Korean J. Soil Sci. Fert. 43(1), 1-7 (2010) **Article**

# Water Transport Characteristics of Paddy Plow Pan Soils as Estimated by Particle Size Distribution Fractal Dimension

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**This study was carried out to investigate plow pan characteristics and to grasp the relationship between its particle size distribution fractal dimension ($D_m$) and water transport in paddy plow pan. Twenty four soil sampling sites with different management groups, ordinary and sandy-textured, were selected and investigated for physical properties of soils such as Yamanaka hardness in April, non-submerged condition, before rice seedling transplanting. The plow pan appearing depth and thickness was determined by penetration resistance profile. Undisturbed core samples with five replicates were sampled at plow pan layer with 2 inch cores for measuring soil bulk density and saturated hydraulic conductivity. The particle size distribution fractal dimension ($D_m$) was calculated by the method following the procedure Tyler and Wheacraft (1992), using the USDA-based particle size analysis data with fractions of 0-0.002, 0.002-0.053, 0.053-0.1, 0.1-0.25, 0.25-0.5, 0.5-1.0, and 1.0-2.0 mm. The plow pan of investigated fields appeared at a range from 5 to 30 cm depth, showing minimum value in sandy-textured management group and maximum value in ordinary management group. The thickness of plow pan were distributed from 5 to 17 cm, showing both minimum and maximum values in sandy-textured management group. Averagely, the plow appearing depth were deeper in ordinary management group than in sandy-textured management group, whereas the reverse in the thickness of plow pan. The particle size distribution fractal dimension ($D_m$) had higher value with finer textures, with higher fractality in coarser texture. Saturated hydraulic conductivities, $K_s$, of plow pan soils distributed from 0.5 to 1420 mm day$^{-1}$, having the highest value in sandy skeletal soils. The $K_s$ decreased with decreasing clay content and $D_m$, showing power function relationships. The coefficient of determination, $R^2$, of the fitted power functions were higher in $D_m$ as x-axis than in clay content. This means that $D_m$ could give us more effective estimation than clay content. Especially, sandy-textured paddy soils had higher $R^2$, compared to ordinary paddy soils. $K_s$ of relatively coarse-textured soils with less than 18% of clay content, therefore, was more dependent on particle size distribution than that of relatively fine-textured soils. From these results, it could be concluded that the fractal scaling gives us a unique quantity describing particle size distribution and then can be applied to estimate saturated hydraulic conductivity, especially more effective in coarse-textured soils.**

**Key words:** Particle size distribution fractal dimension ($D_m$), Paddy plow pan, Saturated hydraulic conductivity

## Introduction

Water is the most critical of all resources used to grow rice, and it is vital to increase the efficiency of water in rice production. The puddling process is one of methods to reduce water percolation rate in rice production (Kyuma, 2004). Stagnating and waterlogged soils, however, are classified as low yielding soils (Xu Qui et al., 1980). The need for drainage and a high percolation rate is probably associated with the accumulation of toxic substances such as $H_2S$ and nutrient imbalances probably related to Fe, Mn, P, Zn, and S (FFTC, 1989). Optimum percolation rate, therefore, has been recognized as an important factor for sustained high rice yields (FFTC, 1989; Jeon et al., 2002). Besides, water percolation in paddy field could be companied by nutrient leaching and ground water recharge, so it has simultaneously an environmentally concern. Water transport in paddy fields commonly restricts at plow pan, a zone at the base of the puddled layer which is slowly compacted, resulting from annual

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process of puddling and reworking the surface soil. Soil pores geometry of plow pan layer, especially depending on the particle size distribution of soils and external forces such as agro-machine load, determine soil hydraulic conductivity. In fact, the sand, silt and clay content calculated from particle size distribution has been used for estimating soil hydraulic conductivity (Mishra et al., 1989). Recently, fractal scaling has been proposed as a model for soil particle size distribution (Tyler and Weatcraft, 1992). Results from many studies suggest that the fractal dimension of the particle-size distribution, $D_m$, is useful in quantifying the relationships between soil texture and associated properties and processes in soils (Milan et al., 2003; Esahin et al., 2006). This study, therefore, was carried out to investigate plow pan characteristics and to grasp the relationship between its particle size distribution fractal dimension ($D_m$) and water transport in paddy plow pan.

## Materials and Methods

**Soil sampling and measurements of physical properties** Soil sampling sites with different management groups, ordinary and sandy-textured, were selected as Table 1 and investigated for physical properties of soils such as Yamanaka hardness in April, non-submerged condition, before rice seedling transplanting. The plow pan appearing depth was determined by sharply increasing depth of penetration resistance, and the thickness of plow pan was measured from the appearing depth to the depth with decreasing penetration resistance again (Fig. 1). Surface soil samples were obtained from the zone over the plow pan appearing depth, and plow pan soil samples were obtained from plow pan layer. Undisturbed core samples with five replicates were sampled with 2 inch cores for measuring soil porosity and saturated hydraulic conductivity.

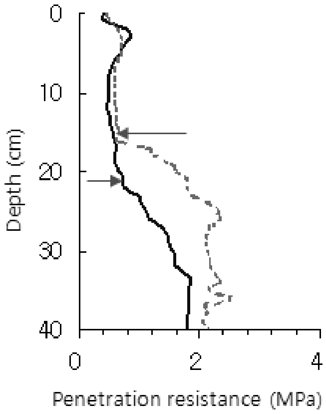


**Fig. 1. Determination of the appearing depth of plow pan using penetration resistance profile. The arrows indicate the plow pan appearing depth of fields.**

Particle size distribution was measured with hydrometer method using combined sedimentation and sieving (NIAST, 2000), based on USDA-based particle size distribution analysis (Klute, 1986) with several fractions of 0-0.002, 0.002-0.053, 0.053-0.1, 0.1-0.25, 0.25-0.5, 0.5-1.0, and 1.0-2.0 mm. Soil cores (diameter, 5 cm and height, 5 cm) were saturated from the bottom with

**Table 1. Characteristics of investigated paddy fields.**

| Management group | Soil textural family | Soil series (Soil taxonomy classified by USDA) | No. of investigated fields | Location |
|---|---|---|---|---|
| Ordinary | Fine | Deogpyeong (Fine, Typic Epiaqualfs) | 2 | Nonsan |
| | | Buyong (Fine, Typic Endoaqualfs) | 2 | Gimje |
| | | Honam (Fine, Typic Endoaqualfs) | 2 | Gwangju |
| | Fine silty | Yuga (Fine silty, Fluvaquentic Endoaquepts) | 2 | Daegu |
| | Fine loamy | Sinheung (Fine loamy, Fluvaquentic Endoaquepts) | 2 | Gwangju |
| | | Imgog (Fine loamy, Aeric Endoaquepts) | 2 | Milyang |
| Sandy-textured | Coarse loamy | Hoegog (Coarse loamy, Aeric Endoaquepts) | 2 | Weonju |
| | | Maegog (Coarse loamy, Fluvaquentic Eutrudepts) | 2 | Weonju |
| | | Eungog (Coarse loamy, Fluvaquentic Eutrudepts) | 2 | Cheongweon |
| | | Gocheon (Coarse loamy over sandy skeletal, Fluvaquentic Dystrudepts) | 2 | Wanju |
| | | Gangseo (Coarse loamy, Fluvaquentic Eutrudepts) | 2 | Cheongweon |
| | Sandy skeletal | Namgye (Sandy skeletal, Aquic Udipsamments) | 2 | Chilgog |

a 0.01 N $CaCl_2$ solution and were left under conditions for more than 24 h. The saturated hydraulic conductivity, $K_s$, of the cores was determined by falling head method (Klute, 1986). In addition, organic matter content with Tyurin method (NIAST, 2000) was analyzed for sampled soils.

**Fractal theory** A fractal object appears morphologically the same, regardless of the scale of observation. Mandelbrot (1993) describes fractals as "shapes whose roughness and fragmentation neither tend to vanish, nor fluctuate up and down, but remain essentially unchanged as one zooms in continually and examination is refined". This is known as scale invariance or scaling. Although natural objects are not fractals in the strict mathematical sense, they often have similar features over a range of scales.

Generally, fractal scaling has a type of power function. The soil particle size distribution has been shown to obey power scaling, indicating an underlying self-similar or scale-invariant structure, *i.e.*, fractals.

**Fractal dimension of soil particle size distribution** Using the USDA-based particle size analysis data, the particle size distribution fractal dimension ($D_m$) was calculated by the method following the procedure of Tyler and Wheacraft (1992). Equation (1) gave us the power function relationship between the mass and size of soil particles.

$$\frac{M(r < R)}{M_T} = \left(\frac{R}{R_{\max}}\right)^{3 - D_m} \quad (1)$$

where, $M(r<R)$ is the mass of soil particles with a radius smaller than R, $R_{max}$ is the upper size limit for the fractal behavior, 2 mm, and $M_T$ is the total mass of the soil lower than $R_{max}$, and $D_m$ is particle size distribution fractal dimension.

## Results and Discussion

**Comparison of physical properties between plow pan and surface soil** Paddy field had the periodic waterlogging and land preparation such as flooding and puddling process, differently from upland fields, which could result in unique characteristics of plow pan in paddy field, depending on management practices and edaphic factors. The plow pan of investigated fields appeared at a range from 5 to 30 cm depth (Fig. 2), showing minimum value in sandy-textured management group and maximum value in ordinary management group. The thickness of plow pan were distributed from 5 to 17 cm, showing both minimum and maximum values in sandy-textured management group. Averagely, the plow appearing depth were deeper in ordinary management group than in sandy-textured management group, whereas the reverse in the thickness of plow pan. This means that ordinary paddy soils could have deeper root zone than sandy-textured paddy soils due to lower resistance for root penetration. In addition, clay contents of ordinary paddy soil samples were higher than those of sandy-textured soils.

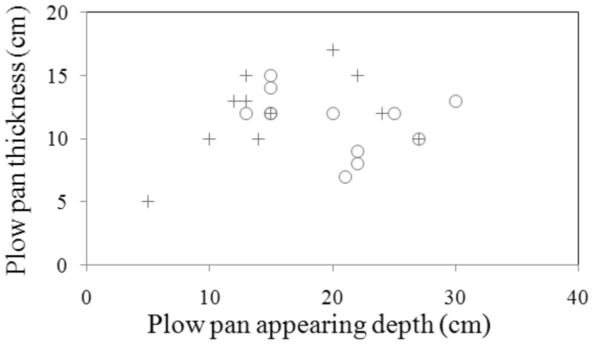


**Fig. 2. Plow pan thickness and appearing depth with different management groups, ordinary (○), and sandy-textured (+).**

Contents in particle size groups, *i.e.*, sand, silt and clay, of surface and plow pan soils were distributed around 1:1 lines (Fig. 3). Unlike this, organic matter content, bulk density and Yamanaka hardness of surface and plow pan soils did not have an 1:1 relationship but were biased. Organic matter contents were higher in surface soils than in plow pan soils, whereas the reverse in bulk density and Yamanaka hardness. The main characteristics of plow pan soils were dense structure compared to surface soil (FFTC, 1989), showing high bulk density and hardness. From comparison between the management groups, sandy-textured group averagely had higher bulk density and hardness than ordinary group. This was probably due to the higher contents of organic matter and finer textures in ordinary groups.

**Particle size distribution fractal dimension, $D_m$, compared to soil textures** The particle size distribution fractal dimension ($D_m$) had higher value with finer

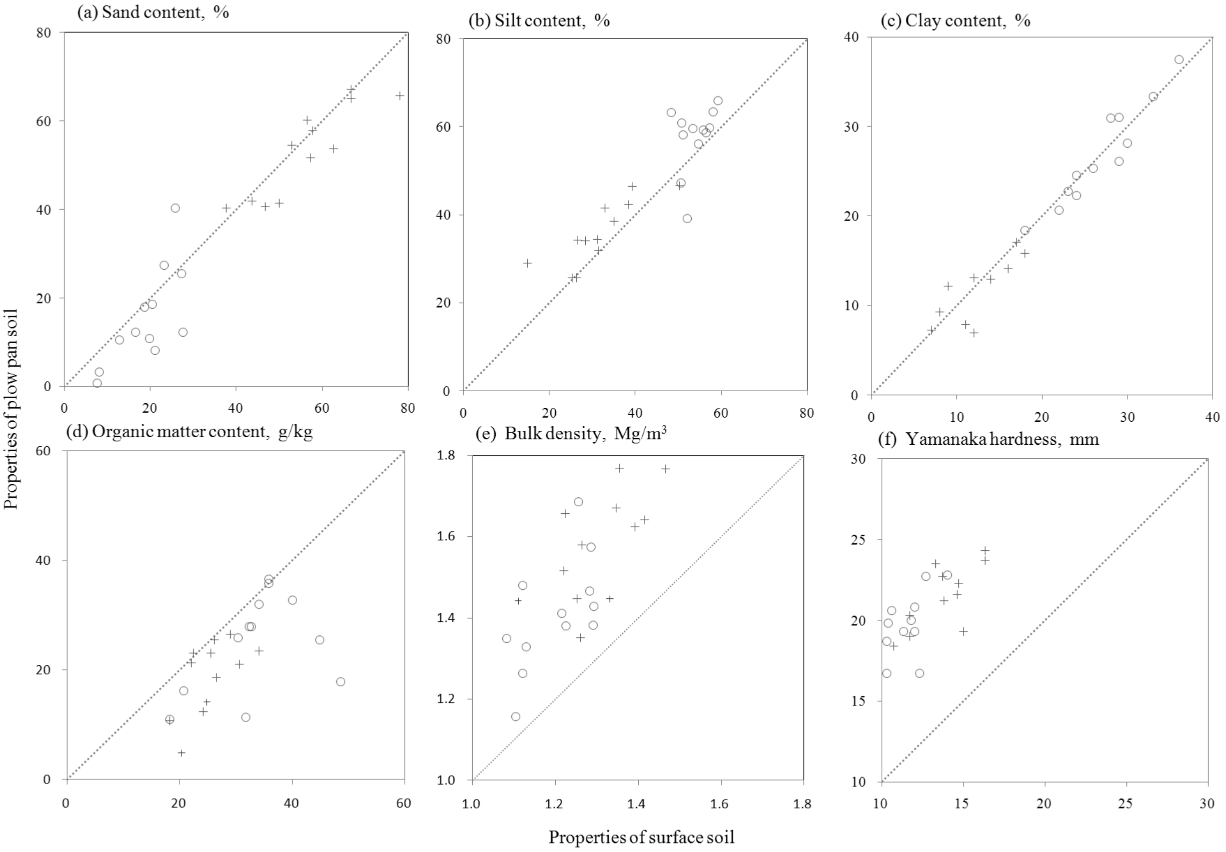


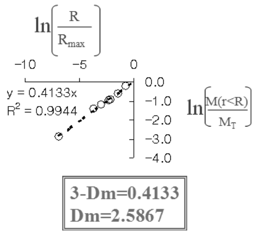
**Fig. 3. Comparison of soil properties between surface and plow pan layer with different management groups, ordinary (○), and sandy-textured (+). Dotted lines indicate 1:1 lines.**

textures (Table 2). Sandy loam and loam soils had a range of $D_m$ values, 2.62-2.75, and 2.72-2.86, respectively, which showed the overlapping $D_m$ range 2.72-2.75. This indicates that soils with different texture could have same $D_m$ values. $D_m$ could, therefore, newly describe soil particle size distribution as a unique quantity differently from textural analysis. $D_m$ resulted from linear regression of log graph between size ratio and mass content. Table 2 showed lower determinant coefficient with finer texture. Indeed, Tyler and Wheatcraft (1992) reported that for soils with coarsest fragment at the 2-mm diameter, strict self-similar or scale-invariant behavior followed a path of texture from sand to clay soils, but that for well-graded soils such as silty loam and silty clay loam, it did not. This means that $D_m$ could be more effective in coarser texture than finer texture. Nevertheless, $D_m$ had high correlation

**Table 2. Comparison of particle size distribution (PSD) fractal dimension (Dm) between different soil textures.**

| Soil texture | No. of soils | PSD $D_m$ | $R^2$ | Sand (%) | Silt (%) | Clay (%) |
|---|---|---|---|---|---|---|
| Sandy Loam | 14 | 2.62-2.75 | 0.87-0.99 | 52.0-71.5 | 14.3-38.2 | 5.3-15.9 |
| Loam | 22 | 2.72-2.86 | 0.73-0.98 | 26.5-51.6 | 30.2-49.0 | 7.4-25.4 |
| Silt Loam | 19 | 2.75-2.87 | 0.55-0.80 | 4.5-38.0 | 50.8-77.7 | 10.1-26.1 |
| Silty Clay Loam | 16 | 2.88-2.91 | 0.52-0.72 | 0.8-14.0 | 49.0-68.0 | 27.4-37.5 |

(Note) $R^2$: Determination coefficient of linear regression in logal form of equation (1) for obtaining PSD $D_m$



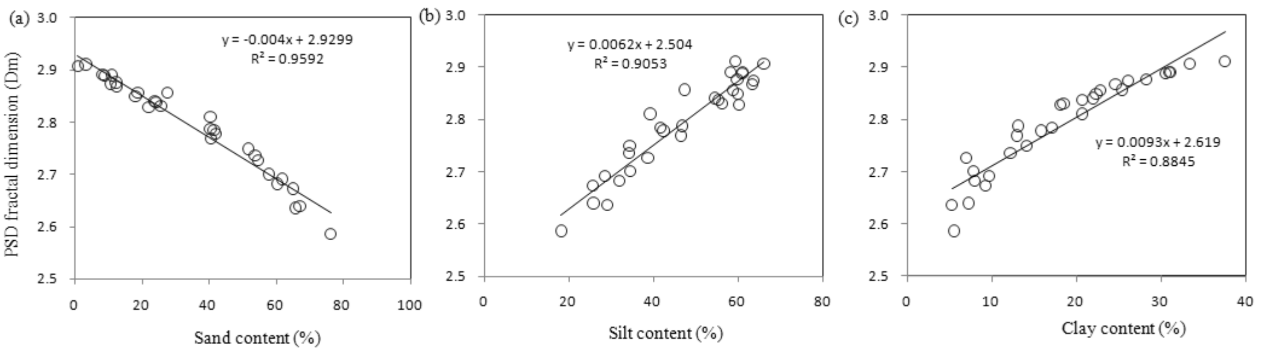


**Fig. 4. Particle size distribution (PSD) fractal dimension (Dm) of soils having different (a) sand, (b) silt, and (c) clay contents.**

with the contents of particle size groups as shown in Fig 4, negative in sand content but positive in silt and clay contents.

**Water transport through plow pan estimated by clay content and *D*$_m$** Water percolation in paddy field generally depends on soil textures and drainage condition (Oh et al., 1974). Especially, drainage condition could be influenced by soil profile characteristics and climate factors. Uprising of ground water table in monsoon season (Yoo et al., 1999), and impermeable bedrock right below plow pan could reduce percolation rate of paddy soil, regardless of plow pan characteristics. In this study, therefore, saturated hydraulic conductivity from laboratory core test of plow pan soils were used to grasp the relationship between water transport and $D_m$ through plow pan.

Saturated hydraulic conductivities, $K_s$, of plow pan soils distributed from 0.5 to 1420 mm day$^{-1}$, having the highest value in sandy skeletal soils. The $K_s$ decreased with decreasing clay content and $D_m$, showing power function relationships. Oh et al. (1974) also reported the power function relationship between the percolation rate and clay content. The coefficient of determination, R$^2$, of the fitted power functions were higher in $D_m$ as x-axis than in clay content (Fig. 5). This means that $D_m$ could give us more effective estimation than clay content. Especially, sandy-textured paddy soils had higher R$^2$, compared to ordinary paddy soils. $K_s$ of relatively coarse-textured soils with less than 18% of clay content, therefore, was more dependent on particle size distribution than that of relatively fine-textured soils.

From these results, plow pan characteristics, especially hydraulic conductivity, depended on particle size distribution such as clay content. The fractal dimension $D_m$ of particle size distribution was a negative correlation with saturated hydraulic conductivity. The estimation of saturated hydraulic conductivity using $D_m$ were implemented by fitting with power function. It could be suggested, therefore, that $D_m$ of plow pan soils could give us the sketchy knowledge of water transport in paddy fields.

## Conclusions

The particle size distribution in plow pan soils of paddy fields is one of keys for grasping the water transport characteristic because plow pan might be very compacted layer through soil profile. The fractal scaling gives us a unique quantity describing particle size distribution and then can be applied to estimate saturated hydraulic conductivity, especially more effective in coarse-textured soils.

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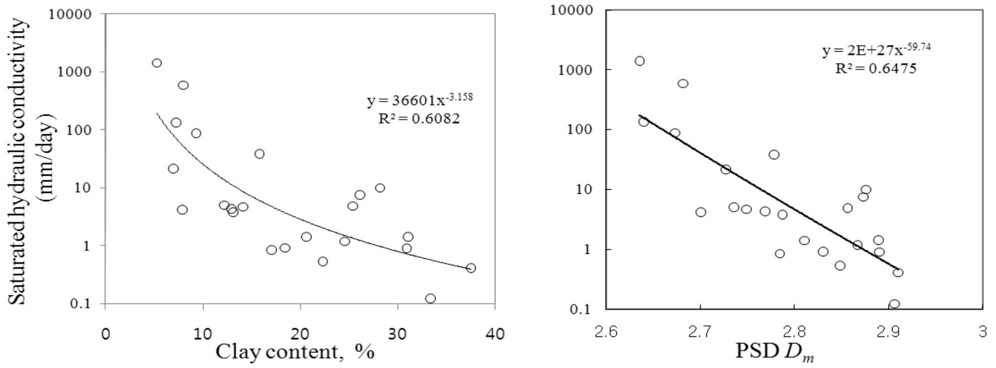
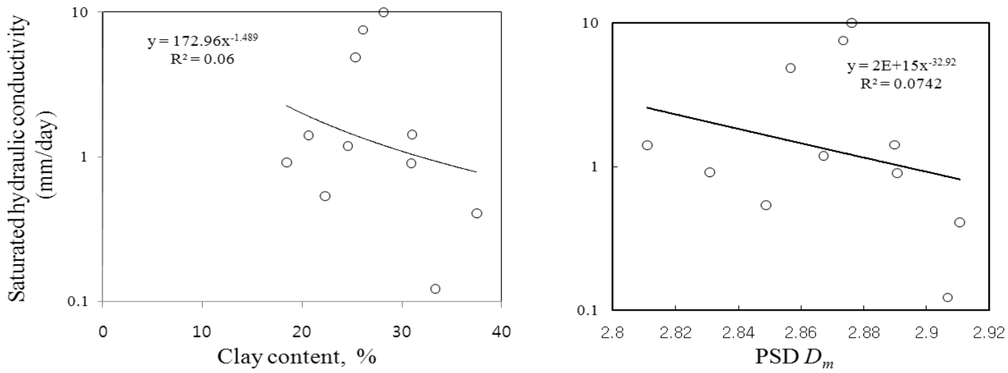
(a) Total



(b) Ordinary management group



(c) Sandy-textured management group

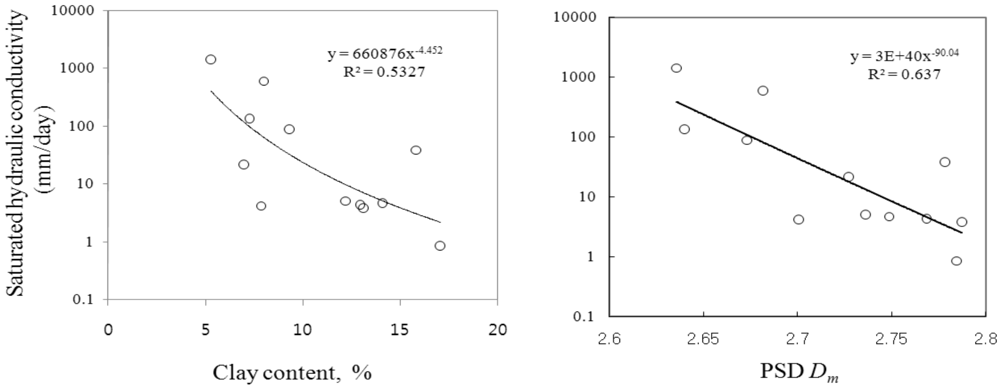


**Fig. 5. Saturated hydraulic conductivity of paddy plow pan related to clay content and particle size distribution (PSD) fractal dimension ($D_m$).**

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# 토양입자분포 프랙탈차원을 활용한 논토양 쟁기바닥층 물이동 추정

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본 연구는 논토양 쟁기바닥층을 대상으로 특성을 파악하고 토양입자분포를 프랙탈차원화하여 물이동을 추정하고자 수행하였다. 모내기전 비담수기에 보통논과 사질논 12지점을 각각 선정하였다. 선정지점에서 깊이별 관입경도를 측정하여 쟁기바닥층 출현깊이와 두께를 도출하였다. 표토와 쟁기바닥층에서 토양입자분포, 유기물함량, 산중식 경도를, 쟁기바닥층에서 2인치 코아시료를 채취한 후 변수위법으로 포화수리전도도를 측정하였다. 토양입자분포의 프랙탈 차원화는 측정한 입자분포 자료, 0-0.002, 0.002-0.053, 0.053-0.1, 0.1-0.25, 0.25-0.5, 0.5-1.0, 1.0-2.0 mm의 함량을 활용하여 Tyler와 Wheatcraft (1992)의 방법을 따랐다. 조사한 연구지점의 쟁기바닥층 출현깊이는 5-30 cm, 두께는 5-17 cm로 분포하였으며 보통논이 사질논보다 평균적으로 출현깊이가 깊고 두께는 얇은 것으로 나타났다. 또한 보통논은 점토함량이 18%이상으로 상대적으로 세립질 토성을, 사질논은 18%이하로 조립질 토성을 나타내었다. 토양입자분포의 프랙탈차원 ($D_m$)은 세립질 토성일수록 높은 값을 나타내었으며 조립질토양에서 더 높은 프랙탈성을 나타내었다. 포화수리전도도는 0.5-1420 mm day$^{-1}$로 분포하였으며 사력질 사질논에서 가장 높은 값을 나타내었다. 포화수리전도도는 점토함량과 $D_m$이 증가함에 따라 감소하는 경향이 나타났으며 멱함수의 형태를 나타내었다. 점토함량보다 $D_m$을 독립변수로 사용했을 시, 적합된 멱함수의 결정계수가 높았으며 특히 사질논이 보통논보다 결정계수가 높게 나타났다. 따라서 본 연구는 토양입자분포를 프랙탈 차원화를 통해 단일 값으로 표현하여 포화수리전도도 등의 물이동 특성 추정에 활용할 수 있다고 보여준다 할 수 있다. 특히 조립질 토성을 가진 논토양의 물이동 추정에 유용할 것으로 판단할 수 있었다.

**주요어 :** 토양입자분포 프랙탈차원 ($D_m$), 논토양 쟁기바닥층, 포화수리전도도