicken manure and eggshell on aggregate stability in alluvial soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	14.09	2.35	214.34	5.9E-13
Within Groups	14	0.15	0.012		
Total	20	14.25			

Table 2.5.3 Effects of chicken manure and eggshell on aggregate stability in acid sulfate soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	6.32	1.05	30.71	2.8E-07
Within Groups	14	0.48	0.034		
Total	20	6.80			

Appendix 2.6: ANOVA statistics in the effects of chicken manure and eggshell on soil organic matter after 45 days incubation

Table 2.6.1 Effects of chicken manure and eggshell on soil organic matter in saline sodic soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	12.1921	2.03	44.44	2.53E-08
Within Groups	14	0.64	0.046		
Total	20	12.83			

Table 2.6.2 Effects of chicken manure and eggshell on soil organic matter in alluvial soil after 45 days incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	9.48	1.58	16.87	1.13E-05
Within Groups	14	1.31	0.094		
Total	20	10.79			

Table 2.6.3 The effects of chicken manure and eggshell on soil organic matter in acid sulfate soil after 45 day incubation

Source of Variation	Degrees of freedom	Sum square	Mean square	F	P
Between Groups	6	18.55	3.09	6.87	0.0015
Within Groups	14	6.31	0.45		
Total	20	24.86			