Studies on transport properties of soil gas and water, as well as pore structure indices, as affected by compaction and existence of the applied organic matter

（締め固めと施用した有機物の影響を受けた土のガスと水の輸送特性及び間隙構造の指標に関する研究）

Doctoral Thesis

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March, 2015

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Acknowledgement

First of all, I would like to express my deepest gratitude to my academic supervisor, Dr. Kiyoshi Koga, Professor, Laboratory of Soil Engineering, Division of Agricultural and Environmental Engineering, The United Graduate School of Agricultural Sciences, Iwate University, for his invaluable advices and endless encouragement upon all stages of my study. I do greatly appreciate him for the chance and also the support of writing and submitting my second and third articles so that they can be successfully published in Soil and Tillage Research Journal through which proper research and other important aspects of scientific concerns I could experience with. Contents of these papers entitled: 1) A study on the effect of compaction on transport properties of soil gas and water I: Gas diffusivity, air permeability, and saturated hydraulic conductivity (Soil Till. Res. 143, 172-179), and 2) A study on the effect of compaction on transport properties of soil gas and water II: Soil pore structure indices (Soil Till. Res. 143, 180-187) are further becoming the main part of this doctoral thesis.

In particular, I wish to thank Ministry of Education, Culture, Sports, Science and Technology – Japan (MEXT) for funding my study.

I also wish to express my sincere thank and extend my heartfelt gratitude to the following:

Dr. Naoya Satta, Professor at Iwate University, Dr. Motohei Kanayama, Associate Professor at Iwate University, and Dr. Takeyuki Annaka, Professor at Yamagata University, for sparing their precious time to intelligently examining this piece of work and also for the constructive suggestions,

Dr. Ken Kawamoto, Associate Professor at Saitama University, for sharing and providing his publications on soil gas diffusivity and air permeability, which has played as valuable references for my study.

Further, I would like to express my wholehearted appreciation and thank to the following:

Dr. Koji Harashina, Associate Professor at Iwate University, Dr. Ippei IIyama, Associate Professor at Utsunomiya University, and Dr. Tetsuya Araki, Associate Professor at The University of

Tokyo, for their kind support and continuous encouragement so that finally I could realize my dream to pursue and complete my graduate study in Japan,

Dr. Koji Harashina, Associate Professor at Iwate University, and his family, for their good care and hospitality so that living in Morioka become joyful and far from loneliness for me.

I wish to extend my wholehearted appreciation to all members of the Laboratory of Soil Engineering, more particularly:

Mr. Naoto Umeda, for his kind assistance and hospitality while he was serving as my tutor during my 1st year stay in Morioka and also for the continuous friendship even up to now,

Mr. Yo Fujiwara and Mr. Syogo Taiji, for their kind support and assistance during the experimental part of my study and for the colorful daily life in the laboratory.

I am also thankful to all my newfound friends more specifically Mr. Tatsuno, Mr. Kenta, and Ms. Yonezawa, for their kind friendship and hospitality during my stay in Morioka.

More importantly, I would like to take this opportunity to express my deepest and sincerest gratefulness to my parents, Joko Sunaryo and Yatmi, and to my brother, Joko Indrianto. Without their spiritual assistances and sacrifices, the completion of this piece of work may not have been possible.

Abstract

Operation of farm machinery in agricultural fields is the main cause of soil compaction, which may have detrimental effects on soil gas and water transport properties which play a role as one of the important determinants of soil quality for supporting plant growth. On the other hand, application of organic matter (OM) into the agricultural field has been well known to reduce the adverse effects of soil compaction and to improve the transport properties of soil gas and water. At present, however, experimental data on the effect of soil compaction on those soil gas and water transport properties and its relationship to the presence of the applied OM particularly at the early period after application when the decomposition process of OM has not yet taken place remains scarce. In addition, data on the effects of soil compaction and applied OM on soil macropore structure indices, more particularly on pore continuity, have yet rarely been documented.

The effect of soil compaction and the applied OM on relative gas diffusivity $(D_p/D_0)_{100}$ as well as air permeability (k_{a100}) at a soil matric suction of −100 cm H_2O (soil pF 2.0) and saturated hydraulic conductivity (k_s) were investigated using disturbed sample taken from 0 – 15 cm layer of a sandy loam Japanese volcanic ash soil (andisol) mixed with rice husk, rice straw, compost, sawdust, and wood bark at a rate of 20% of the soil volume. This disturbed sample was collected from the site of "Takizawa" experimental field of Iwate University (39°46'59.5" N, 141°07'35.7" E) and was preliminary lightly sieved (4.76 mm) to maintain its uniformity. The rate of 20% OM was chosen since this rate was considered to be practical and yet distinctive to see the effectiveness of the applied OM in changing soil physical properties.

The measurement of $(D_p/D_0)_{100}$ and k_{a100} was performed using the tool and method from Kuncoro and Koga (2012) whereas the measurement of k_s was performed using the constant head method. In this case, the measurement of $(D_p/D_0)_{100}$ and k_{a100} was conducted at soil pF 2.0 because soil water matric suction at this level represents condition near to the field capacity for the most common

agricultural field at which air content (ε) is minimum after immediate drainage so that the measured variables may represent the least value. Moreover, this pF level has been shown describing well D_p/D_0 for many soils with different texture taken from different soil horizons, and the measured k_a may provide information about changes and differences in soil structure. Besides, higher pF condition may result in a shrinkage of soil which can lead into failures on the measured D_p/D_0 and k_a.

The common compaction caused by farm machinery in agricultural fields was simulated in the laboratory using a static compression load of 150, 225, and 300 kPa at 0.7 g g^{-1} in soil water content referring to the original state of the soil when the sampling was conducted. This static compression was performed upon a targeted 471 cm^3 soil cylinder (10 cm wide and 6 cm long) using a floating-type soil cylinder with a piston those attached to the triaxial cell test machine by which friction between the soil sample and cylinder wall may be suppressed by about a half as the mechanism allowed a concomitant downward and upward compressions. This compression device also allows the production of a rather large diameter of soil specimen which suppresses edge effects between the soil sample and cylinder wall so that possible leakage or bypass along the cylinder perimeter can be minimized. The effect of compaction as well as the applied OM on the corresponding dry bulk density (ρ_d), total porosity (f), air content at soil pF 2.0 (ε_{100}), and pore size distributions was also further examined.

Volume of macropores ($\phi \geq 30$ μm) and micropores ($\phi < 30$ μm) were expressed as volume of air and water at −100 cm H_2O soil matric suction, respectively.. The volume of air and water should be expressed in air volume ratio and water volume ratio, respectively, relative to the volume of soil solid in order to address the matter of fact that the volume of soil has actually changed. This change in soil volume is more pronounced as a reduction in the volume of macropores, whereas the volume of soil solid remains constant or do not undergo an appreciable change after the compaction process took place. For determination of the other pore structure indices, specific gas diffusivity (S_{D100}) and specific air permeability (S_{ka100}) were calculated as $(D_p/D_0)_{100}/\varepsilon_{100}$ and $k_{a100}/\varepsilon_{100}$, respectively, as previously defined by other researchers in the literatures. By referring to knowledge that soil macropore is the almost exclusive determinant of water transport when the soil is saturated and by taking an analogy to the concept of S_{D100} and S_{ka100}, specific hydraulic conductivity (S_{ks}) was proposed as another index of the soil pore structure indices and defined as k_s/ε_{100} in this study. In addition, a generalized Kozeny-Carman equation as found in the literature has been employed to analyze the sensitivity of $(D_p/D_0)_{100}$, k_{a100}, and k_s to the change in the volume of macropore (ε_{100}) by using the slope of linear regression line of the log-log graph of these targeted variables and ε_{100}, respectively.

The results showed that compaction significantly increased ρ_d, which was followed by a reduction in f, and the mixed OM resulted in a significantly lower ρ_d and higher f than the control. The compaction also reduced ε_{100}, $(D_p/D_0)_{100}$, k_{a100}, and k_s, with the more pronounced significant difference between 150 and 300 kPa compactions. The decrease in $(D_p/D_0)_{100}$ was likely attributable to a reduced air content, and the decrease in k_{a100} and k_s was likely attributable to a reduced volume of macropores, as indicated by the reduced ε_{100} values.

Compared with the control, addition of sawdust and wood bark seemed to have the most positive effect on $(D_p/D_0)_{100}$, k_{a100}, and k_s in term of resistance to compaction, while rice straw had the opposite effect. The presence of OM was likely to block the soil pores and increase capillary water in the bottle-neck, leading to lower values of $(D_p/D_0)_{100}$ and k_{a100} for a given value of ε_{100} ("blockage effect"). These pores blocked by OM, however, seemed to allow the water to flow through the soil matric ("ceramic filter effect").

The volume of macropores was reduced by compaction whereas the volume of micropores remained unaffected. In this case, the mixed OM tended to result in a higher volume of macropores than the control. Compaction resulted in more tortuous macropores for gas diffusion (lower S_{D100}) and less continuous macropores for gas convection (lower S_{ka100}) for which a significant difference was more pronounced between the 300 and 150 kPa compactions. Compaction also resulted in fewer continuous macropores for water movement as indicated by lower S_{ks}.

The mixed OM was likely to result in a lower S_{D100}. On the other hand, it tended to result in a higher S_{ka100} except for rice straw. In addition, the mixed OM also seemed to result in a higher S_{ks} than the control. Of the OM-mixed soils, the decrease in $(D_p/D_0)_{100}$ and k_{a100} was more sensitive to compaction (i.e., decrease in ε_{100}) than that of the control even though this was not clear for k_s. Further studies on the prolonged application of OM at field scale, taking into account the decomposition process, should be conducted.

Japanese abstract / 要旨

農地における圃場機械の運行は土壌の締固めの主な原因である。締固めは作物の生育を支えるための土壌の質の重要な決定要因の一つである土壌ガスと水の輸送に対して悪い影響となる場合がある。他方，有機物（OM）を農地に施用することは土壌の締固めの悪い効果を減じ，また土壌ガスと水の輸送特性を改善することがよく知られている。しかしながら現在までのところ，土壌ガスと水の輸送特性に対する締固めの効果と，特に OM の分解がまだおきていない施用初期の期間での施用された OM と締固めの効果の関係についての実験的データは少ない。加えて，土壌の締固めと施用された有機物の土壌の粗間隙構造指標への影響，特に間隙の連続性についてのデータはあまり情報が提供されていない。

-100 cm H_2O（土壌 pF 2.0）の土壌のマトリクスサクションにおける相対ガス拡散係数 $(D_p/D_0)_{100}$ と通気係数(k_{a100})及び飽和透水係数(k_s)を，0-15 cm から採取した日本の火山灰土（andisol）の撹乱試料にモミガラ，イナワラ，堆肥，オガクズ，バークを土壌体積の 20%の割合で混ぜたものを用いて調べた。この撹乱試料は岩手大学滝沢農場 39°46’59.5” N, 141°07’35.7” E から採取し，均一にするため 4.76 mm で予め軽く篩った。20%という割合は，実際的でかつ施用された OM が土壌の物理性を変化させる明確な効果を見る事ができると考えられたので選んだ。

$(D_p/D_0)_{100}$ と k_{a100} の測定は Kuncoro and Koga (2012)の器具と方法により実施し，一方 k_s の測定は定水頭法によった。この場合，$(D_p/D_0)_{100}$ と k_{a100} の測定は pF 2.0 で行った。なぜなら，この水準の土壌水分張力はほとんどの農地の圃場容水量を表しているからである。圃場容水量においては空気含量(ε)が排水直後の最小値であり，測定される値は最小値を示す。加えて，この pF レベルの等価間隙径は様々な土壌断面から採取された様々な土性の多くの土壌について D_p/D_0 をよく表すことが示されており，測定された k_a は土壌構造の変化や相違についての情報を与えてくれる。さらに，より高い pF 条件では土壌の収縮がおきる可能性があり，D_p/D_0 と k_a の測定の失敗につながる可能性がある。

農地での圃場機械による通常の締固めを，実験室では採取した時の元の状態の土壌水分 0.7 gg^{-1}で，150，225，300 kPa の静的圧縮荷重で模した。この静的荷重はフローティングタイプの土壌円筒を用いて 471 cm^3の土壌円筒（幅 10 cm，長さ 6 cm)に対してピストンにより加えられた。このピストンは三軸圧縮試験機に取り付け，上下から圧縮させる機構により土壌と円筒の間の摩擦を約半分に減ずることができる。この圧縮装置はまた土壌試料の直径をかなり大きくすることができる。このことは土壌試料と円筒壁面の間の壁面効果を減じ，その結果円筒内壁に沿う漏れを最低限にできる。さらに，締固めと施用した OM の乾燥密度(ρ_d)，全間隙率(f)，pF 2.0 における空気含量(ε_{100})，間隙径分布への影響も検討した。

粗間隙($\phi \geq 30$ μm)と微細間隙($\phi < 30$ μm)の体積は−100 cm H_2O の土壌吸引圧における空気と水分の体積でそれぞれ表される。土壌の体積が実際に変化したことを表すためには，空気と水の体積は土壌の固相体積に対する空気体積比と水体積比で表されるべきである。この土壌体積の変化は粗間隙の体積の減少である一方，土壌の固相の体積は締固め過程がおきた後でも一定であるか，感知しできるほどの変化は起きない。この他の土壌構造の指標を決定するために，比ガス拡散係数(S_{D100})と比通気係数 S_{ka100} を，文献における過去の他の研究者による定義にならって, それぞれ$(D_p/D_0)_{100}/\varepsilon_{100}$ と $k_{a100}/\varepsilon_{100}$ で計算した。土壌が飽和している時，土壌の粗間隙は水移動のほとんど唯一の決定要因であるとの知見を参考にして，本研究では S_{D100} と S_{ka100} の概念に似せて, 比透水係数(S_{ks})をもう一つの土壌間隙構造の指標として提案し，k_s/ε_{100} で定義した。加えて，文献に見られるように一般化された Kozeny-Carman 式が粗間隙の体積(ε_{100})の変化に対する$(D_p/D_0)_{100}$，k_{a100},と k_s の感受性を分析するために，これらの変数と ε_{100} の log-log グラフの回帰直線の勾配により用いられてきた。

結果は締固めは明確にρ_dの増加とこれに伴う f の減少を示した。また，混入された OM は対照区と比べて有意に低いρ_dと高い fをもたらした。$(D_p/D_0)_{100}$ の減少は空気含量の減少に，k_{a100} と k_s の減少は粗間隙の体積の減少に起因すると考えられた。

対照区と比較して，オガクズとバークの添加は$(D_p/D_0)_{100}$，k_{a100}， と k_s に対して締固めへの抵抗に関して最も正の効果が高く，イナワラは逆であった。OM の存在は土壌間隙を閉塞

しボトルネックにおける毛管水の増加をもたらし，与えられた ε_{100} に対しより低い$(D_p/D_0)_{100}$ と k_{a100} をもたらすと考えられた（閉塞効果）。しかしながら，OM によって閉塞された間隙は土壌を通しての水の流れは許すと考えられた（セラミックフィルター効果）。

締固めによって粗間隙の体積が減少する一方，微細間隙の体積は影響を受けなかった，この場合，OM の混合は対照区と比べて粗間隙の体積を増加させた。締固めはガス拡散のためのより屈曲した粗間隙をもたらす（低い S_{ka100}）。これについては，300 kPa と 150 kPa の間の相違がより明瞭であった。また，締固めにより，より低い S_{ks} で示されるように水移動のための連続間隙がより少なくなった。

OM の混合はより低い S_{D100} をもたらした。一方，OM の混合はイナワラを除くとより高い S_{ka100} となる傾向があった。加えて，OM の混合は対照区より高い S_{ks} をもたらす傾向があった。OM 混合土については, 対照区と比べて締固め（すなわち, ε_{100} の減少）に対して$(D_p/D_0)_{100}$ と k_{a100} **の減少は**より敏感であった，これに対し k_s の減少は明瞭とはいえなかった。分解過程を考慮した圃場スケールでの長期にわたる OM の施用についての研究が今後必要である。

Chapter 1

Introduction

1.1. Background of the study

1.1.1. Relationship among transport properties of soil gas and water, soil compaction, and applied organic matter (OM)

Transport properties of gases and water in soil are important determinants of soil quality for supporting plant growth. The transport properties of soil gases may be used to describe aeration (Glinski and Stepniewski, 1985; Taylor, 1949; Yoshikawa and Hasegawa, 2000), which is important for allowing O_2 intake and CO_2 discharge by plant roots (Hillel, 1998). With better aeration, plant growth may be improved (Jackson, 1962; Liang et al., 1996), while conversely, reduced aeration may reduce plant growth (Wall and Heiskanen, 2009). Other than requiring air for respiration, plants require water, which plays a central role as a major metabolic agent for growth that is a source of H atoms for photosynthesis (Hillel, 1998). Plant roots absorb water from the soil, and thus, transport properties of the soil water become determinants of plant growth.

In agricultural fields, farm machinery used in tillage is recognized as the most common cause of compaction (Hill, 1990; Hill and Meza-Montalvo, 1990), which increases soil bulk density and reduces porosity (Etana et al., 2013; Ishaq et al., 2001) resulting in a decline in permeability so that aeration (Lipiec and Hakansson, 2000; Startsev and McNabb, 2009) and water infiltration (Kozlowski, 1999; Plaster 1997) become difficult. Hydraulic conductivity is also reduced (Etana et al., 2013, Marsili et al., 1998), which leads to drainage becoming more difficult. Other studies have also shown that compaction decreases the growth of plant roots (Glab and Kopec, 2009; Grzesiak, 2009; Janssen and van der Weert, 1977).

Organic matter (OM) application into agricultural fields is one of the means of improving soil physical properties and hence enhancing crop growth and yield. Other than this means, there are some mechanical methods like deep plowing, subsoil breaking, subsoil plowing, and hardpan breaking. OM application reduces bulk density and cone penetration resistance (Aggelides and Londra, 2000; Celik et al., 2010) and increases soil aggregation (Garcia-Orenes et al., 2005; Oyedele et al., 1999), porosity (Khan et al., 2000; Oyedele et al., 1999), and water retention (Johnson et al., 2006; Nyamangara et al., 2001) as well as hydraulic conductivity (Gonzalez and Cooperband, 2002; Schjønning et al., 2005). Also, it has been shown to improve soil aeration (Khan et al., 2000; Khan, 1996). In addition, the applied OM may increase carbon content of the soil and is of importance for plant nutrient supply.

While there are some studies on the effects of compaction on transport properties of soil gases (e.g. Ball and Ritchie, 1999; Berisso et al., 2012; Simojoki et al., 2008) and also soil water (e.g. Etana et al., 2013; Kim et al., 2010; Marsili et al., 1998), experimental data related to the presence of applied OM, particularly data derived from crop debris or its products, are not sufficient. In my other study, effect of the applied rice husk, rice straw, compost, sawdust, and wood bark at different rates of 10%, 20%, and 30% by volume on soil gas flow was investigated at a week and a year after the application. The results showed that soils with these OM application tended to have a higher gas diffusivity (D_p/D_0) and air permeability (k_a) than the control under the same compaction load although the trend became less apparent after a year. Sawdust, followed by rice husk, was found to be the most effective OM in increasing D_p/D_0, and the rice husk was also the most effective in increasing k_a. Rice straw tended to be the least effective OM in increasing both D_p/D_0 and k_a particularly after a week. These higher D_p/D_0 were thought to be ascribed to the increase in soil air content and less tortuous soil pore network after the OM application. While, the higher k_a were thought to be attributed to the increase in volume of soil macropores after the OM application.

According to the past literatures, however, data on the effect of applied OM on the transport properties of soil gas as well as soil water particularly at a very short period after the OM application when the decomposition process of OM has not yet taken place remain scarce. In this study, the effect of compaction on soil gas and water transport was investigated following the application of OM (crop debris and its product) within a very short period after the OM application.

1.1.2. Soil pore structure indices as affected by compaction

The soil compaction process is defined as a simple operation of a change in volume for a given mass of soil due to an applied load (McKibben, 1971) for which the volume of soil solid and liquid do not undergo an appreciable change (Harris, 1971). The volume change takes place in the gas phase of soil and is mostly attributable to a decrease in soil macropores (e.g., Alakukku, 1996; Alaoui et al., 2011; Berisso et al., 2012).

To evaluate this volume change, the air volume of a compacted soil specimen may then be expressed in a form analogous to the expression of 'water volume ratio' (in common textbook, e.g., Hillel, 1998) as a proportion of the relatively constant solid volume of the soil, termed 'air volume ratio', as shown below in Equation (1.1):

$$\nu_a = \frac{V_a}{V_s} \tag{1.1}$$

where ν_a is air volume ratio, V_a is volume of air (cm^3), and V_s is volume of soil solid (cm^3). Rather than expression of 'soil air content' or 'air-filled porosity' (i.e., quotient of V_a and total volume of soil), the expression 'air volume ratio' might be preferable to describe the actual change in air volume by compaction, namely the change in air volume of a given soil layer by compaction can be directly evaluated by ν_a. Conversely, 'soil air content' cannot be directly used because the total soil volume has changed.

The volume and arrangement (organization) of the soil macropores are determinants of the state of soil air (e.g., Blackwell et al., 1990; Kuncoro et al., 2014a; Schjønning et al., 2005) and water (e.g., Alaoui et al., 2011; Iversen et al., 2003; Kuncoro et al., 2014a) being transported. It is proposed that the transport process may take place through pore arrangements 'a', 'b', and 'c' in Fig. 1-1 in which gas diffusion is more affected by the 'b' arrangement, and either gas convection or hydraulic conductivity (saturated) is more influenced by the 'c' arrangement compared with the 'a' arrangement. In the case of 'd' arrangement, it is considered inactive at high soil matric potential (wetter conditions), but it may be open connected at low soil matric potential (drier conditions) through which the soil air can be transported. The transport process, however, does not occur for the dead-end or confined pores ('e' arrangement).

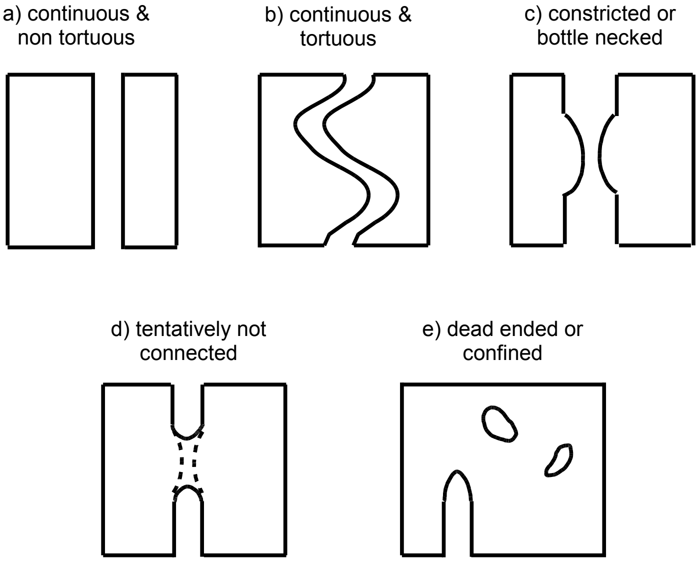

Fig. 1-1. Simplified qualitative model of soil macropores arrangement through which soil air and water may be transported.

Soil compaction, besides obviously affecting the volume of soil pores and their size distribution, may alter the pore arrangement. The altered pore organization (pore continuity) has been shown to affect gaseous transport (e.g., Arthur et al., 2013; Dörner et al., 2012; Schjønning and Rasmussen, 2000) and has been discussed to play an important role in water transport (e.g. Bormann and Klaassen, 2008; Dörner et al., 2010; Osunbitan et al., 2005). The index of pore continuity is commonly determined from the measured gaseous transport properties and air content (e.g. Blackwell et al., 1990; Dörner and Horn, 2006; Schjønning et al., 2005). In this study, we propose another index of pore continuity which is determined from the measured water transport property and volume of macropores. To my knowledge, there are only a few studies available concerned with the relationship between applied organic matter

(OM) and pore continuity.

1.2. Objectives of the study

This study aimed to investigate effects of compaction on: 1) soil gas and water transport properties within a very short period after OM (crop debris and its product) application, and 2) selected pore structure indices of these OM-mixed soils, including total porosity, pore size distribution, and quantitative pore organization in term of both gas and water transport properties. Result of this study is expected to give basic information of the positive effects of OM application in reducing the adverse effects of compaction, including upon the issue of soil gas and water transport properties.

Chapter 2

Materials and methods

2.1. Soil sampling

Disturbed samples of a sandy loam volcanic ash soil (Table 2-1; and also as used in Kuncoro et al., 2014a and Kuncoro et al., 2014b) were collected at a depth of 0–15 cm from the "Takizawa" experimental field of Iwate University (39°46'59.5" N, 141°07'35.7" E) in Iwate prefecture, northern Japan. The field has been fallow for the last four years and only subjected to mowing four times annually using a mowing tractor; the soil quality of this field is poor as implied by low gas and water transport properties shown in Table 2-1. The collected samples were lightly sieved (4.76 mm) and gravel and crop debris were carefully removed. The samples were set for 0.70 g g^{-1} in water content referring to the original state of the soil when the sampling was conducted. Not different from the common andisols, the volcanic ash soils in Japan are described having high content of OM and low bulk density which can reach 17%–27.5% and 0.51–0.60 g cm^{-3}, respectively (e.g. Resurreccion et al., 2007; Hamamoto et al., 2009b).

Table 2-1 Physical properties of the undisturbed soil and its texture.

[a] Organic matter content (%)	20.2
Gravimetric water content (g g^{-1})	0.70
[b] Particle density (g cm^{-3})	2.52
[c] Dry bulk density (g cm^{-3})	0.700
Relative gas diffusivity at soil pF 2.0 (m^2 s^{-1} m^{-2} s)	0.003
Air permeability at soil pF 2.0 (μm^2)	0.448
Saturated hydraulic conductivity (cm s^{-1})	4.8×10^{-5}
Texture: sand [2–0.02 mm] (%)	72.5
silt [0.02–0.002 mm] (%)	16.1
clay [< 0.002 mm] (%)	11.4

[a] Muffle oven test (750°C) [b] Pycnometer method [c] Gravimetric method

2.2. Organic matter (OM) treatment

A soil sample without any applied OM treatment was used as a control. For the soil with applied OM treatments, samples of each of rice husk, rice straw (cut into 2 cm lengths), wood bark compost, sawdust, and wood bark (Table 2-2) were mixed with the soil at a rate of 20% by volume immediately before they were repacked into the soil cylinder and compacted. This rate of 20% OM was considered to be practical and yet distinctive to see the effectiveness of the applied OM in changing soil physical properties. Typically, the rice husk was 7 mm in length, sawdust was 0.5–2 mm granular, and wood bark was 20–40, 3–5, and 0.5–1 mm in length, width, and thickness, respectively. For the soil volume determination, volume of soil at field condition when the sampling was conducted was taken as a basis. Thus, the volume of soil could be determined from the data of field wet bulk density (1.19 g cm^{-3}) and the mass of the prepared soil (0.7 g g^{-1} in water content). The volume of the applied OM could easily be determined by multiplying the volume of soil by 0.2. For an example, the prepared 1000 g soil sample has a bulk density of 1.19 g cm^{-3} (0.70 g cm^{-3} x (1 + 0.70 g g^{-1})) will give 840 cm^{-3} in soil volume, and by multiplying this volume with 0.2 will give 168.07 cm^{-3}, that is, the volume of OM should be applied. Finally, the required mass of OM can be obtained by multiplying this volume of OM with each wet bulk density of OM.

Table 2-2 Physical properties of the applied OM.

	Solid phase density (g cm^{-3})	Dry bulk density (g cm^{-3})	Organic content (%)
Rice husk	1.61	0.106	78.8
Rice straw	1.54	0.071	87.5
Compost	1.64	0.199	82.1
Sawdust	1.48	0.135	99.1
Wood bark	1.51	0.078	97.4

2.3. Compaction experiment

Prior to the compaction, the soil sample was remolded in the following manner. A targeted 471 cm^3

cylinder (10 cm wide and 6 cm long) was connected with two collars (each collar was 471 cm^3 in volume) at the both ends of this cylinder (Fig. 2-1). The sample was filled through the upper one-third part of the lower collar, the targeted cylinder, and the lower one-third part of the upper collar. The sample was then compressed by a prescribed static pressure as shown in Fig. 2-1. The pressure was 150, 225, and 300 kPa within the compaction speed about 2.55 mm per minute. Finally, excessive parts of the soil over the both ends of the targeted cylinder (471 cm^3) were trimmed (Kuncoro et al., 2014a).

These static loads chosen were taken to emulate static compaction commonly occurring in agricultural fields by the operation of farm machinery. Mechanism of static compression shown in Fig. 2-1 provided a concomitant downward and upward compression by which friction between soil sample and cylinder wall may be suppressed by about a half comparing with compression from a single direction. The device also allows the production of a rather large diameter of soil specimen which suppresses edge effects between the soil sample and cylinder wall so that possible leakage or bypass along the cylinder perimeter can be minimized. Further, this larger diameter also contributes to reduce the effect of friction between the soil sample and cylinder wall.

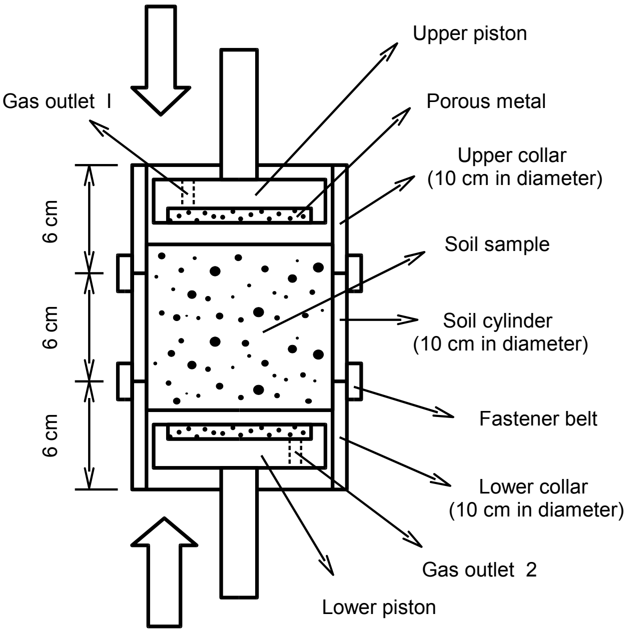

Fig. 2-1. Schematic diagram of a floating-type soil cylinder and a piston for static compression (attached to the triaxial cell test machine).

2.4. Outline of measurements

The compacted soil specimen was kept one night for preventing evaporation and in the next day it was saturated with water for measurement of saturated hydraulic conductivity (k_s) in which the constant head method was applied. The specimen was then drained at soil pF 1.0 and 1.5 by the sand bed method, and soil pF 2.0 by the hanging water column method. For each of these soil pF, mass of the sample was measured to determine the related water content.

At the soil pF 2.0, that is soil matric suction of -100 cm H_2O, measurement of relative gas diffusivity (D_p/D_0) and air permeability (k_a) were conducted. These measurements at soil pF 2.0 is preferable since pF 2.0 represents condition near to the field capacity for the most common agricultural field at which air content (ε) is minimum after immediate drainage so that the measured variables may represent the least value. Moreover, equivalent pore diameter derived at this soil pF has been shown enables to describe D_p/D_0 well for 126 soils with different texture taken from different soil horizons (Mouldrup et al., 2000), and the measured k_a may provide information about changes and differences in soil structure (Kirkham et al., 1958). Besides, higher pF condition may result in a shrinkage of soil which can lead into failures on the measured D_p/D_0 and k_a.

Gas diffusion coefficient in the soil (D_p) was measured at 20°C using a tool devised by Kuncoro and Koga (2012) by which D_p is determined from the change in O_2 concentration in a diffusion chamber over a sufficient time (2 hours in this study) as described by Rolston and Moldrup (2002). Gas diffusion coefficient in free air (D_0) at 20°C was taken as 2.0×10^{-5} m^2 s^{-1} (Currie 1960; Hamamoto et al. 2009a).

After the measurement of D_p/D_0, k_a was measured using an air permeameter as described by Kuncoro and Koga (2012). Using a measured volume flux of air q_a (m s^{-1}) at the center of the specimen, k_a (m^2) was determined as (Darcy's law):

$$k_a = q_a \eta_a \frac{L}{\Delta P} \qquad (2.1)$$

where η_a is the air viscosity (1.86×10^{-5} Pa s, Hamamoto et al., 2009a), L is the length of the specimen (m), and ΔP is the pressure difference between the top and bottom of the specimen (Pa).

After the measurement of D_p/D_0 and k_a, soil core was sampled into a 100 cm^3 soil sampler and it was subjected to soil pF 3.0 and 4.2 measurements by the centrifugal method.

Finally, all specimen was oven dried at 105°C for 24 hours to determine its dry bulk density, from which total porosity (f) and the related air content (ε) at each soil pF can be derived. All these measurements were performed in triplicate using three soil specimens for each combination of compaction level and OM treatment.

Equivalent pore diameter of a certain volume of soil pores as represented by air content (ε) at each soil pF was calculated using the theory of capillary rise after Terzaghi and Peck (1967):

$$h_c = \frac{0.15}{r} \cos \alpha \qquad (2.2)$$

where h_c is the capillary rise (cm), r is radius of the capillary tube (cm), and α is the contact angle (°), which is taken as zero for soil.

2.5. Determination of soil pore structure indices

For quantitative evaluation of soil pore organization, Groenevelt et al. (1984) introduced quotient of air permeability and soil air content as a pore continuity index, which was further used in Ball et al. (1988), Blackwell et al. (1990), and Dörner et al. (2012). The authors term the index ‘specific air permeability’ in this study after Schjønning et al. (2005) as seen below in Equation (2.3):

$$S_{ka} = \frac{k_a}{\varepsilon} \qquad (2.3)$$

in which S_{ka} is specific air permeability (μm^2), k_a is air permeability (μm^2), and ε is air-filled porosity namely air content (cm^3 cm^{-3}).

The pore continuity index of soil may also be expressed in terms of gas diffusion, which is more attributable to the pore tortuosity. This concept was first implied in the study of Gradwell (1961) and further used by other researchers (e.g., Ball, 1981; Ball et al., 1988; Schjønning, 1989; Schjønning et al. 2005). In this study, the index was termed ‘specific gas diffusivity’ as in Schjønning et al. (2005) as seen below in Equation (2.4):

$$S_D = \frac{[D_p/D_0]}{\varepsilon} \qquad (2.4)$$

in which S_D is the specific gas diffusivity and D_p/D_0 is the relative gas diffusivity.

When the soil is fully saturated with water, macropores are the almost exclusive determinant of transport process of this soil water (Iversen et al., 2003; Kuncoro et al., 2014a; Poulsen et al., 1999). Accordingly, by analogy with k_a and D_p/D_0, the following index (Equation (2.5)) can be defined for quantifying the macropore continuity in terms of saturated hydraulic conductivity:

$$S_{ks} = \frac{k_s}{\varepsilon_{100}} \qquad (2.5)$$

where S_{ks} is 'specific hydraulic conductivity' (cm s^{-1}), k_s is saturated hydraulic conductivity (cm s^{-1}), and ε_{100} is volume of macropores namely air content measured at −100 cm H_2O soil matric suction (cm^3 cm^{-3}). This value of ε_{100} may represent the volume of pores with an equivalent pore diameter ≥ 30 μm; that is, of soil macropores or inter-aggregate pore systems.

Ahuja et al. (1984) have successfully used a generalized Kozeny-Carman equation to characterize spatial distribution of saturated hydraulic conductivity (k_s) from measurements of effective porosity (ϕ_e) (or macroporosity) as seen below in Equation (2.6):

$$k_s = B\phi_e^{\,n} \qquad (2.6)$$

where B and n are empirical constants, and ϕ_e is the subtraction of soil water content at a pressure head of −33 kPa from total porosity. The exponent n is the slope or tangent of the fitted line through the log-log graph of k_s vs. ϕ_e ($k_s : \phi_e$ characteristic), and therefore, expresses the sensitivity of k_s with regard to ϕ_e. In a form analogous to this concept, sensitivity of the measured D_p/D_0 and k_a at −100 cm H_2O soil matric suction as well as k_s with regard to ε_{100} in this study can be studied from the log-log graph of $(D_p/D_0)_{100}$ vs. ε_{100}, k_{a100} vs. ε_{100}, and k_s vs. ε_{100}, respectively.

2.6. Statistical analysis

Statistical significance of compaction levels and OM treatments upon the measured data were analyzed using KaleidaGraph 4.1 software (Synergy Software 2012, USA) for analysis of variance (ANOVA). Post-hoc analysis was performed using Tukey's HSD test ($P < 0.05$).

Chapter 3

Results and discussion

3.1. Dry bulk density (ρ_d) and total porosity (f)

Soil dry bulk density (ρ_d) significantly increased with increased levels of compaction and consequently was followed by a reduction in total porosity (f) as shown in Table 3-1. This result was in a good agreement with Botta et al. (2009) who found a significant increase in ρ_d and reduction in f, particularly at the topsoil layer, after several passages with 5.8 and 4.8 Mg in total weight of tractors on fine clayey soil. Hassan et al. (2007) also reported a significant increase in ρ_d and decrease in f of alluvial silt loam soil after compaction using a 7.0-Mg self-propelled steel roller for 2, 4, and 6 passes. In Abu-Hamdeh and Al-Jalil (1999), ρ_d and f of a clay loam soil were found to significantly increase and decrease, respectively, even down to a depth of 50 cm after 3 passes of a tractor with a 1.5-Mg planter mounted.

Table 3-1 Arithmetic mean and standard deviation of dry bulk density (ρ_d) and total porosity (f) of the compacted soil at 150, 225, and 300 kPa compaction levels.

OM	ρ_d (g cm^{-3})			f (cm^3 cm^{-3})		
treatment	150 kPa	225 kPa	300 kPa	150 kPa	225 kPa	300 kPa
Control	0.667 ± 0.001 Ba	0.693 ± 0.005 Ca	0.717 ± 0.005 Aa	0.735 ± 0.000 Ab	0.725 ± 0.002 Cb	0.715 ± 0.002 Bb
Rice husk	0.633 ± 0.005 Bd	0.664 ± 0.004 Cc	0.688 ± 0.002 Ad	0.744 ± 0.002 Ac	0.732 ± 0.002 Cc	0.722 ± 0.001 Bab
Rice straw	0.621 ± 0.003 Bc	0.653 ± 0.010 Cc	0.680 ± 0.008 Abd	0.750 ± 0.001 Aa	0.737 ± 0.004 Cac	0.726 ± 0.003 Bac
Compost	0.624 ± 0.006 Bcd	0.654 ± 0.006 Cc	0.687 ± 0.012 Acd	0.745 ± 0.002 Ac	0.732 ± 0.002 Cc	0.719 ± 0.005 Bbc
Sawdust	0.604 ± 0.007 Bb	0.632 ± 0.006 Cb	0.661 ± 0.007 Ab	0.753 ± 0.003 Aa	0.742 ± 0.003 Ca	0.730 ± 0.003 Ba
Wood bark	0.617 ± 0.002 Bc	0.655 ± 0.003 Cc	0.679 ± 0.004 Abd	0.751 ± 0.001 Aa	0.736 ± 0.001 Cac	0.726 ± 0.002 Bac

Either values of ρ_d or f followed by same capital letter (row), and lowercase letter (column), are not significantly different ($P < 0.05$).

Similar with the results shown in Table 3-1, Berisso et al. (2012) also found a significant reduction in f of a sandy clay loam soil at soil depths of 0.3, 0.7, and 0.9 m after four repeated wheelings with a

35-Mg sugar-beet harvester the calculated vertical stresses ranged from 207 to 84 kPa in these depths. Ishaq et al. (2001) also reported a significant decrease in f of a sandy clay loam soil particularly below a soil depth of 0.15 m after compaction using a powered vibratory tamper with a weight of 60 kg, a base area of 0.3 m x 0.3 m, a static pressure of 8.4 kPa, and operating at 80 strokes per minute.

Almost all data in Table 3-1 showed that the addition of OM to soils resulted in significantly lower ρ_d and higher f than the control, and only for rice husk and compost-mixed soils at 300 kPa the differences in f were not statistically significant. Among the OM additions, sawdust and rice husk addition led to the lowest and highest ρ_d values, respectively, and consequently had a converse effect upon f. Compost-mixed soil, in particular, led to a similarly low f as rice husk-mixed soil, despite the lower ρ_d in compost-mixed soil compared with that of rice husk-mixed soil.

This result suggested a positive effect of the mixed OM on either ρ_d or f even after the compaction took place. In accordance with this result, Celik et al. (2004) also reported a significant decrease in ρ_d and an increase in f within 0–30 cm soil depth after 5-year application of compost and farm manure on a clay-loam soil with OM content ranged from 1.4 to 1.6%. Schjønning et al. (2005) also observed a significantly larger f (in average) of a loamy sand soil supplied with animal manure for about a century (1.30–1.35% in OM content) compared with soil with no addition (1.07% in OM content).

3.2. Air content at −100 cm H_2O soil matric suction (ε_{100})

Table 3-2 shows that the air content measured at a soil matric suction of −100 cm H_2O (ε_{100}) decreased with the level of compaction, with a pronounced significant difference between 300 and 150 kPa. This result is in accord with that reported by Berisso et al. (2012). According to the theory of capillary rise (Terzaghi and Peck, 1967), the value of ε_{100} may represent the volume of pores with an equivalent pore diameter ≥ 30 μm; that is, of soil macropores or inter-aggregate pore systems. Thus, the reduced ε_{100} values (Table 3-2) may be taken to indicate a reduction in the volume of macropores. Similarly, Etana et al. (2013) also reported a reduction in macroporosity (equivalent pore diameter ≥ 30 μm) in a loamy soil at a soil depth of 0.30–0.95 m after compaction by 6-row sugar-beet harvester with a maximum wheel load of 10.4 Mg.

Table 3-2 Arithmetic means and standard deviations of soil air content at −100 cm H_2O soil matric suction (ε_{100}) of the compacted unamended soil and the soil amended with various forms of OM at compaction levels of 150, 225, and 300 kPa.

OM treatment	ε_{100} (cm^3 cm^{-3})		
	150 kPa	225 kPa	300 kPa
Control	0.186 ± 0.003 Ab	0.160 ± 0.013 Cbd	0.128 ± 0.009 Bab
Rice husk	0.230 ± 0.016 Aa	0.191 ± 0.012 Bac	0.156 ± 0.018 Ba
Rice straw	0.198 ± 0.014 Aab	0.164 ± 0.013 Cbc	0.119 ± 0.007 Bab
Compost	0.183 ± 0.011 Ab	0.151 ± 0.011 ABb	0.106 ± 0.030 Bb
Sawdust	0.227 ± 0.019 Aa	0.205 ± 0.010 Aa	0.160 ± 0.012 Ba
Wood bark	0.230 ± 0.010 Aa	0.189 ± 0.004 Cacd	0.159 ± 0.011 Ba

Values of ε_{100} followed by the same capital letter (row: compaction effect), and lowercase letter (column: OM effect), are not significantly different ($P < 0.05$)

The soils mixed with OM tended to have higher ε_{100} values than the control at compaction levels of 150 and 225 kPa except for the soil mixed with compost. However, the difference in ε_{100} values between the soils mixed with OM and the control became less when the level of compaction increased to 300 kPa. In contrast to the other soils mixed with OM, the soil mixed with compost had lower ε_{100} values than did the control in spite of its higher f value (Table 3-1), which was probably related to its greater volume of semi-macropore/micropore of which the equivalent pore diameter is less than 30 μm (subchapter 3.6.).

3.3. Relative gas diffusivity (D_p/D_0)$_{100}$

Relative gas diffusivity measured at a soil matric suction of −100 cm H_2O ((D_p/D_0)$_{100}$) decreased with the level of compaction. For the soil mixed with wood bark, the difference was significant among all levels of compactions, while for the remaining soils, the difference was significant between compaction levels of 300 and 150 kPa (Fig. 3-1). Such a reduction in D_p/D_0 caused by compaction has also been reported by Berisso et al. (2012) after repeated wheelings with a wheel load of 10.4 Mg (and calculated vertical stresses of 207 – 84 kPa in soil depth of 0.3, 0.7, and 0.9 m, respectively) on a sandy clay loam soil. Similarly, Simojoki et al. (2008) reported a reduction in estimated D_p/D_0 values of a silt loam soil after wheelings with a 35-Mg 6-row sugar-beet harvester. Ball and Ritchie (1999) found a reduction in D_p/D_0 on both a loam and sandy loam soils after heavy compaction using a 4.2-Mg laden tractor with an inflation pressure of 220 and 80 kPa in the front and rear tyres, respectively.

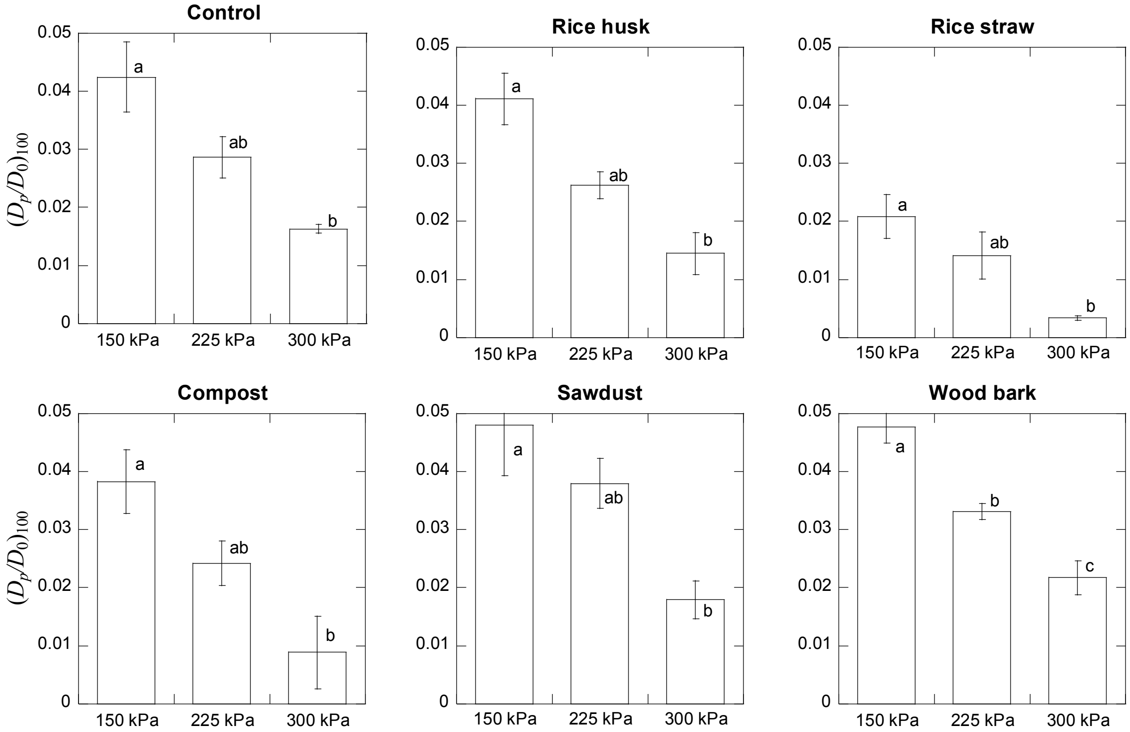

Fig. 3-1. Comparison of the measured relative gas diffusivity $(D_p/D_0)_{100}$ after compaction at stress levels of 150, 225, and 300 kPa. Mean values for the stress levels of a certain OM treatment followed by the same letter are not significantly different ($P < 0.05$).

Although there were no statistically significant differences between the soils mixed with OM and the control soil (data and statistical analysis not shown), the following tendencies were observed. The soils mixed with sawdust and wood bark resulted in higher values of $(D_p/D_0)_{100}$ than the control, while the soil mixed with rice straw had the lowest value (Fig. 3-1). The higher values of $(D_p/D_0)_{100}$ for the soils mixed with sawdust and wood bark were probably related to the higher values of ε_{100} (Table 3-2). Additionally, properties of the sawdust and wood bark (shape, size, and hardness) might contribute to the soil becoming more resistant to compaction, resulting in greater preservation of pores effective for D_p/D_0. Conversely, the softer and thinner rice straw seemed to be easily subjected to compaction with a consequent reduction in pores effective for D_p/D_0, leading to the lower values despite its somewhat higher ε_{100} values at compaction levels of 150 and 225 kPa (Table 3-2).

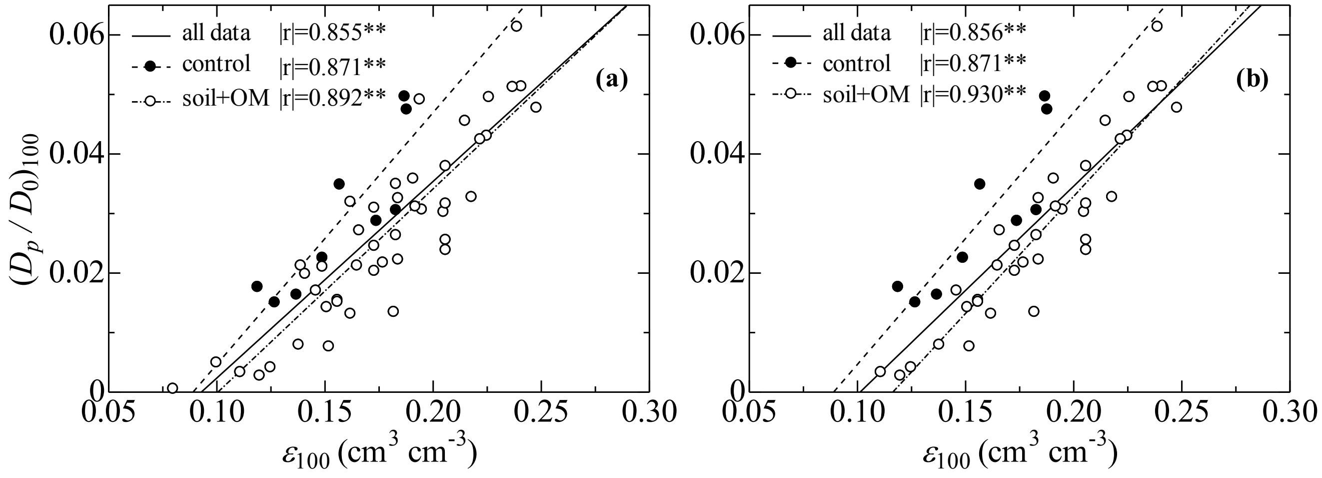

Fig. 3-2. Estimated linear relationship between relative gas diffusivity $(D_p/D_0)_{100}$ and soil air content (ε_{100}) (**$P < 0.01$) for the all data (a), and without the data of soil with compost (b).

Fig. 3-2a shows a positive linear relationship between the values of ε_{100} and $(D_p/D_0)_{100}$ for all the measured data (r = 0.855). This may suggest that the observed decrease in $(D_p/D_0)_{100}$ in this study might reasonably be attributable to the reduced values of ε_{100}, that is, the reduced soil air content after compaction. At present, air content (ε) is recognized as the main determinant factor affecting gas diffusion, on which D_p/D_0 mainly depends (Moldrup et al., 2000; Osozawa, 1998; Stepniewski, 1981).

Interestingly, Fig. 3-2a also shows that, for a given ε_{100}, the soils mixed with OM tended to have a lower $(D_p/D_0)_{100}$ than the control soil. This possibly suggests an existence of “blockage effect” from the presence of OM, namely the not yet decomposed OM itself was likely to block soil pores so that gas diffusion could be hindered. Adding to this, the OM might also facilitate the formation of water menisci at bottle-necks in the pore system, resulting in a decrease in D_p/D_0. Even though this "blockage effect" has not been fully investigated in this study, this hypothesis may then support the foregoing discussion about the lower $(D_p/D_0)_{100}$ of the soil mixed with rice straw at compression levels of 150 and 225 kPa (Fig. 3-1) despite its higher ε_{100} (Table 3-2).

If data of soil with compost are omitted, the linearity between values of ε_{100} and $(D_p/D_0)_{100}$ for soil with OM as shown in Fig. 3-2b was even better (r = 0.930) than that of the condition as if data of soil with compost are included (0.892) as shown in Fig. 3-2a. Adding to this, the difference in $(D_p/D_0)_{100}$ between the soil with OM and control soil for a given ε_{100} also became more evident after the data of soil with compost have been omitted (Fig. 3-2b). This result might suggest that the "blockage effect" was more evident for the not yet-decomposed raw OM used in this study: rice husk, rice straw, sawdust, and wood bark than the compost which is to some extents already decomposed.

3.4. Air permeability (k_{a100})

As the level of compaction increased, the measured air permeability at a soil matric suction of −100 cm H_2O (k_{a100}) decreased, with the difference being significant between 300 and 150 kPa (Fig. 3-3). A significant difference was also present between 150 and 225 kPa for the control soil and for the soils mixed with rice straw and wood bark, as well as between 225 and 300 kPa for the soil mixed with rice straw. This result supports the findings of Tang et al. (2011), who noticed a strong negative correlation between k_a and an applied vertical stress of 30–800 kPa on remolded sandy loam soils. Berisso et al. (2012) observed a decrease in k_a at soil depths of 0.3 to 0.9 m after compaction by a sugar-beet harvester, for which the vertical stress below the tyres was estimated to decrease from 207 to 84 kPa in the corresponding depths. Ball and Ritchie (1999) also showed lower k_a values between 0 and 0.15 m of soil depth in loam and sandy loam soils after heavy compaction using a 4.2-Mg laden tractor with inflation pressure of the front and rear tyres of 220 and 80 kPa, respectively.

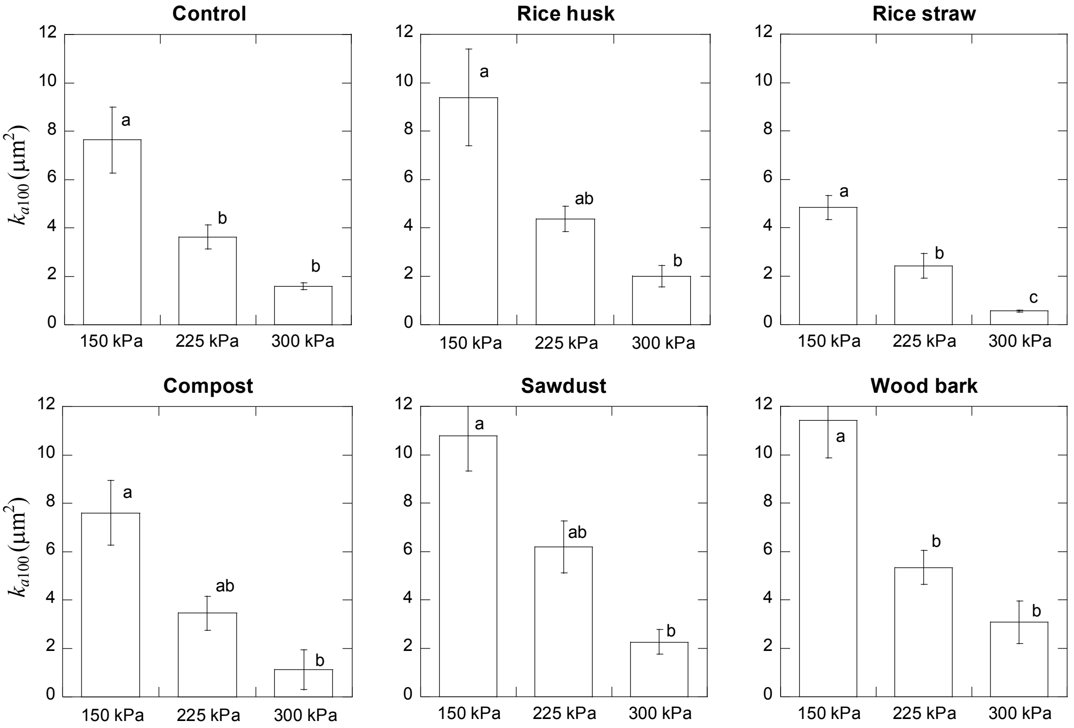

Fig. 3-3. Comparison of the measured air permeability (k_{a100}) after compaction at stress levels of 150, 225, and 300 kPa. Means for the stress levels of a certain OM treatment followed by the same letter are not significantly different ($P < 0.05$).

Fig. 3-4a shows a strong positive linear relationship between values of ε_{100} and log k_{a100} (r = 0.902). This relationship may suggest that reduced values of k_{a100} can be reasonably attributed to a decrease in ε_{100} (Table 3-2), namely a decrease in the volume of soil macropores after compaction. Blackwell et al. (1990) and Osozawa (1998) also showed that k_a is mainly controlled by soil pore size distribution, especially the volume of soil macropores. Iversen et al. (2003) confirmed the conclusion of Iversen et al. (2001) that macropores are the almost exclusive determinant of k_a in accordance with Pouseuille's law after their study on spatial variability of air and water permeability.

Soils mixed with rice husk, sawdust, and wood bark gave higher values of k_{a100} than the control regardless the level of compaction (Fig. 3-3). These higher values of k_{a100} are mainly ascribable to higher values of ε_{100}, that is, a greater volume of macropores (Table 3-2). However, the observed differences were not statistically significant, neither between the control and soils mixed with OM nor among the soils mixed with OM (data and statistical analysis not shown). Particularly in the case of soil mixed with rice straw, a somewhat higher ε_{100} (Table 3-2) was not accompanied by a higher k_{a100}, particularly at compression levels of 150 and 225 kPa. This was probably related to the presence of "blockage effect" from the mixed rice straw on k_a, like in the case of D_p/D_0, as shown in Fig. 3-4a and Fig. 3-2a,b, respectively. The Fig. 3-4a showed that for a given ε_{100} soils mixed with OM tended to have a lower k_{a100} than the control, suggesting the existence of "blockage effect" by OM on k_{a100}.

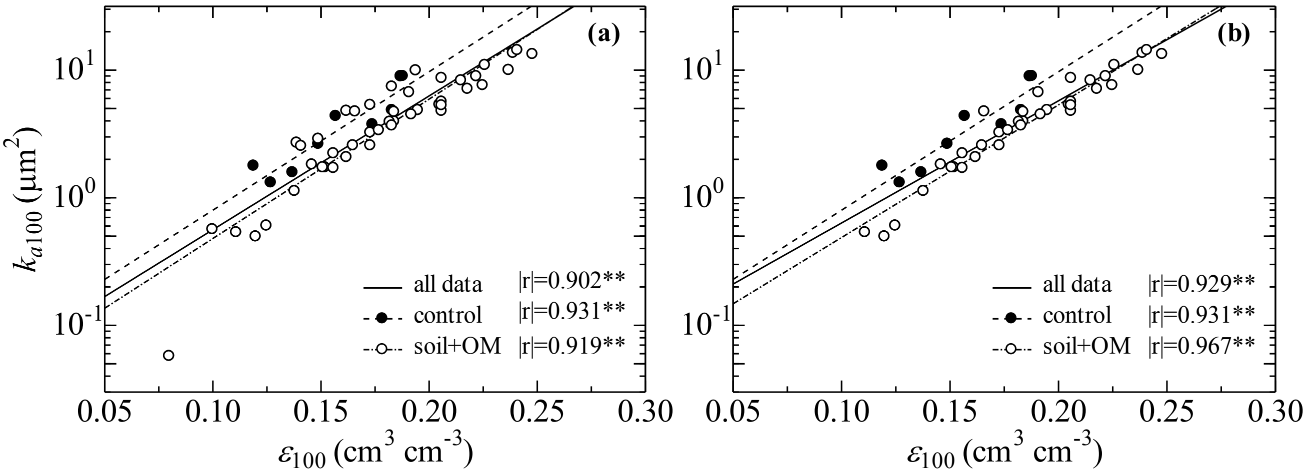

Fig. 3-4. Estimated linear relationship between air permeability (k_{a100}) and soil air content (ε_{100}) (**$P < 0.01$) for the all data (a), and without the data of soil with compost (b).

The linearity between ε_{100} and k_{a100} for soil with OM, however, was observed to be better (r = 0.967) and the difference in k_{a100} between the soil with OM and control soil for a given ε_{100} also became more evident as if the data of soil with compost are omitted (Fig. 3-4b). This result might suggest that the "blockage effect" was more evident for the not yet-decomposed raw OM: rice husk, rice straw, sawdust, and wood bark than the compost which is to some extents already decomposed even before being used in this study.

As discussed, k_a mainly depends on volume of macropores whereas D_p/D_0 is greatly affected by air content. Besides the volume of macropores, k_a is also controlled by continuity of the macropores (Moldrup et al., 2003; Osozawa, 1998). The role of macropore continuity in controlling k_a may be illustrated by considering the potential effect of bottle-necks formed by water menisci in the macropore system (inter-aggregate pore system) at air-filled condition, by which k_a may be restricted even though gas diffusion still can take place. Thus, it would logically be expected that the values of k_{a100} may show greater variability than the values of $(D_p/D_0)_{100}$ when they are expressed as a function of ε_{100} which merely indicate the volume of macropores but not the pore continuity. Moldrup et al. (2003) found that variability in k_a (as a function of volumetric water content) was greater than that in D_p/D_0 for the same soil core after their study on air permeability of undisturbed volcanic ash soils. Furthermore, they showed that k_a was more dependent on differences in soil structure (in that study: pore connectivity and continuity), than was D_p/D_0. In our study, however, linear regression between k_{a100} and ε_{100} resulted a higher linear regression coefficient than between $(D_p/D_0)_{100}$ and ε_{100} as shown in Fig. 3-4a and Fig. 3-2a, respectively (r = 0.902 and r = 0.855, respectively), which may imply a higher variability in $(D_p/D_0)_{100}$ than in k_{a100} as a function of ε_{100}. Reason for this unexpected result, however, remains unclear.

3.5. Saturated hydraulic conductivity (k_s)

Compaction reduced saturated hydraulic conductivity (k_s), with significant differences between compaction levels of 300 and 150 kPa, except for soil mixed with sawdust which had a large standard deviation (Fig. 3-5). However, compaction at 225 kPa showed no significant differences to compaction at 300 and 150 kPa of soils mixed with rice straw and sawdust. Decreases in k_s because of compaction were also found by Etana et al. (2013) for a loamy soil at 0.3 to 0.95 m depths after wheelings by a 6-row sugar-beet harvester with a maximum wheel load of 10.4 Mg. Kim et al. (2010) also found a decrease in k_s of about 69% in a silt loam at soil depths of 0 to 0.3 m in their study on field treatments of uniformly compacted plots using a water tanker with an estimated vertical stress at the soil surface of 500 to 1000 kPa. Marsili et al. (1998) also reported a decrease in k_s of a clay soil at 0 to 0.1 m depths after wheelings by large 10.2 and 13.0 Mg tractors with an average ground contact pressure of

48 and 50 kPa, respectively.

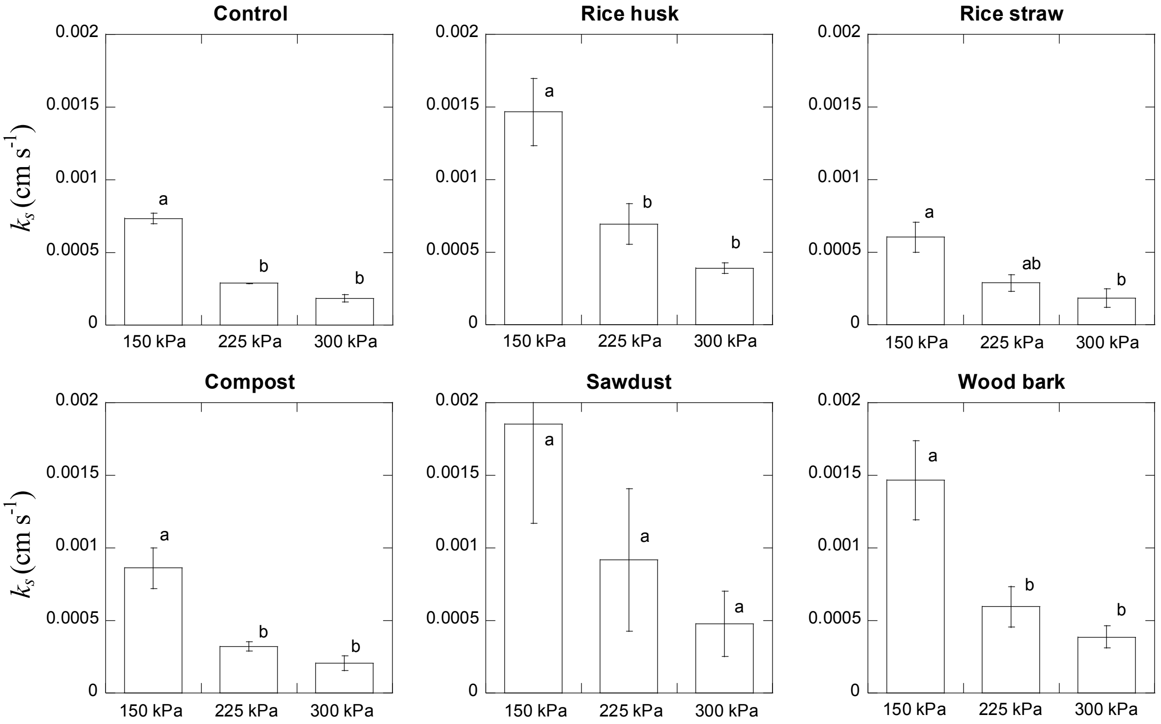

Fig. 3-5. Comparison of the measured saturated hydraulic conductivity (k_s) after compaction at stress levels of 150, 225, and 300 kPa. Means for the stress levels of a certain OM treatment followed by the same letter are not significantly different ($P < 0.05$).

Except for rice straw treatment, soils mixed with OM had higher values of k_s compared with the control soil (Fig. 3-5). However, differences between the control soil and soils mixed with OM or among the soils mixed with OM were not statistically significant (data and statistical analysis not shown). These higher values of k_s were probably attributable to a greater volume of macropores, as indicated by higher values of ε_{100} (Table 3-2). In case of soil mixed with compost, which had a lower ε_{100} than the control, k_s was almost the same as in the control. This was probably related to the high semi-macropore/micropore content of this soil (subchapter 3.6.) which was to some extent effective for water percolation.

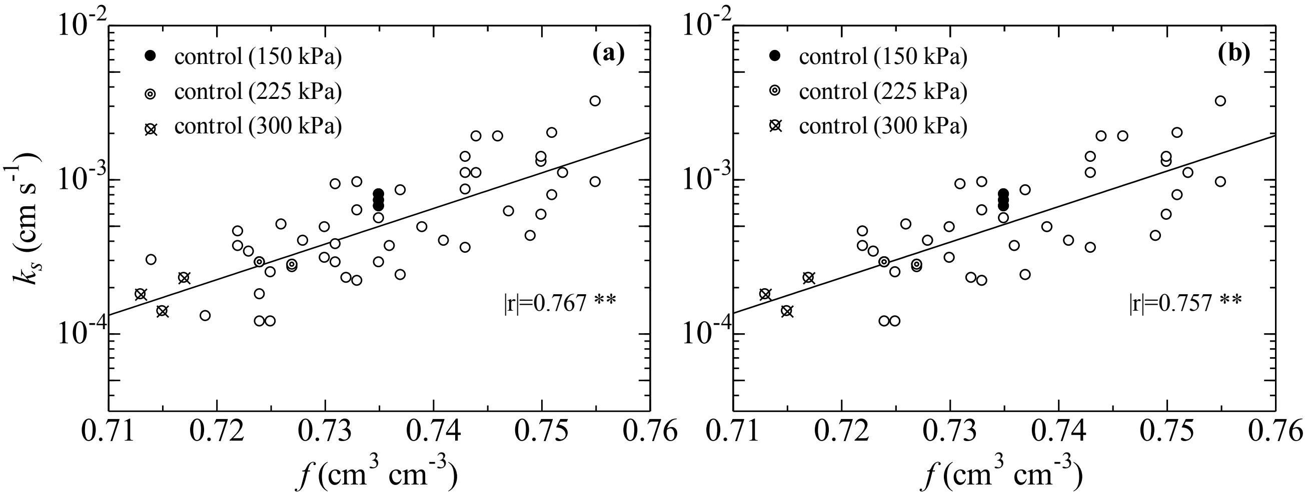

Fig. 3-6. Estimated linear relationship between saturated hydraulic conductivity (k_s) and total porosity (f) (**$P < 0.01$) for the all data (a), and without the data of soil with compost (b).

Fig. 3-6a shows a positive linear relationship between total porosity (f) and k_s (r = 0.767), and similar positive linearity (r = 0.757) was also observed even after the data of soil with compost have been omitted (Fig. 3-6b). From this result, it might be expected that reductions in k_s are related to a reduction in f values (Table 3-1) after the compaction occurred. However, a stronger positive linear relationship was observed between k_s and ε_{100} for the all data measured (r = 0.868) as shown in Fig. 3-7a or after the data of soil with compost have been omitted (r = 0.867) as shown in Fig. 3-7b. This may suggest that the reduced k_s are probably attributable to the reduction in ε_{100} (Table 3-2); that is a reduction in volume of macropores after the compaction took place. These results therefore support those of Iversen et al. (2003) and Poulsen et al. (1999) who found that macropores (ε_{100}) are the almost exclusive determinant of water transport when a soil is fully saturated (k_s). A relatively low coefficient of linear regression of f vs. k_s found by Osunbitan et al. (2005) also indicated that total porosity (f) was not the major determinant of k_s. They suggested that their result was attributable to disturbance of the macropore continuity.

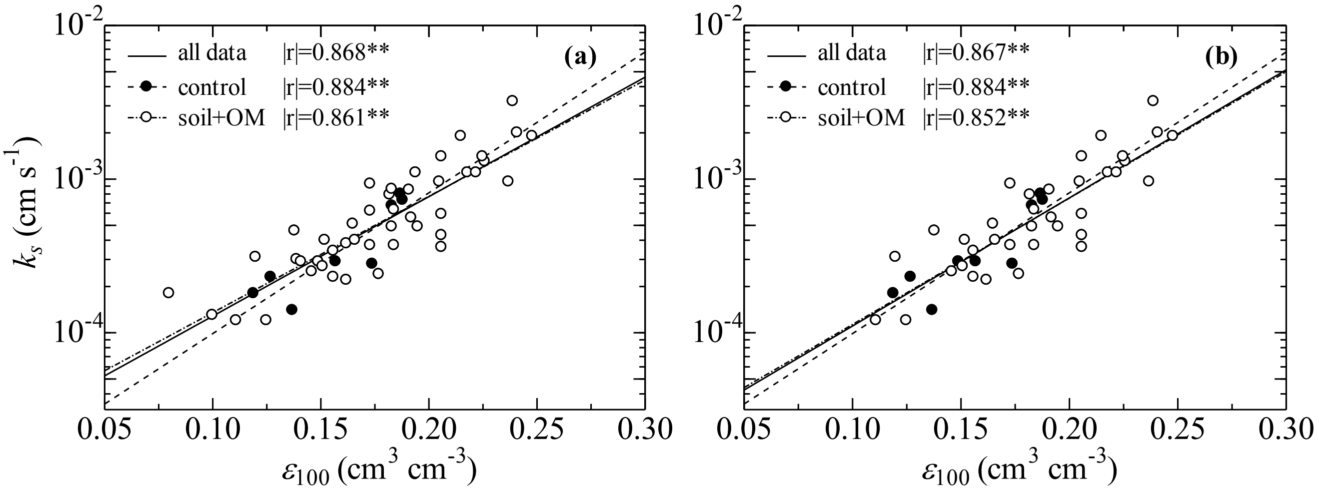

Fig. 3-7. Estimated linear relationship between saturated hydraulic conductivity (k_s) and soil air content (ε_{100}) (**$P < 0.01$) for the all data (a), and without the data of soil with compost (b).

In contrast to the "blockage effect" found for D_p/D_0 and k_a, values of k_s were not likely affected by the presence of OM because the difference in k_s between the control soil and soils mixed with OM for a given ε_{100} was inconsistent (Fig. 3-7a,b). Despite blocking the soil pores (and thus the entailed gas transport), the mixed OM seemed to absorb water and yet allow water flow under saturated conditions. This mechanism was analogous to ceramic filters or millipore filters sometimes used in the soil pF test which are impassable for air due to high air-entry values under wet conditions, but passable for water under saturated condition. We therefore suggest calling the effect "ceramic filter effect" as a simple descriptor.

The direct measurement of soil hydraulic permeability is labor intensive, time-consuming, and expensive, while the measurement of air permeability (k_a) is rapid and easy (Iversen et al., 2003). Thus, indirect methods for estimating saturated hydraulic conductivity (k_s) from the more easily measured k_a using pedotransfer functions have been proposed. Loll et al. (1999) have suggested to measure k_a at pF 2.0 in 100 cm^3 soil cores, while Iversen et al. (2003) proposed to determine k_a at the actual field water content (close to field capacity at pF 2.0) in 6280 cm^3 soil cores to infer the spatial distribution of k_s values. Iversen et al. (2001) as mentioned in Iversen et al. (2003) have proposed the use of k_a measured at soil pF 1.7 of either a 100- or a 6280-cm^3 soil core for the same purpose. Undisturbed samples were used in these studies, and the measurement of k_a ranged from ~10^{-1} to 10^2 μm^2. The measured k_{a100} and k_s from the cited studies and our study were plotted as a log-log plot, and a reasonable agreement between the findings was observed within the same range of values (Fig. 3-8a). The result was even better if the data of soil with compost are omitted as shown in Fig. 3-8b.

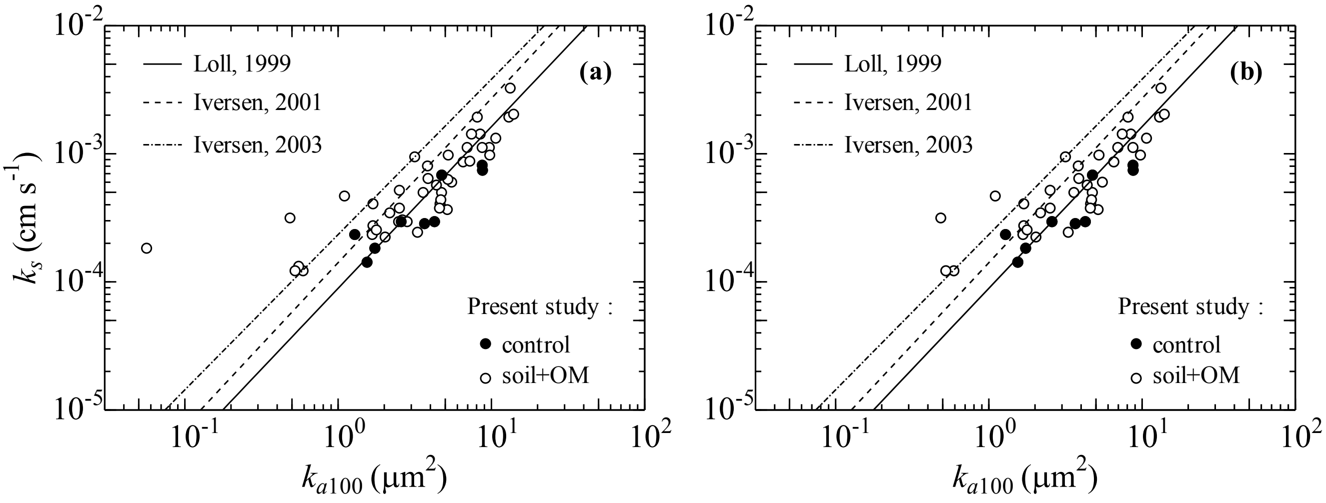

Fig. 3-8. Estimated linear relationship between saturated hydraulic conductivity (k_s) and air permeability (k_{a100}) for the all data (a), and without the data of soil with compost (b).

3.6. Pore size distribution

In order to examine the effect of compaction, the volume of macropores ($\phi \geq 30$ μm) is expressed in a measure relative to the volume of soil solid using ν_{a100} (Table 3-3). It was found that the volume of macropores decreased with increased levels of compaction, and a significant difference was more pronounced between the 300 and 150 kPa compactions. The volume of micropores ($\phi < 30$ μm), however, did not undergo an appreciable change (ν_{w100}).

Table 3-3 Effect of compaction on distribution of macro and micro-pores as indicated by air volume ratio (ν_{a100}) and water volume ratio (ν_{w100}) at -100 cm H_2O soil matric suction, respectively.

OM treatment	ν_{a100} (cm^3 cm^{-3}) [$\phi \geq 30$ μm]			ν_{w100} (cm^3 cm^{-3}) [$\phi < 30$ μm]		
	150 kPa	225 kPa	300 kPa	150 kPa	225 kPa	300 kPa
Control	0.70 ± 0.01 Ab	0.58 ± 0.05 Cb	0.45 ± 0.04 Bab	2.08 ± 0.01 Abc	2.05 ± 0.03 Abc	2.06 ± 0.04 Aa
Rice husk	0.90 ± 0.07 Aa	0.71 ± 0.05 Cac	0.56 ± 0.06 Bac	2.01 ± 0.04 Ab	2.02 ± 0.04 Ab	2.04 ± 0.07 Aa
Rice straw	0.79 ± 0.06 Aab	0.62 ± 0.04 Cbc	0.43 ± 0.03 Bbc	2.21 ± 0.06 Aa	2.18 ± 0.08 Aa	2.22 ± 0.04 Aa
Compost	0.72 ± 0.04 Ab	0.56 ± 0.04 Ab	0.38 ± 0.10 Bb	2.20 ± 0.06 Aac	2.17 ± 0.06 Aac	2.18 ± 0.16 Aa
Sawdust	0.92 ± 0.09 Aa	0.80 ± 0.05 Aa	0.59 ± 0.05 Ba	2.13 ± 0.04 Aab	2.08 ± 0.01 Aab	2.11 ± 0.04 Aa
Wood bark	0.93 ± 0.04 Aa	0.71 ± 0.01 Cac	0.58 ± 0.04 Bac	2.09 ± 0.04 Aab	2.07 ± 0.03 Aab	2.07 ± 0.04 Aa

Either values of ν_{a100} or ν_{w100} followed by same capital letter (row), and lowercase letter (column), are not significantly different ($P < 0.05$).

Fig. 3-9 shows the measured air volume ratio (ν_a) at various soil pF for which the applied OM except compost tended to result a higher ν_a than the control regardless the level of compactions. For each OM treatment except compost at 300 kPa, it was obvious that the value of ν_a decreased with the level of compaction at each soil pF as shown in Fig. 3-10. In the case of compost at 300 kPa, the value of ν_a at soil pF 3.0 and 4.2 seemed to be similar or superimposed with those of 225 kPa compaction, which might be acknowledged as a shortage of the measurement.

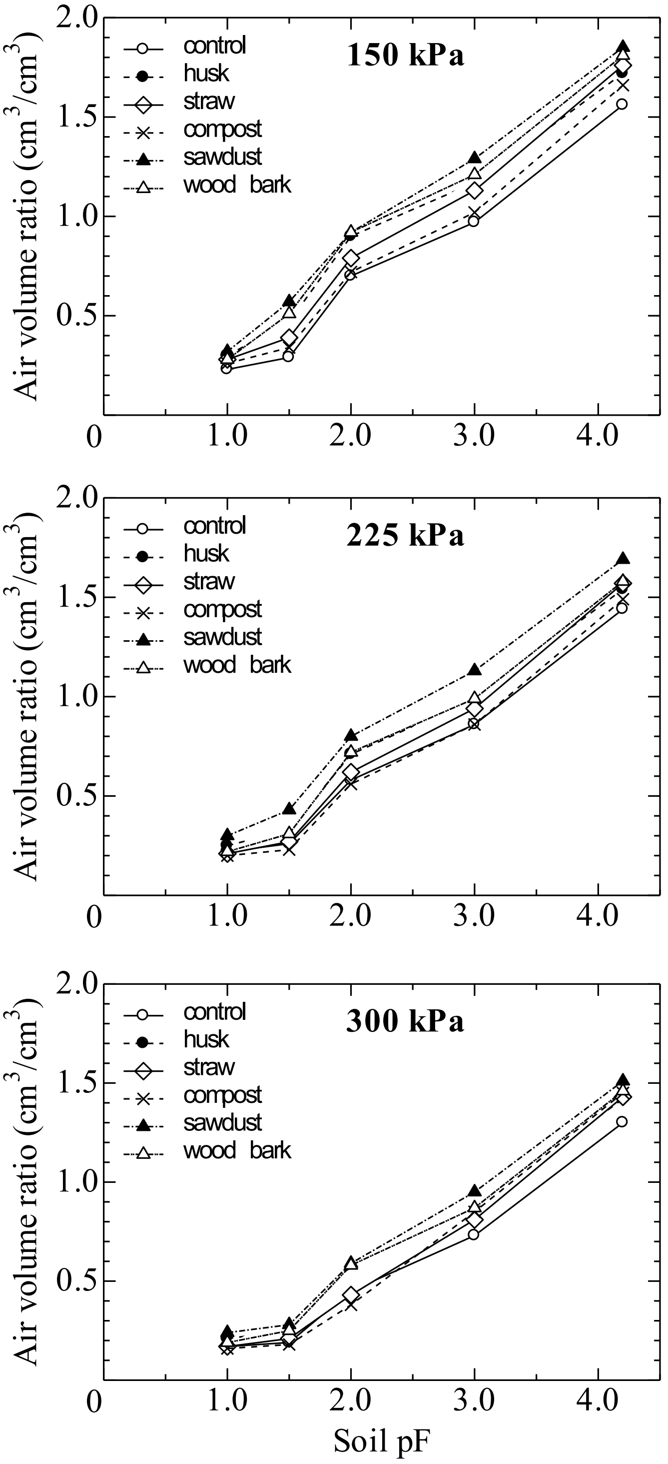

Fig. 3-9. Air volume ratio (ν_a) as a function of soil pF at 150, 225, and 300 kPa compaction levels.

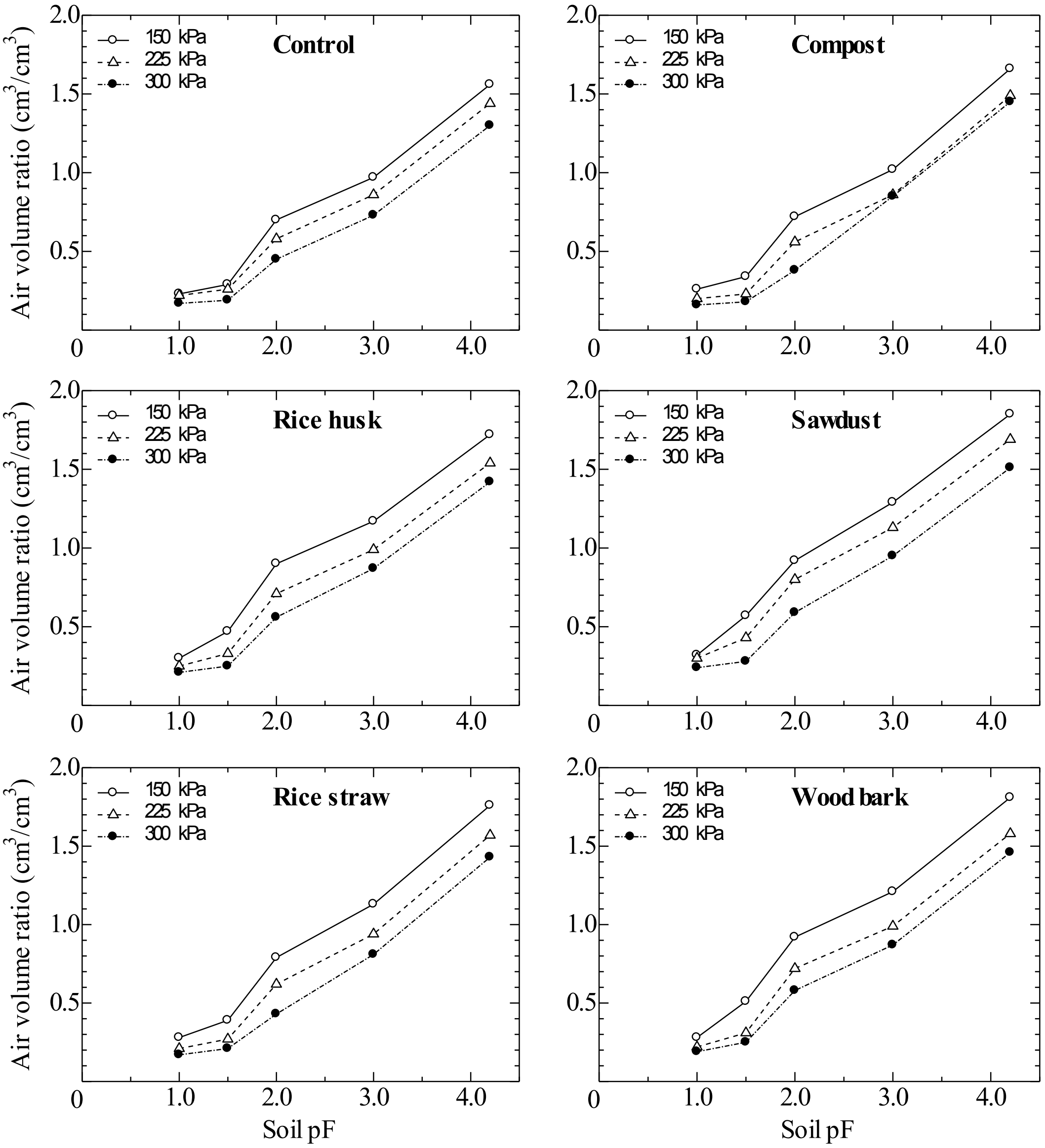

Fig. 3-10. Air volume ratio (ν_a) as a function of soil pF at 150, 225, and 300 kPa compaction levels under certain kind of OM treatment.

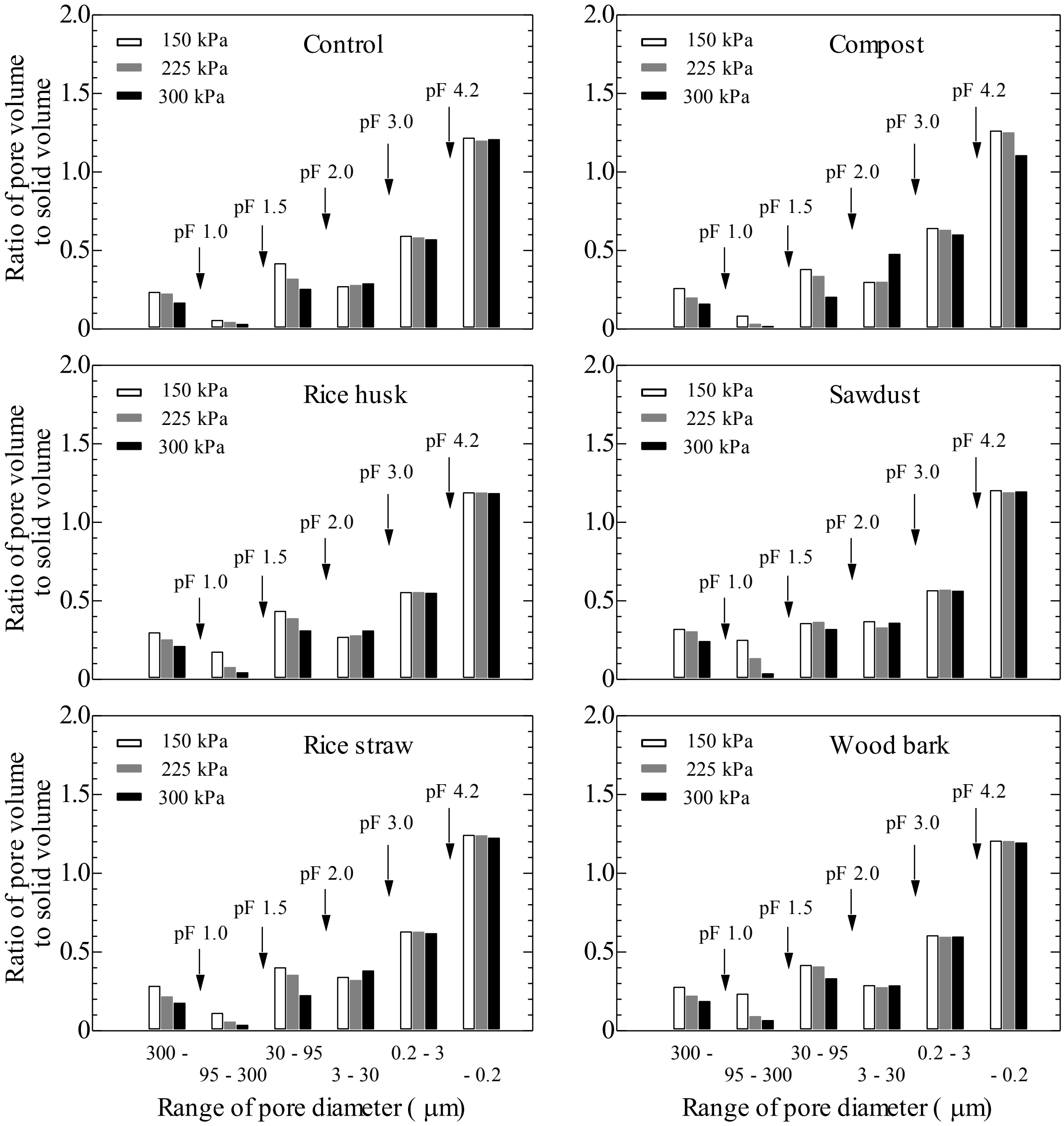

Fig. 3-11. Ratio of pore volume to the solid volume of soil at various ranges of pore diameter as affected by compaction treatments.

Fig. 3-11 shows distribution of the pore volume relative to the solid volume at various range of pore diameters referring to the result of pF tests conducted. It can be seen that the volume of pores with diameter range of > 300 μm, 95–300 μm, and 30–95 μm, namely the macropores, decreased with the level of compaction. Meanwhile, the change in volume of pores at the rest ranges of pore diameter observed (3–30 μm, 0.2–3 μm, and < 0.2 μm) acted in different manners individually with respect to the range of pore diameter, kind of OM treatment, or level of compaction referred.

If the volume of macropores is expressed in a measure relative to the total volume of soil using ε_{100} (Table 3-4), it decreased with the increased level of compaction, and likewise, the difference was found to be particularly significant between the 300 and 150 kPa compactions. This decrease in macropores was followed by an increase in volume of micropores ($\phi < 30$ μm) as indicated by the increased θ_{100} in Table 3-4.

Table 3-4 Effect of compaction on distribution of macro and micro-pores as indicated by air content (ε_{100}) and volumetric water content (θ_{100}) at -100 cm H_2O soil matric suction, respectively.

OM	ε_{100} ($cm^3\ cm^{-3}$) [$\phi \geq 30$ μm]			θ_{100} ($cm^3\ cm^{-3}$) [$\phi < 30$ μm]		
treatment	150 kPa	225 kPa	300 kPa	150 kPa	225 kPa	300 kPa
Control	0.186 ± 0.003 Ab	0.160 ± 0.013 Cbd	0.128 ± 0.009 Bab	0.549 ± 0.002 Bac	0.565 ± 0.011 Bab	0.587 ± 0.009 Aa
Rice husk	0.230 ± 0.016 Aa	0.191 ± 0.012 Bac	0.156 ± 0.018 Ba	0.514 ± 0.013 Bb	0.541 ± 0.012 ABb	0.566 ± 0.018 Aa
Rice straw	0.198 ± 0.014 Aab	0.164 ± 0.013 Cbc	0.119 ± 0.007 Bab	0.552 ± 0.015 Bac	0.574 ± 0.014 Bac	0.608 ± 0.008 Aa
Compost	0.183 ± 0.011 Ab	0.151 ± 0.011 ABb	0.106 ± 0.030 Bb	0.561 ± 0.012 Aa	0.582 ± 0.012 Aa	0.612 ± 0.035Aa
Sawdust	0.227 ± 0.019 Aa	0.205 ± 0.010 Aa	0.160 ± 0.012 Ba	0.526 ± 0.016 Bbc	0.537 ± 0.008 Bb	0.570 ± 0.010 Aa
Wood bark	0.230 ± 0.010 Aa	0.189 ± 0.004 Cacd	0.159 ± 0.011 Ba	0.521 ± 0.010 Bbc	0.547 ± 0.005 Abc	0.567 ± 0.010 Aa

Either values of ε_{100} or θ_{100} followed by same capital letter (row), and lowercase letter (column), are not significantly different ($P < 0.05$).

These results suggested that compaction decreased the volume of macropores either as a proportion to the solid volume of soil (ν_{a100}) or as a proportion to the total volume of soil (ε_{100}), whereas the volume of micropores seemed to be subject to the volume indices being used, namely ν_{w100} or θ_{100}. To appreciate the volume change that actually occurred when a soil specimen was compacted, it might be preferable to summarize here that the volume of macropores decreased with the level of compaction (ν_{a100}), while the volume of micropores did not undergo an appreciable change (ν_{w100}) in this study. This summation was consistent with the result of Kutilek et al. (2006) that the change of pore size distribution is mainly in the macropores system (structural domain), while it is negligible in the micropores system (matrix domain), after their study on a sandy loam Alfisol soil subjected to 0 and 300 kPa compression.

The results shown in Table 3-4 were in accordance with the study from Alakukku (1996) who found that wheeling with 19 Mg of a tractor-trailer combination was found to reduce macroporosity ($\phi > 30$ μm) of a clay soil. Furthermore, an organic soil was found to have a reduced macroporosity and an increased microporosity ($\phi < 30$ μm) over 20–50 cm soil depth after wheeling with a 16-Mg tractor-trailer combination. Berisso et al. (2012) also observed a reduction in volume of macropores ($\phi > 30$ μm) of a sandy clay loam soil after repeated wheelings with an ~10 Mg sugar beet harvester. Matthews et al. (2010) found that a 522 kPa compaction caused a greater loss of larger pores ($\phi > 30$ μm) in clay loam, silty clay loam, and clay loam soil than a 174-kPa compaction, whereas the smaller pores remained unaffected.

With the purpose of discussing the effect of OM, Table 3-4 was examined. It was observed that the compost-mixed soil had the lowest volume of macropores (even lower than the control), whereas the other OM treatments tended to result in a higher volume of macropores than the control even though the difference was not consistent. This result implied that the OM treatments (other than compost) have a positive effect on the volume of macropores in terms of resistance to compaction. This positive effect could be related to the capability of OM in increasing a loading or mechanical stress resistance as described in the study of Ellies (1988), Gregory et al. (2009), and Dörner et al. (2011) after their study on volcanic ash and grassland soils.

The compost-mixed soil, conversely, had the highest volume of micropores, and together with rice straw-mixed soil, had a higher volume of micropores than the control (Table 3-4). Celik et al. (2004) also reported a higher volume of micropores due to the application of compost for 5 years on a clay-loam soil (OM content 1.4–1.6%). In their study, however, the volume of macropores ($\phi > 4.5$ μm) was also observed to significantly increase. Similarly, Schjønning et al. (1994) and Schjønning et al. (2005) reported a significantly larger volume of micropores ($\phi < 30$ μm) in soil dressed with animal manure (1.32% and 1.30–1.35% in OM content, respectively) than in soil dressed with inorganic fertilizers (1.19% and 1.15–1.25% in OM content, respectively), but the volume of macropores ($\phi > 30$

μm) remained unaffected.

If result of the corresponding air contents (ε) derived from the pF test are used to examine the change in pore volume at more specific diameter ranges, it revealed that the decrease in volume of macropores occurred for all macropore diameter ranges measured (> 300 μm, 300–95 μm, 95–30 μm) after compaction, but there was no pattern of significance observed among either the compaction levels or the type of OM applied (data and statistical analysis not shown). In case of the micropores, a relatively constant volume was observed for the size ranges < 0.2 μm and 0.2–3.0 μm, whereas a slight change in volume was observed for the pores ranging from 3.0–30 μm.

3.7. Specific gas diffusivity (S_{D100})

As the level of compaction increased, specific gas diffusivity (S_{D100}) measured at −100 cm H_2O soil matric suction decreased and a significant difference was found between 300 and 150 kPa (Fig. 3-12). This result implied that compaction led to a more tortuous pore network for gas diffusion, which may have resulted in lower relative gas diffusivity (D_p/D_0). To some extent, the more tortuous pores (lower S_{D100}) were likely to have contributed to the lower $(D_p/D_0)_{100}$ mentioned in subchapter 3.3. A reduction in S_D due to compaction was also reported by Schjønning and Rasmussen (2000) after compaction with direct drilling using a triple-disc drill on a coarse sandy soil at 4–8 and 14–18 cm depth and for a loamy sand soil at 4–8 cm depth. Ball et al. (1988) also reported a lower S_D of either chisel ploughed or direct drilled clay loam soil after traffic treatment using an unladen tractor.

The addition of OM tended to result in more tortuous pores for gas diffusion than the control, as indicated by lower values of S_{D100} (Fig. 3-12), even though the difference was generally not significant (data and statistical analysis not shown). The most tortuous pores were observed in the rice straw-mixed soil (significantly different from the control at 150 and 225 kPa compaction). This may explain the low value of $(D_p/D_0)_{100}$ of this soil despite its high air content (subchapter 3.3. and 3.2.). Conversely, despite their slightly lower values of S_{D100}, sawdust and wood bark-mixed soils resulted in higher $(D_p/D_0)_{100}$ (e.g., 0.0480 and 0.0477 at 150 kPa, respectively) than the control (e.g., 0.0425 at 150 kPa) (subchapter 3.3.). This result might imply that their higher $(D_p/D_0)_{100}$ were more likely ascribed to the higher air content (subchapter 3.3. and 3.2.), and thus, the pore tortuosity may not necessarily be providing a significant contribution.

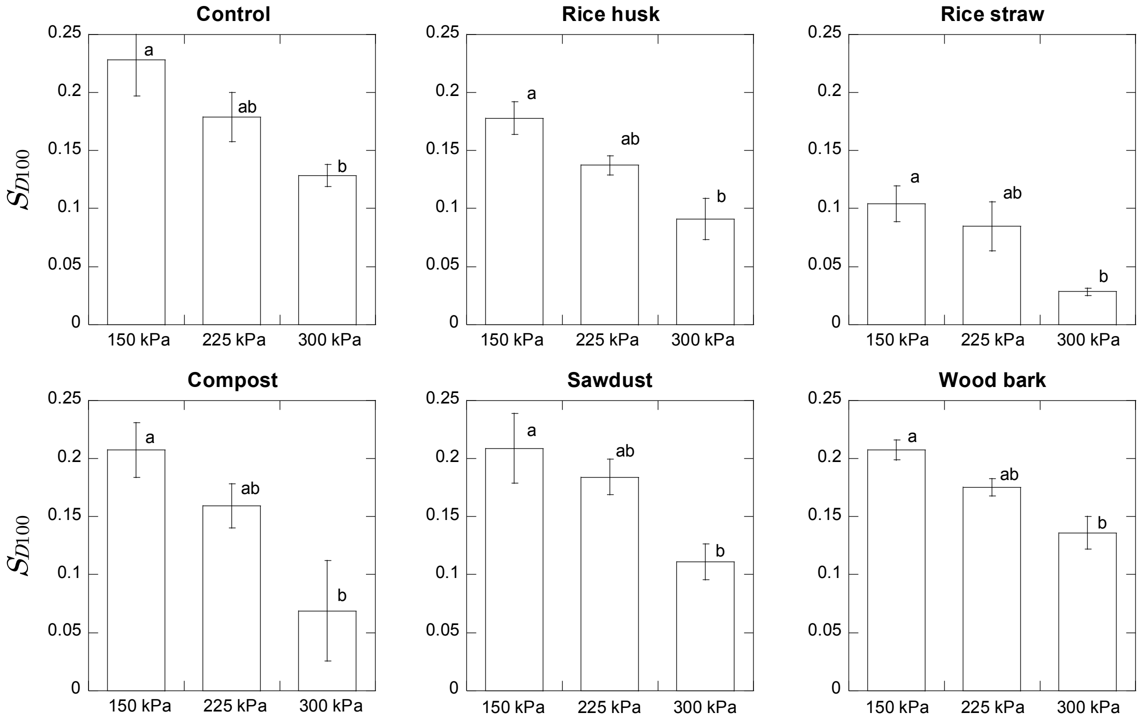

Fig. 3-12. Specific gas diffusivity (S_{D100}) at -100 cm H_2O soil matric suction as a function of compaction levels. Means for the compaction levels of a certain OM treatment followed by same letter are not significantly different ($P < 0.05$).

This result, however, was different from Schjønning et al. (2005) who found that there was a tendency for a reduced tortuosity (higher S_D) of the loamy sand soil with a long-term (about a century) application of animal manure and mineral fertilizer (1.15–1.35% in OM content) than the unfertilized soil (1.07% in OM content). This difference was attributable to the difference in the type of OM applied and the type of soil observed, besides observation in the present study was limited to the very early period of OM application so that a prolonged observation is expected to give a different result after the applied OM decomposes.

In order to evaluate sensitivity of the measured $(D_p/D_0)_{100}$ with regard to the measured ε_{100}, $(D_p/D_0)_{100}$ and ε_{100} were plotted in a log-log graph, after following the equation 2.6 in chapter 2, as shown in Fig. 3-13a. It can be seen that the control and the OM-mixed soils gave a high linearity r = 0.898 and r = 0.908, respectively, which was even higher than its linearity shown in linear-linear graph of $(D_p/D_0)_{100}$ and ε_{100} in Fig. 3-2a (r = 0.871 and r = 0.892, respectively). Compared to the control, the OM-mixed soils tended to result a lower $(D_p/D_0)_{100}$ for a given ε_{100}, which might suggest an existence of "blockage effects" from the presence of OM on gas diffusion namely the mixed OM itself and the increased capillary water in the bottle-neck may give a hindrance to the gas diffusion process (subchapter 3.3.).

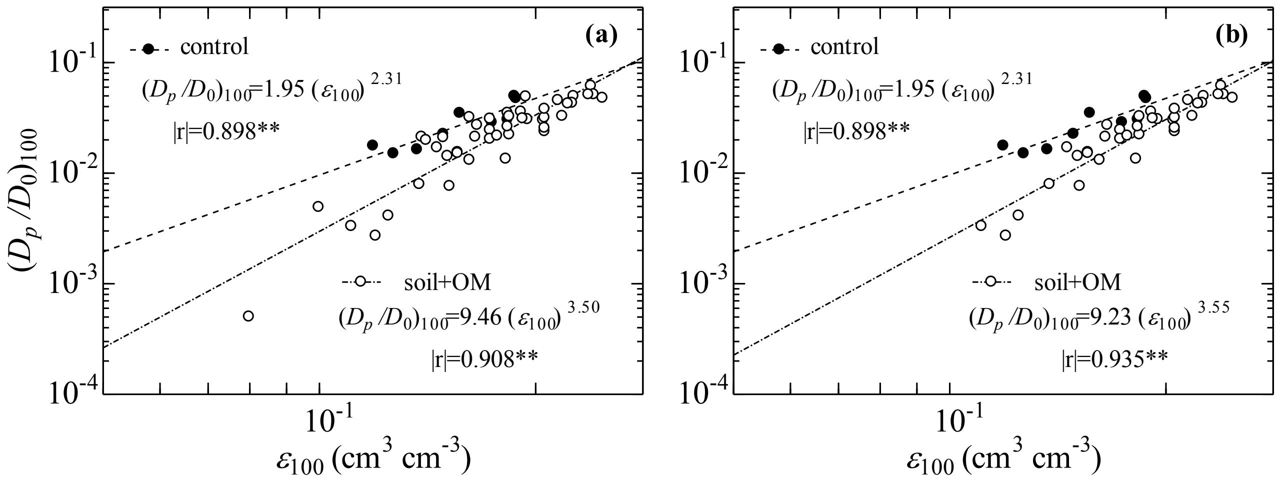

Fig. 3-13. Sensitivity of the measured relative gas diffusivity at -100 cm H_2O soil matric suction $(D_p/D_0)_{100}$ with regard to the corresponding air content (ε_{100}) ($^{**}P < 0.01$) for the all data (a), and without the data of soil with compost (b).

As can be seen from Fig. 3-13a, the OM-mixed soils also had a higher value of n (3.50) than that of the control (2.31). This higher value of n implied a steeper decrease in $(D_p/D_0)_{100}$ with the level of compaction (i.e., decrease in ε_{100}). Thus, $(D_p/D_0)_{100}$ of the OM-mixed soils were more sensitive to the change in ε_{100} compared with that of the control, and this was probably related to the existence of the aforementioned blockage effect which seemed becomes larger as the ε_{100} decreases.

If data of soil with compost are omitted, the OM-mixed soils gave a higher linearity between $(D_p/D_0)_{100}$ and ε_{100} (r = 0.935) as shown in Fig. 3-13b, and the difference in $(D_p/D_0)_{100}$ for a given ε_{100} between the OM-mixed soils and control soil became more evident. This might suggest that the "blockage effect" was more evident for the not yet-decomposed raw OM: rice husk, rice straw, sawdust, and wood bark than the compost which is to some extents already decomposed. Adding to this, the data omission of soil with compost also resulted a slightly higher value of n (3.55) as can be seen in this Fig. 3-13b. This result might imply that $(D_p/D_0)_{100}$ of the raw OM-mixed soils were more sensitive to the change in ε_{100} compared with that of the control or of the compost-mixed soil either.

3.8. Specific air permeability (S_{ka100})

Specific air permeability (S_{ka100}) measured at −100 cm H_2O soil matric suction decreased with compaction level, and a significant difference was more pronounced between 300 and 150 kPa (Fig. 3-14). This result confirmed that compaction had a negative effect on soil pore continuity (S_{ka}) by which gas convection might be constrained so that the measured air permeability (k_a) would be reduced. Thus, the reduced k_{a100} in subchapter 3.4. was also thought to be reasonable to attribute to the reduced pore continuity (lower S_{ka100}).

A reduction in pore continuity caused by compaction has also been reported by other researchers. Dörner et al. (2012) demonstrated that compaction with a 1.5-Mg roller caused a decrease in continuity of macropores (S_{ka}) of silty loam – silty clay loam volcanic ash soil. Ball et al. (1988) also revealed a reduction in S_{ka} of a direct drilled clay loam soil after traffic treatment using an unladen tractor. Arthur et al. (2013) reported a negative relationship between soil bulk density and pore organization (S_{ka}) at −100 hPa (field capacity) of silt loam soil with long-term application of animal manure and mineral fertilizer. Furthermore, they observed that it was the soil bulk density, rather than the organic content, that seemed to differentiate the pore connectivity and arrangement. Schjønning and Rasmussen (2000) reported a reduced S_{ka} of coarse sandy soil and loamy sand soil after compaction by direct drilling using a triple-disc drill.

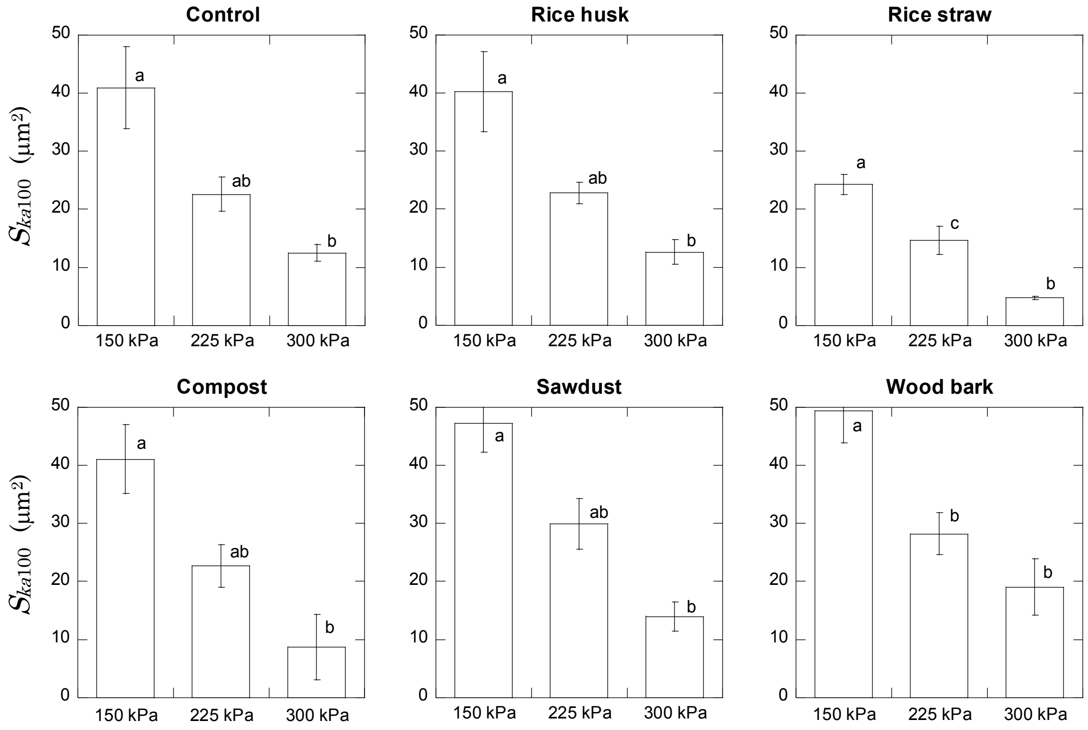

Fig. 3-14. Specific air permeability (S_{ka100}) at -100 cm H_2O soil matric suction as a function of compaction levels. Means for the compaction levels of a certain OM treatment followed by same letter are not significantly different ($P < 0.05$).

Although it was not statistically significant, there was a tendency toward higher pore continuity (higher S_{ka100}) of the OM-mixed soils than the control except for rice straw-mixed soil (data and statistical analysis not shown). This result might imply a positive effect of the mixed OM on the pore continuity, more particularly that of sawdust and wood bark, so that higher air permeability (k_{a100}) might be the result. This higher pore continuity of sawdust and wood bark-mixed soils was in accordance with the remarkably high k_{a100} in subchapter 3.4. A similar positive effect of the applied OM on pore continuity (S_{ka}) has also been reported by Schjønning et al. (2005) after their study on a loamy sand soil dressed with animal manure and mineral fertilizer for about a century (1.15–1.35% in OM content). Similarly, Arthur et al. (2013) also reported an increase in pore connectivity (S_{ka}) of silt loam after a 105-year animal manure and mineral fertilizer application (1.53–2.37% in OM content).

The rice straw-mixed soil, conversely, gave the lowest S_{ka100} (least continuous pores) which was also in accordance with the lowest k_{a100} in subchapter 3.4. This result, however, was different from the result described by Schjønning et al. (2005) that incorporation of rice straw for years led to a tendency towards higher air permeability (k_a) and pore continuity (S_{ka}). Likewise, this difference was probably due to the difference in type of soil observed and period length of the rice straw application.

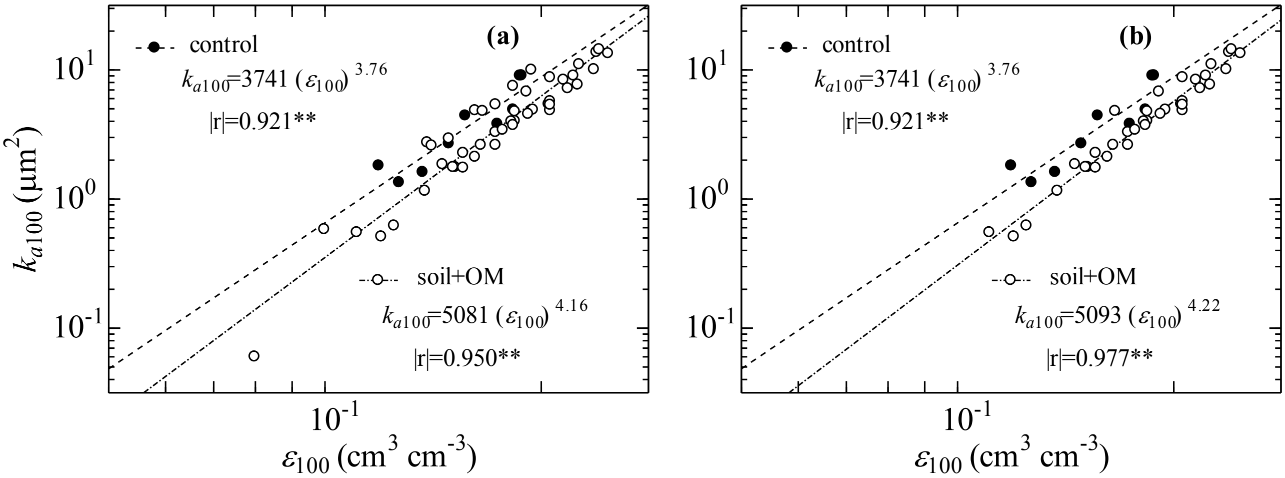

Fig. 3-15. Sensitivity of the measured air permeability at -100 cm H_2O soil matric suction (k_{a100}) with regard to the corresponding air content (ε_{100}) (**$P < 0.01$) for the all data (a), and without the data of soil with compost (b).

As in the case of $(D_p/D_0)_{100}$ (subchapter 3.7.), k_{a100} and ε_{100} were plotted in a log-log graph to evaluate sensitivity of the measured k_{a100} with regard to the measured ε_{100} as shown in Fig. 3-15a. The control and OM-mixed soils resulted a high linearity r = 0.921 and r = 0.950, respectively, which was a bit lower for the control but higher for the OM-mixed soils than its linearity shown in log-linear graph of k_{a100} and ε_{100} in Fig. 3-4a (r = 0.931 and r = 0.919, respectively). For a given ε_{100}, the k_{a100} value of the control tended to be a bit higher than that of the OM-mixed soils. This result might imply the existence of a "blockage effect" from the presence of OM on gas convection (k_a) as in the case of gas diffusion (D_p/D_0) (subchapter 3.3., 3.4., and 3.7.). The OM-mixed soils had a slightly higher value of n (4.16) than that of the control (3.76), which to some extent implied a steeper decrease in k_{a100} with the level of compaction (i.e., decrease in ε_{100}). In other words, k_{a100} values of the OM-mixed soils were more sensitive to changes in ε_{100} than that of the control, which can probably be ascribed to the existing blockage effect from the presence of OM that seemed to be larger with the decreased ε_{100}.

Fig. 3-15b shows that the OM-mixed soils gave an even higher linearity between k_{a100} and ε_{100} ($r = 0.977$) as if the data of soil with compost are omitted, and the difference in k_{a100} between the OM-mixed soils and the control for a given ε_{100} also became slightly clearer. This result might suggest that the “blockage effect” was more evident for the not yet-decomposed raw OM rather than the compost. In addition, the omission of data of soil with compost also resulted a slightly higher value of n as 4.22 (Fig. 3-15b). This result might imply that k_{a100} of the raw OM-mixed soils were more sensitive to the change in ε_{100} compared with that of either the control or compost-mixed soil.

3.9. Specific hydraulic conductivity (S_{ks})

The value of specific hydraulic conductivity (S_{ks}) decreased with the level of compaction (Fig. 3-16), which suggested a reduction in macropore continuity. This result was in accordance with the reduced k_s in subchapter 3.5. Therefore, it became evident that the decrease in k_s could not merely be ascribed to the lower volume of macropores (subchapter 3.5.), but also related to the reduced macropore continuity after the compaction took place as discussed in Dörner et al. (2010), Fuentes et al. (2004), and Osunbitan et al. (2005) amongst others. As shown in Fig. 3-16, the differences were significant between 300 and 150 kPa compactions except for rice straw and sawdust-mixed soils, which gave no significant differences among the three compaction levels because of their high standard deviations. Compared with the control, the OM-mixed soils resulted a higher S_{ks}, except for rice straw-mixed soil, even though the difference was not significant (data and statistical analysis not shown). This result implied that the applied OM tended to enable maintenance of macropore continuity of the compacted soil sample for the higher k_s. In case of the rice straw-mixed soil, the lower S_{ks} was also coincident with lower k_s than the control in subchapter 3.5. This revealed that the addition of rice straw failed to improve the status of macropores in terms of continuity for better k_s in this study.

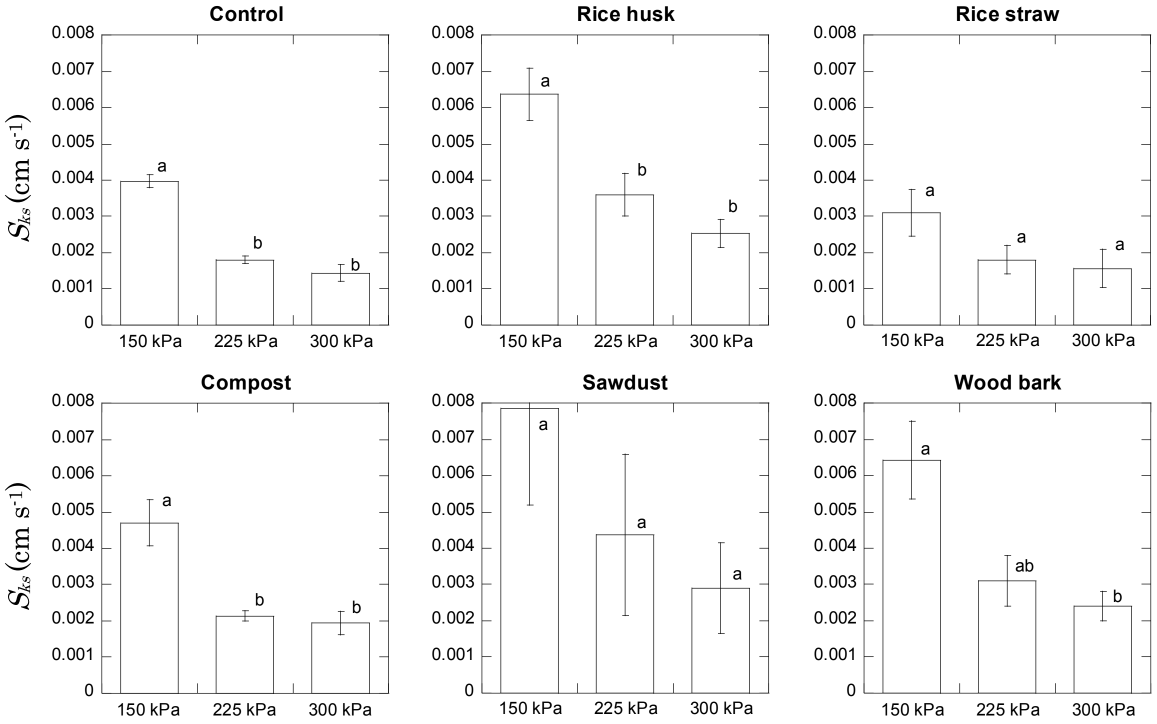

Fig. 3-16. Comparison of specific hydraulic conductivity (S_{ks}) at different level of compactions. Means for the compaction levels of a certain OM treatment followed by same letter are not significantly different ($P < 0.05$).

As in the case of $(D_p/D_0)_{100}$ (subchapter 3.7.) and k_{a100} (subchapter 3.8.), k_s and ε_{100} were plotted in a log-log graph, following the equation 2.6 in chapter 2, in order to evaluate sensitivity of the measured k_s with regard to the measured ε_{100} (Fig. 3-17a). The control and the OM-mixed soils resulted a high linearity r = 0.865 and r = 0.829, respectively, even though it was a bit lower than its linearity shown in log-linear graph of k_s and ε_{100} in Fig. 3-7a (r = 0.884 and r = 0.861, respectively). As shown in Fig. 3-17a, the control resulted a slightly higher value of n (3.17) than that of the OM-mixed soils (2.70). If data of soil with compost are omitted (Fig. 3-17b), however, the n value of these OM-mixed soils became higher (3.27) and this was even slightly higher than that of the control (3.17).

Nevertheless, the scattering pattern of these data (Fig. 3-17a as supported by Fig. 3-17b) suggested that neither the control nor OM-mixed soils is obviously different from one to another, which probably was ascribed to existence of ceramic filter effect from the OM mixed. This result might suggest that sensitivity of k_s to compaction (i.e., decrease in volume of macropores) of neither the control nor OM-mixed soils is obviously different from one to another for the range of ε_{100} measured, different from the case of $(D_p/D_0)_{100}$ (subchapter 3.7.) and k_{a100} (subchapter 3.8.).

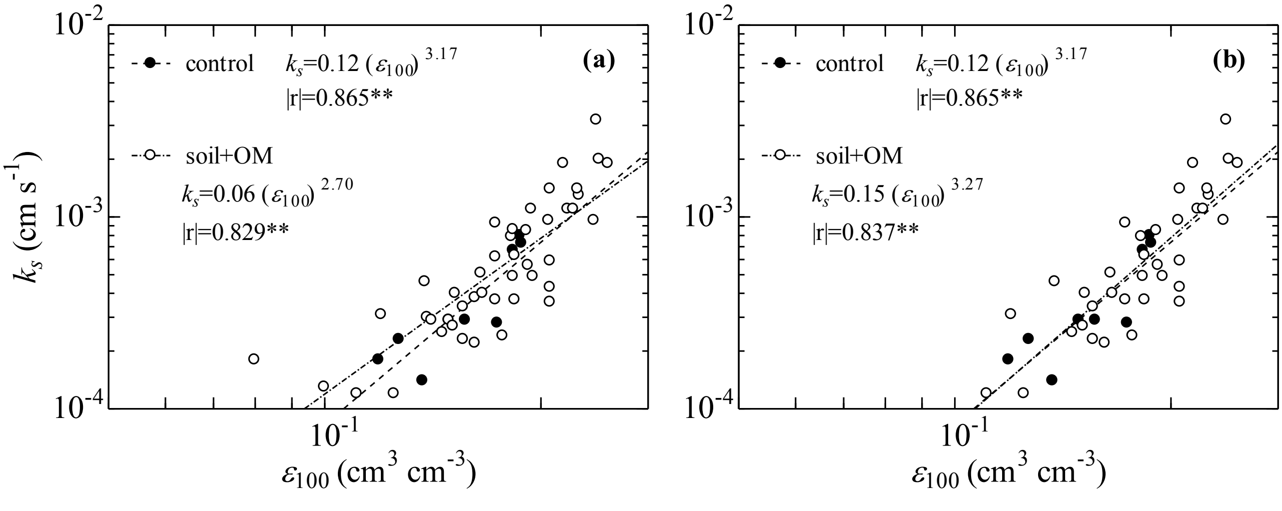

Fig. 3-17. Sensitivity of saturated hydraulic conductivity (k_s) with regard to the volume of macropores (ε_{100}) (**$P < 0.01$) for the all data (a), and without the data of soil with compost (b).

These values of n (3.17 and 2.70 in Fig. 3-17a, and 3.17 and 3.27 in Fig. 3-17b), however, were lower than that in Ahuja et al. (1984) where they measured 3.98 and 3.81 for Renfrow silt loam and Hawaii oxic soils, respectively. This difference in the value of n was probably ascribed to the difference in the size range of macropores being considered where we used $\phi \geq 30$ μm in this study (ε_{100}) and Ahuja et al. (1984) used $\phi > 9.1$ μm (i.e., air content measured at −330 cm H_2O soil matric suction ε_{330}).

Chapter 4

Conclusions and prospective future studies

Based on the aforementioned results of this study, the following points could be concluded:

1) Compaction significantly increased dry bulk density (ρ_d), which was followed by a reduction in total porosity (f), and the addition of OM resulted in significantly lower ρ_d and higher f than the control. The volume of macropores ($\phi \geq 30$ μm) was reduced by the compaction whereas the volume of micropores ($\phi < 30$ μm) remained unaffected. The addition of OM tended to result in a higher volume of macropores than the control.
2) Compaction reduced relative gas diffusivity $(D_p/D_0)_{100}$, air permeability (k_{a100}), and saturated hydraulic conductivity (k_s). Doubling the level of compaction from 150 to 300 kPa resulted in a significant reduction of these parameters. The decrease in $(D_p/D_0)_{100}$ was most likely attributable to a reduced air content, and the decrease in k_{a100} and k_s was most probably attributable to a reduced volume of macropores, as indicated by reduced ε_{100} values.
3) Sawdust and wood bark seemed to have the greatest positive effect on $(D_p/D_0)_{100}$, k_{a100}, and k_s in terms of resistance to compaction, while rice straw had the opposite effect. The presence of OM was likely to block air flow in soil pores by numerous bottle-necks caused by water menisci ("blockage effect"), leading to lower values of $(D_p/D_0)_{100}$ and k_{a100} for a given value of ε_{100}. These pores, blocked by the mixing in of OM, however, seemed to allow the water yet to flow ("ceramic filter effect"). The effect of OM decomposition on these parameters was not studied, therefore further long-term studies at field scale are necessary.
4) Compaction resulted in more tortuous macropores for gas diffusion (lower specific gas diffusivity S_{D100}) and less continuous macropores for gas convection (lower specific air permeability S_{ka100}) for which a significant difference was more pronounced between the 300 and 150 kPa compactions. The compaction also caused less continuous macropores for water movement as

indicated by lower specific hydraulic conductivity S_{ks}. The addition of OM was likely to result in lower S_{D100}, but except for rice straw tended to result in higher S_{ka100} than the control. The addition of OM also seemed to result in a higher S_{ks} than the control.

5) The decrease in relative gas diffusivity $(D_p/D_0)_{100}$ and air permeability k_{a100} was more sensitive to compaction (i.e., decrease in ε_{100}) in OM-mixed soils than in the control, but this was not clear for saturated hydraulic conductivity k_s.

6) The following topics remain as prospective future studies for a better and more comprehensive understanding of the studied soil gas and water transport properties as well as soil pore structure indices:

   a) Effects of the prolonged application of OM at field scale to take into account the decomposition process of OM

   b) Peculiarity effects of rice straw: whether it has a correlation with the geometric factor of rice straw, anisotropy effect, etc..

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