JOURNAL OF DEGRADED AND MINING LANDS MANAGEMENT
ISSN: 2339-076X, Volume 2, Number 3 (April 2015): 319 - 326
DOI:10.15243/jdmlm.2015.023.319

Research Article

The effect of Al, Si and Fe contents (selective dissolution) on soil physical properties at the northern slope of Mt. Kawi

I. Nita*, S. R. Utami, Z. Kusuma

Department of Soil Science, Faculty of Agriculture, Brawijaya University Malang Jl. Veteran, Malang 65145, Indonesia

*corresponding author: istikanita173@gmail.com

Abstract: A toposequence at the northern slope of Mt. Kawi (East Java), having andic properties, were studied. Soil samples at various horizons from five profiles along the toposequence were selected for this study. Selective dissolution analyses (oxalate acid, pyrophosphate and dithionite citrate extractions) were performed to predict the amorphous materials, as reflected from the extracted Si, Al, and Fe. The contents of these three constituents were then correlated to the soil physical properties. The andic characters were indicated by low bulk density (0.43-0.88 g/cm^3) and considerable amounts of Al_o (1.3-4.2%) and Fe_o (0.6-2%), which tended to increase with depth. As a consequence, high content of total pores (>70%) and water content at pF 0, 2.54, and 4, as well as strong aggregate stability were detected (MWD of 2.4-4.5 mm and 1.4-4.5 mm, respectively, in Andisols and Non-Andisols). Water content at pF 0, 2.54, and 4, were significantly affected by respectively %Si_o, % Fe_d, % Fe_p, and % Fe_d. However, bulk density was closely related to %Al_d only.

Keywords: *aggregat stability, amorphous material, andic properties, bulk density, pF*

Introduction

Soil physical properties are affected by soil forming factors such as parent material, organism, topography, climate and time. In a particular parent material, topography factor closely associated with microclimate and organism factors. This results in a strong influence of organic matter on soil properties, such as soil bulk density, porosity and water holding capacity (Emadi et al., 2008; Khresat et al., 2008). Previous study at northern slope of Mt. Kawi, however, revealed that % water available and bulk density were not significantly related to% organic matter. As this area was developed from volcanic ash, we then assumed that the soil physical properties would be much determined by the amorphous materials, such as allophane, imogolite, ferrihydrite (Otsuka and Takahara, 2010).

Soil developed from volcanic ash has special physical and chemical characteristics, such as low bulk density, high permeability, stable soil aggregate, high P fixation capacity, and considerable amount of variable charges as consequences of the high content of active Al/Fe (Nanzyo, 2002). The presence of the amorphous materials mentioned is also a reason of high water-holding capacity and availability of the water for plants (Khan et al., 2006).

Putra et al. (2013) classified soils at the northern slope of Mt. Kawi (from upper to lower slope) as Typic Hapludands (P1 and P2), Humic Udivitrand (P3), and Andic Dystrudept (P4). The study showed that the andic character weaken at the lower slope. As a result, soil physical properties would also be affected. However these authors were focussing on the pedogenesis, but very little emphasize on the effect of amorphous materials on the soil physical properties.

This study was aimed to elucidate the effect of Al, Si and Fe contents determined by oxalate acid, pyrophosphate and dithionite citrate extractions, on soil physical properties at the northern slope of Mt. Kawi.

Materials and Methods

A toposequence at the northern slope of Mt. Kawi, located in Bendosari Sub-district, Pujon

District of Malang, East Java was selected for this study. Soil samples were collected from four pedons, which previously described by Putra et al. (2013). Soil samples were selected from horizons having bulk density <0.9 g/cm^3, with a short range of organic material content. Soil physical properties (water content at pF 0, 2.54, and 4.2, aggregate stability, and soil pores) were measured using routine methods (Landon, 1984). Selective dissolution analyses (using oxalate acid, pyrophosphate and dithionite citrate) were then performed to determine Si, Al and Fe contents (Mizota and van Reeuwijk, 1989). Si, Al and Fe extracted by oxalate acid, pyrophosphate and dithionite citrate were measured with AAS, and respectively designated as Al_o, Si_o, Fe_o (oxalate), Al_p, Fe_p (pyrophosphate), Al_d and Fe_d (dithionite). The content of these constituents were then correlated to the soil physical properties.

Results and Discussion

Al, Si, and Fe content

Table 1 shows the variation of Al, Si, and Fe contents in the studied pedons. The results showed that %Al_o was the highest (1.32-4.24%), followed by %Fe_d (0.65-3.12%) and %Fe_o (0.62-1.97%). Andic characters (as reflected by %Al_o + ½ %Fe_o higher than 2%), occured in all samples, even in the non-Andisol (P4). These results indicated strong influence of amorphous materials in the toposequence. However, the considerably high content of Fe_d reflected high amount of Fe in the crystalline form, suggesting that the pedons were already developed. The contents of Al_o, Fe_o, Al_d and Fe_d generally increased with soil depth. However, no specific pattern was found for $Si_{o,}$ Al_p and Fe_p. This result was comparable to the research of Bartoli et al. (2007). These authors suggested that the organic matter content in the soil supports the production of complex ligand and amorphous material (pyrophosphate extracted) and blocks the production of amorphous material (oxalate extracted). Increasing content of Fe_p with soil depth was also observed in P3 and P4, but not in P1 and P2. Apparently this could be related to the variation of organic material content in these pedons. García-Rodeja et al. (2004) stated that the pyrophosphate extraction could separate the Al and Fe in the humus complex. Pedons P1 and P2 were under forest, supplying more organic matter and hence forming high content of Fe-humus complex in the upper layer (Liu et al., 2005).

Soil physical characteristics

The soil physical characteristics (% water content, bulk density, aggregate stability, and % total pores) of the study area are presented in Table 2.

Table 1. The contents of soil Al, Si and Fe in the studied pedons

Pedons	Elevation (m)	Soil Types	Horizon	Al_o^a	Si_o^a	Fe_o^a	Al_p^b	Fe_p^b	Al_d^c	Fe_d^c
				%						
P1	2150	Typic Hapludands	A	2.03	0.01	0.62	0.02	0.47	0.79	0.65
			AB	3.85	0.05	1.46	0.02	0.42	0.88	1.36
			BA	3.94	0.04	1.49	0.02	0.36	0.86	1.80
			Bw1	4.24	0.03	1.64	0.02	0.38	1.35	3.05
P2	1610	Typic Hapludands	A	2.14	0.01	0.96	0.02	0.48	0.81	0.70
			AB	3.25	0.01	0.87	0.02	0.42	0.79	1.05
			Bw1	3.95	0.01	1.28	0.02	0.45	0.93	1.63
			Bw2	4.25	0.01	1.57	0.02	0.47	1.03	2.07
P3	1195	Humic Udivitrand	A	3.41	0.45	1.32	0.02	0.29	0.48	0.94
			AB	3.88	0.08	1.50	0.03	0.44	0.53	1.02
P4	1149	Andic Dystrudept	Ap	2.64	0.10	2.64	0.04	0.40	0.44	3.01
			Bw1	1.84	0.18	1.84	0.01	0.59	0.36	3.12
			Bw2	1.97	0.25	1.97	0.01	0.83	0.62	2.81

a = Oxalate Extraction, b = Pyrophosphate Extraction, c = Dithionite Extraction

Table 2. Soil physical characteristics of the studied pedons

Pedons	**Horizon**	**pF 0**	**pF 2.54**	**pF 4.2**	**BD**	**MWD**	**Macro Pore**	**Meso Pore**	**Micro Pore**	**OM**
			%		**(g/cm^3)**	**(mm)**		**%**		**(%)**
P1	A	73.21	35.54	15.66	0.75	4.51	42.92	19.88	15.66	6.10
	AB	70.03	38.78	24.72	0.65	3.67	31.26	14.06	24.72	5.65
	BA	89.58	47.17	21.59	0.60	3.88	42.82	25.58	21.59	5.09
	Bw1	72.77	43.69	25.61	0.43	3.26	29.07	18.09	25.61	6.52
P2	A	63.13	34.67	18.89	0.64	4.06	34.09	15.77	18.89	6.61
	AB	74.31	34.79	25.21	0.71	3.81	40.49	10.35	25.21	8.07
	Bw1	82.09	42.52	27.73	0.62	3.05	39.56	14.80	27.73	8.67
	Bw2	74.84	44.77	25.48	0.52	2.44	30.07	19.30	25.48	9.44
P3	A	96.60	31.52	12.79	0.88	3.76	65.08	18.73	12.79	6.66
	AB	66.65	35.06	19.19	0.68	3.86	30.59	17.33	19.19	7.07
P4	Ap	69.33	33.81	24.86	0.85	3.14	35.52	8.94	24.86	2.31
	Bw1	62.83	40.51	26.38	0.70	1.35	30.37	14.14	26.38	1.36
	Bw2	94.76	57.33	33.79	0.83	3.49	37.43	23.54	33.79	4.46

BD = bulk density; MWD = mean weight diameter; OM = organic matter

Bulk density

Soil bulk density in the studied pedons ranged from 0.43 to 0.88 g/cm^3. In P1, P2 and P3, the bulk density tended to decrease with depth. This pattern was apparently in accordance with the pattern of Al_o, Fe_o, Al_d and Fe_d which also increased with depth. Özaytekin and Karakaplan (2012) mentioned that there is a negative relationship between the bulk density and the amorphous material content. In P4, a non-Andisol, however soil bulk density tended to increase in the third horizon. A high bulk density could be due to the increase of clay content (Tracy et al., 2013).

Soil pores

The number of macro, meso and micro pores varied with depth. The pores were dominated by macro pores, followed by micro and meso pores. Total porosity ranged from 67 to 97%. The high porosities were commonly recognizable in the soils having amorphous materials. The occurence of allophane and imogolite (Sinha et al., 2003; Levard et al., 2012) and the ferrihydrite (Xiong and Peng, 2008) produce very porous structure, as they contain *intra-* and *interpores*.

Water content at pF 0, 2.54, and 4.2

Water contents at pF 0, 2.54, and 4.2 ranged from 67 % to 97%, from 32% to 57%, and from 13% to 34%, respectively. The high water-holding capacity is common for soils having andic properties (Qafoku et al., 2000). The highest water content at pF 0 was found in P3, a Humic Udivitrand. The vitrandic character, which has coarse soil texture, is known to have very porous structure (Soil Survey Staff, 2014). This character together with humic properties (rich in organic matter) were possible reasons behind the very high water content at saturated condition (pF 0). The highest water content at pF 2.5 and pF 4.2 were, however, found in P4, a non-Andisol pedon. This showed that water content at high tension was mostly affected by the composition of the clay particles. Pedon P4 was a more developed soil than other pedons, as shown by lower content of amorphous materials (%Al_o + ½%Fe_o) and higher content of crystalline materials (%Fe_d). The increase of water content at pF 0, 2.54, and 4.2 with depth was in accordance with the increasing amount of amorphous material (Al_o and Fe_o), soil porosity and the decrease of bulk density (Dixon and Schulze, 2002).

Aggregate stabilility

Mean weight diameter (MWD) of the soil samples ranged from 2.5 mm to 4.5 mm in Andisols (P1-P3) and from 1.5 mm to 3.5 mm in non-Andisol (P4). The results showed that the aggregate stability of the soil samples were classified as stable to very stable. According to Candan and Broquen (2009), the stable aggregate is one of the characteristics of andic soil.

Relationship between Al, Si, Fe constituent, organic matter and soil bulk density

The statistical analysis showed that %Al_d, Si_o, Al_o, and %organic matter had relatively strong correlation to the bulk density (Appendix 1). The amorphous and crystalline material contents (Schipper et al., 2007) and the organic matter (Özcan and Özaytekin, 2011) strongly affected soil bulk density. The stepwise regression analysis showed that %Al_d had a significant influence on the bulk density. Figure 1 indicates that about 70% variation of the bulk density could be explained by the variation of % Al_d.

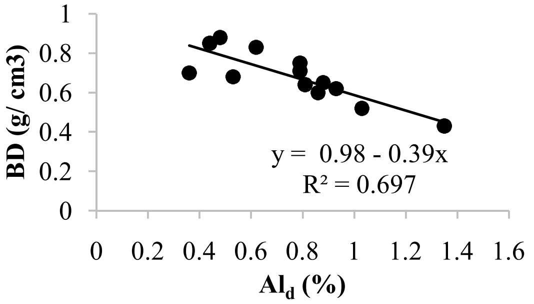

Figure1. Relationship between %Al_d and soil bulk density.

According to Nanzyo (2002), the bulk density of Andic soils is determined by the amorphous material < organic matter < crystalline minerals with decreasing magnitude. The structure of amorphous particles has very high porosity, hence resulting in a very low bulk density (Moldrup et al., 2003). These authors proved that allophane mineral is extremely porous, in which it may have 60%-85% of porosity. However, the significant role of %Al_d in this study showed that in the Andisol itself, the overall constituents might have combined effect on the bulk density.

Relationship between Al, Si, and Fe constituents, organic matter and soil water contents

Table 3 shows the coefficient of correlations between soil constituents and water content at pF 0, 2.54, and 4.2. The results showed that Al, Si, and Fe constituents and the organic matter content were significantly correlated to water content in various pF values. Previous studies also showed that amorphous material (Qafoku et al., 2000) and organic matter (Wiskandar, 2002) had very significant contribution to water holding capacity through the formation of very high porosity.

Table 3. The correlation coefficient between amorphous material, organic matter, and water content.

Variables	Correlation Coefficient		
	pF 0	pF 2.54	pF 4.2
Al_o	0.21	0.11	0.14
Si_o	0.57	0.06	0.19
Fe_o	0.03	0.43	0.50
Al_p	0.28	0.47	0.29
Fe_p	0.07	0.58	0.66
Al_d	0.002	0.24	0.17
Fe_d	0.002	0.59	0.70
OM	0.15	0.06	0.17

Figure 2 shows that about 31% of variation in water content at pF 0 could be explained by the $\%Si_o$variation. Although the proportion was relatively small (31%), the regression analysis showed that among the observed variables, only $\%Si_o$ affected water content at pF 0 significantly (Appendix 2). Van Ranst et al. (2002) stated that the concentration of Si_o in the soil negatively correlated to bulk density. These authors suggested that a lower bulk density meaned a higher porosity, which resulted in higher capacity to retain water.

The coefficient of determination (R^2) between the $\%Fe_d$ and the water content at pF 2.54 was 35% (Appendix 3 and Figure 3), meaning that 35% variation of water content at pF 2.54 was determined by $\%Fe_d$. According to Hausner et al. (2009), ferrihydrite minerals are very active because of the hydroxylation of the soil surface and the wide range of the high surface (220-560 m^2/g), hence it may form very high soil porosity (Pokrovski et al., 2003). These characteristics result in the high ability of the soil to retain water content even at pF 2.54. As shown previously, bulk density in the study area was less than 0.88 g/cm^3, reflecting relatively high soil porosity.

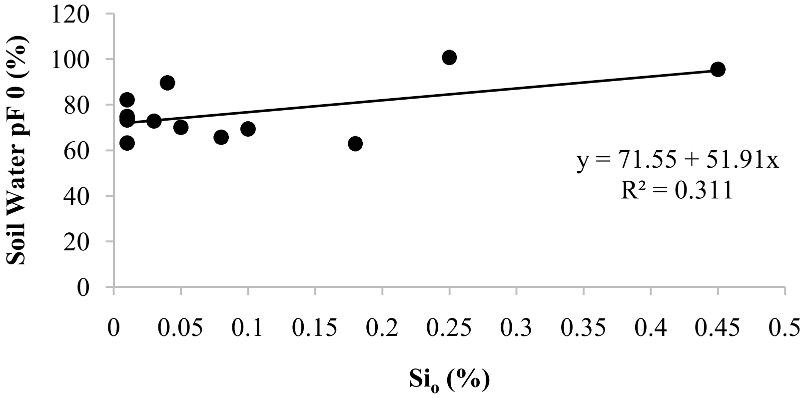

Figure2. Relationship between $\%Si_o$ and % water content at pF 0.

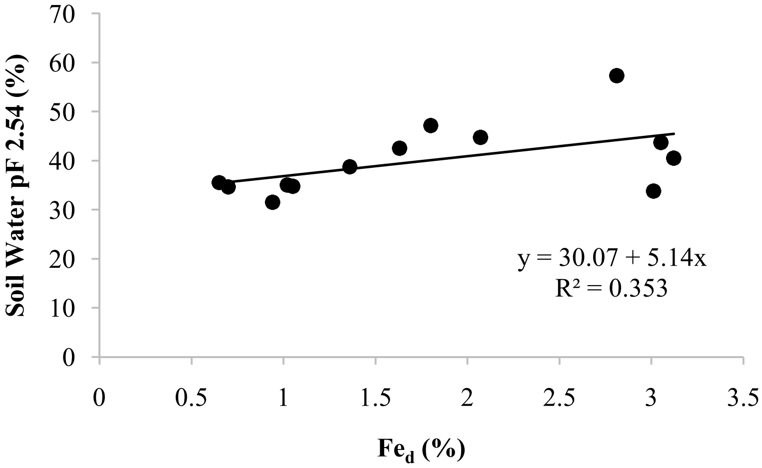

Figure3. Relationship between $\%Fe_d$ and % water content at pF 2.54

The stepwise regression analysis showed that only Fe_d and Fe_p significantly affected %water content at pF 4.2 (Appendix 4).

$$y = 8.76 + 3.07x_1 + 19.45x2 \quad (R^2 = 0.67)$$

where:

y = Soil water pF 4.2 (%)
x_1 = Fe_d (%)
x_2 = Fe_p (%)

The content Fe-humus complexes (Fe*p*) and Fe_d affected water holding capacity at pF 4.2 through the hydrophilic characters that can multiply binding capacity to water (Özcan and Özaytekin, 2011).

Conclusion

The studied pedons showed andic properties, as indicated by low bulk density (0.43-0.88 g/cm^3) and considerable amounts of Al_o (1.3-4.2%) and Fe_o (0.6-2%). The content of Al_o, Fe_o, Al_d and Fe_d generally increased with soil depth. However no specific pattern was found for Si_o, Al_p and Fe_p. All pedons had very high content of total pores (>70%) and water content at pF 0, 2.54, and 4.2 as well as strong aggregate stability (MWD of 2.4-4.5 mm and 1.4-3.5 mm respectively, in Andisols and non-Andisols). Water content at pF 0, 2.54, and 4.2 were significantly affected $\%Si_o$; $\% Fe_d$; $\% Fe_p$ and $\% Fe_d$respectively. However, bulk density was closely related to $\%Al_d$ only. About 70% variations of the bulk density could be explained by the variation of $\%Al_d$.

Acknowledgements

The first author wishes to thank staff of Bendosari village, Pujon, Malang Regency for their kind help in collecting soil samples. Special thanks are also given to DGHE (Directorate General of Higher Education) for scholarship grant under the frame of MSc-Fast Track Programme.

References

Bartoli, F., Poulenard, A.J. and Schouller, B.E. 2007. Influence of allophane and organic matter contents on surface properties of Andosols. *European Journal of Soil Science* 58: 450-464.

Candan, F. and Broquen, P. 2009. Aggregate stability and related properties in NW Patagonian Andisols. *Geoderma* 154: 42-47.

Dixon, J. B. and Schulze, D. G. 2002. Soil mineralogy with environmental application. Soil Science Society of America Inc., Madison, USA. 866p.

Emadi, M., Bagherjenad, M., Fathi, H. and Saffari, M. 2008. Effect of land use change on selected soil physical and chemical properties in North Highland of Iran. *Journal of Applied Sciences* 8 (3): 496-502.

García-Rodeja, E., Nóvoa, J. C., Pontevedra, X., Martínez-Cortizas, A. and Buurman, P. 2004. Aluminium fractionation of European volcanic soils by selective dissolution techniques. *Catena* 56: 155-183.

Hausner, F., Bhandari, N., Pierree-Louis, A., Kubicki, J. and Strongin, D. 2009. Ferrihydrite reactivity toward carbon dioxide. *Journal of Colloid and Interface Science* 337: 492-500.

Khan, H., Matsue, N. and Hemni, T. 2006. Adsorption of water on nanoball allophane. *Clay Science* 12 (2): 261–266.

Kherast, S., Al-Bakri, J. and Al-Tahhan, R. 2008. Impacts of land use/cover change on soil properties in the Mediterranean region of northwestern Jordan. *Journal Land Degradation Development* 19: 397-407.

Landon, J. R. 1984. Booker Soil Tropical Manual. Booker Agriculture International Ltd. 450 pp.

Levard, C., Doelsch, E., Basile-Doelsch, I., Abidin, Z., Miche, H., Masion, A., Rose, J., Borschneck, D. and Bottero, J.Y. 2012. Structure and distribution of allophanes, imogolite and proto-imogolite in volcanic soils. *Geoderma* 183-184: 100-108.

Liu, A., Ma, B. L. and Bomke, A. A. 2005. Effects of cover crop on soil aggregate stability, total organic carbon, and polysaccharides. *Soil Science Society of America Journal* 69: 2041-2048.

Mizota, C. and van Reeuwijk, L.P. 1989. Clay mineralogy and chemistry of soils formed in volcanic material in diverse climatic regions.Soil Monograph 2, Department of Agricultural Chemistry, Kyushu Univ. Fukuoha, Japan. 186p.

Moldrup, P., Seiko, Y., Torben, O., Toshiko, K. and Dennis, E.R. 2003. Air permeability in undisturbed volcanic ash soils: Predictive model test and soil structure fingerprint. *Soil Science Society of America Journal* 67: 32-40.

Nanzyo, M. 2002. Unique properties of volcanic ash soils. *Global Environmental Research* 6 (2): 99-112.

Nita, I., Listyarini, E. and Kusuma, Z. 2014. Study of available moisture on toposequence of the northern slopes of Mount Kawi Malang in East Java. *Jurnal Tanah dan Sumberdaya Lahan* 1(2): 49-57 (*in Indonesian*).

Otsuka, H. and Takahara, A. 2010. Structure and properties of imogolite nano tubes and their application to polymer nano composites. In: *Inorganic and Metallic Nanotubular Materials. Springer Berlin Heidelberg* 117: 169-190.

Özaytekin, H. H. and Karakaplan, S. 2012. Soil formation on the Karadag volcano at a semiarid environment from the Central Anatolia. *African Journal of Agricultural Research* 7 (15): 2283-3396.

Özcan, S. and Özaytekin, H. 2011. Soil formation overlying volcanic materials at Mount Erenler, Konya, Turkey. *Turkey Journal Agriculture Forestry* 35: 545-562.

Parfitt, R. L. 2009. Allophane and imogolite: role in soil biogeochemical processes. *Clay Minerals* 44: 135-155.

Pokrovski, G. S., Schott, J. Farges, F. and Hazemann, J-L. 2003. Iron (III)-silica interactions in aqueous solution: Insights from X-ray absorption fine structure spectroscopy. *Geochim Cosmochim Acta* 67: 3559-3573.

Putra, A.N, Sudarto and Rayes, M.L. 2013. Studies on the level of soil development on toposequence of the northern slopes of Mount Kawi Malang in East Java. *Jurnal Tanah* 1(1) (*in Indonesian*).

Qafoku, N.P., Sumner,M. E. and West, L. T. 2000. Mineralogy and chemistry of some variable charge subsoils. *Communication of Soil Science and Plant Analysis* 31: 1051–1070.

Schipper, L. A., Baisden, W. T., Parfitt, R. L., Ross, C., Claydon, J. J. and Arnold, G. C. 2007. Large losses of C and N from soil profiles under pasture in New Zealand during the past 20 years. *Global Change Biology* 13: 1138-1144.

Sinha, R.S., Yamada, K.,Okamoto, M.,Ogami,A.and Ueda, K. 2003. New polylactide/layered silicate nanocomposites. 3 High performance biodegradable materials. *Chemistry of Materials* 15: 1456-1465.

Soil Survey Staff. 2014. Keys to Soil Taxonomy. 11th ed. USDA-NRCS. Washington DC. p77-96.

Tracy, S. R., Black, C. T., Roberts, J. A. and Mooney, S. J. 2013. Exploring the interacting effect of soil texture and bulk density on root system development in tomato (*Solanum lycopersicum* L.). *Environmental and Experimental Botany* 91: 38-47.

Van Rast, E., Utami,S.R. and Shamshuddin, J. 2002. Andisols on volcanic ash from Java Island, Indonesia: Physico-chemical properties and classification. *Soil Science* 167 (1): 68-79.

Wiskandar. 2002. Utilization of manure to improve soil physical properties in the terraced critical land area. Soil Science Socity of Indonesia, National Congress VII (*in Indonesian*).

Xiong, W and Peng, J. 2008. Development and characterization of ferrihydrite-modified diatomite as a phosphorus adsorbent. *Water Research* 42: 4869-4877.

.

Appendix 1. The stepwise regression analysis of all variables towards the bulk density

Regression	R^2	Equation
$y = 0.98 – 0.39x$	69.7*	$y = 0.98 – 0.39x$
$y = 0.9 -0.32x_1+ 0.26x_2$	74.1	
$y = 0.9 - 0.26x_1+ 0.29x_2- 0.02x_3$	75.8	
$y = 0.87- 0.27x_1+ 0.32x_2- 0.04x_3+0.02x_4$	79.8	
$y = 0.75 -0.19x_1+0.44x_2-0.05x_3+0.02x_4+ 3.79x_5$	83.6	
$y = 0.81 - 0.17x_1+ 0.5x_2- 0.05x_3+ 0.01x_4+ 5.15x_5- 0.05x_6$	85.4	
$y = 0.6 -0.12x_1+0.63x_2- 0.03x_3-0.003x_4+ 9.93x_5-0.11x_6+0.34x_7$	87.9	
$y = 0.63- 0.08x_1+ 0.59x_2- 0.04x_3-0.001x_4+ 7.57x_5- 0.04x_6+ 0.28x_7 -0.04x_8$	88.4	

* = significant ($p_{value}<\alpha$); y = Bulk Density; $x = Al_d$;$x_1 = Al_d$; $x_2 = Si_o$; $x_3 = Al_o$;$x_4 = OM$; $x_5 = Al_p$; $x_6 = Fe_o$;$x_7 = Fe_p$; $x_8 = Fe_d$

Appendix 2. The stepwise regression analysis of all variables towards the soil water level at pF 0

Regression	R^2	Equation
$y = 71.42 + 49.33x$	0.319*	$y = 71.42 + 49.33x$
$y = 77.14 + 46.19x_1 - 260.99x_2$	0.349	
$y = 66.17 + 54.85x_1 - 274.17x_2 + 3.52x_3$	0.486	
$y = 64.18 + 56.73x_1 - 253.67x_2 + 2.52x_3 + 0.73x_4$	0.495	
$y = 48.23 + 59.11x_1 - 79.32x_2 + 3.92x_3 + 0.53x_4 + 19.83x_5$	0.517	
$y = 48.41 + 58.82x_1 - 92.38x_2 + 3.83x_3 + 0.59x_4 + 19.04x_5 + 0.28x_6$	0.517	
$y = 35.36 + 77.27x_1 + 204.97x_2 + 3.13x_3 - 0.05x_4 + 28.69x_5 - 2.78x_6 + 14.57x_7$	0.549	
$y = 36.58 + 75.62x_1 + 112.03x_2 + 2.72x_3 - 0.004x_4 + 26.15x_5 + 0.12x_6 + 16.18x_7 - 1.42x_8$	0.55	

* = significant ($p_{value}<\alpha$); y = Soil water pF 0; $x = Si_o$; $x_1 = Si_o$; $x_2 = Al_p$; $x_3 =Al_o$; $x_4 = OM$; $x_5 = Fe_p$; $x_6= Fe_o$; $x_7=Al_d$; $x_8 = Fe_d$

Appendix 3. The stepwise regression analysis of all variables towards the soil water level at pF 2.54

Regression	R^2	Equation
$y = 30.07 + 5.14x$	0.353*	$y = 30.07 + 5.14x$
$y = 20.6 + 3.79x_1 + 25.74x_2$	0.502	
$y = 31.57+4.15x_1+14.88x_2-318.49 x_3$	0.564	
$y = 34.03 +0.66x_1+ 9.24x_2- 577.02x_3+ 7.97x_4$	0.604	
$y = 11.39 - 5.99x_1+ 18.17x_2- 760.08x_3+ 21.43x_4+ 18.95x_5$	0.839	
$y = 4.13 - 1.76x_1+ 31.15x_2- 521.25x_3+ 13.63x_4+ 7.58x_5+2.99x_6$	0.887	
$y = 3.96 -1.76x_1+ 32.87x_2-497.76x_3+13.09x_4+ 7.66x_5+ 3.32x_6-0.22x_7$	0.888	
$y = 9.16- 2.61x_1+ 26.78x_2-661.88x_3+16.11x_4+ 5.72x_5+ 2.94x_6+ 0.02x_7- 8.53x_8$	0.893	

* = significant ($p_{value}<\alpha$); y = Soil water pF 2.54; $x = Fe_d$; $x_1 = Fe_d$; $x_2 = Fe_p$; $x_3 = Al_p$; $x_4 = Fe_o$; $x_5 = Al_d$; $x_6 = Al_o$;$x_7 = OM$; $x_8 = Si_o$

Appendix 4. The stepwise regression analysis of all variables towards the soil water level at pF 4.2

Regression	R^2	Equation
$y = 15.92 + 4.09x$	0.483*	$y = 8.76 + 3.07x_1 + 19.45x_2$
$y = 8.76 + 3.07x_1 + 19.45x_2$	0.667*	
$y = 9.74+ 3.65x_1+ 18.97x_2- 1.21x_3$	0.671	
$y = 7.94+ 4.17x_1+ 21.28x_2- 2.51x_3+82.79x_4$	0.675	
$y = 14.27 + 0.62x_1+ 13.69x_2+ 6.38x_3-285.78x_4- 20.28x_5$	0.785	
$y = 7.27 - 0.03x_1+17.77x_2+7.24x_3-233.04x_4-14.99x_5+ 4.48x_6$	0.806	
$y = 6.98+1.52x_1+ 14.5x_2+ 7.07x_3-286.78x_4- 18.89x_5-1.89x_6+0.93x_7$	0.851	
$y = 6.09 + 1.84x_1+16.56x_2+6.12x_3- 249.42x_4- 18.32x_5- 2.42x_6+ 0.81x_7+ 0.37x_8$	0.852	

* = significant ($p_{value}<\alpha$); y = Soil water pF 4.2; $x = Fe_d$; $x_1 = Fe_d$; $x_2 = Fe_p$; $x_3 = Fe_o$;$x_4 = Al_p$; $x_5 = Si_o$; $x_6 = Al_d$; $x_7 = OM$; $x_8 = Al_o$