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A DEGREE INDEX OF HYSTERESIS IN SOIL WATER RETENTION WITH WIDE RANGE OF CARBONATE CONTENTS

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ABSTRACT
Water movement in unsaturated soils is commonly affected by hysteresis, a phenomenon often ignored as to keep the mathematical description of water flow and solute transport simple. In this article we observed that the mismatch between the hydraulic capacity functions of the primary drying and wetting curves can serve as generalized index for degree of hysteresis (H). Moreover, we observed that hysteresis indices of a wide range of carbonate in soil are polynomial related with the van Genuchten *n* parameter ($R^2 = 0.948$).

KEYWORDS: unsaturated soils, hysteresis, water flow, generalized index.

INTRODUCTION

Soil Water Retention Curve (SWRC) represents the relationship between the water pressure and water content, is basic to researching water flow and chemical transport in unsaturated media (Pollacco *et al*., 2017; Moret-Fernández and Latorre, 2017). Direct measurements of the SWRC consume both time and money (Arya and Paris, 1981; Mohammadi and Vanclooster, 2011). Soil water retention (SWR) hysteresis by porous media refers to the different values in the equilibrium water content at any water potential depending on wetting and drying measurements (Hillel, 1998; Mirus, 2015). Soil water retention hysteresis is typically characterized by drying and wetting curves that refer to removal/addition of water from (to) completely saturated or dry porous media. Major causes behind Soil water retention hysteresis are: contact angle variation at different wetting and drying cycles, entrapped air in a newly wetted soil, temperature, swelling and shrinking, and inkbottle effect due to nonuniformity in shape and sizes of both individual pores and interconnected pore networks (Bachmann and van der Ploeg, 2002; Dullien, 1992; Maqsoud *et al*., 2004; Or and Wraith, 1999). Laboratory experiments for characterizing hysteresis in soil water retention curves (SWR) are still difficult and expensive due to the relatively long time necessary to its determination. However, some works focused on the hysteresis phenomenon in SWRC (Konyai *et al*., 2006; Li, 2005; Pham *et al*., 2003; Witkowska-Walczak, 2006). Hysteresis is known to impact flow in unsaturated porous media undergoing wetting and drying. Lehmann *et al*. (1998) showed that a column of sand subjected to symmetrical capillary fringe fluctuations exhibit dampened and asymmetrical water content dynamics as direct consequences of hysteresis redistribution after rain or irrigation is particularly sensitive to hysteretic phenomena because drying and wetting occur concurrently at different parts of the soil (Rubin, 1967; Simunek *et al*.,1999).The boundary between the wetting and wetting zones of a soil profile is marked by a discontinuity in wetness because of hysteresis. Specifically, in the lower imbibing side of the boundary, the water content (hence, hydraulic conductivity) is smaller than it would have been in the absence of hysteresis. Thus, more hysteretic soils tend to have lower losses of water to deep percolation (Elmaloglou and Diamantopoulos, 2008).

MATERIALS AND METHODS

One loamy-texture soil samples were used in this experiment of representative sites of the fields a region located in south part of Baghdad (longitude 44° 45' 34" E, latitude 33° 72' 78" N, altitude 33 m above sea level), Iraq. The soil material has dried by air in the laboratory, crushed and sieved through a 2 mm screen. Some of physical and chemical properties have been estimated for the soil material before the experiment procedure and table 1 shown the analysis results.

These samples used to prepare 7 samples with 305, 251, 203, 152, 103, 50.1 and 3.2 g.kg^{-1} carbonate, respectively. Carbonate removed with NaOAc, gradually (Holford and Mattingly, 1975). Another sample prepared by adding pure carbonate to reach 352 g.kg^{-1} carbonate as suggested by Dudas and AL-Ani (1988).

Drying and wetting curves of the SWRC were determined with a constant temperature (T=25°C) the degree of hysteresis was calculated and analyzed from the drying and wetting curves. Soil samples were initially saturated with water and then subjected to drying; the drying curve of the SWRC was measured first and the wetting curve was determined afterward starting from a soil water potential of 25, 50, 75, 100, 330, 500, 1000 and 2500 cm which was reached at the end of the drying phase. Soil water contents were determined for soil water potential of 1, 10, 25, 50, 75, 100, 330, 500, 1000, 2500, 5000, 10000 and 15000 cm for the drying curve.

TABLE 1. Physical and chemical properties of the soil

Parameter	Quantality
Sand (g.kg^{-1})	387.8
Clay(g.kg^{-1})	258.8
Bulk Density (Mg.m^{-3})	1.52
Volumetric water content at 330 cm (cm^3.cm-^{3})	0.23
Volumetric water content at 15000 cm (cm^3.cm^{-3})	0.08
Electrical Conductivity (dSm^{-1})	1.33
pH	7.58
CEC (Cmol^c.kg^{-1} soil)	18.21
Carbonate (g.kg^{-1})	334

The main hysteretic soil water retention curves according to the parametric equation of van Genuchten (1980) are given by:

$$\Theta_d = \{1 + (\alpha_d\psi)^n\}^{-m} \quad (1)$$
$$\Theta_w = \{1 + (\alpha_w\psi)^n\}^{-m} \quad (2)$$

where ψ is (cm) water potential; α (cm^{-1}) refers to represents capillary strength and n is a fitting parameter that represents pore size distribution; and m = 1– 1/n. The effective saturation is defined as $\Theta = (\theta - \theta_r)/(\theta_s - \theta_r)$. The subscripts d and w denote the drying and wetting curves, respectively; θ_s and θ_r are saturated and residual water contents, respectively (θ_s and θ_r for the drying and wetting curves are the same).

There are two approaches that attempt to quantify the degree of hysteresis. The first approach, commonly referred to as total hysteresis (Witkowska-Walczak, 2006), defines degree of hysteresis as the area between the drying and wetting curves $H_t = \int_{-\infty}^{0}(\Theta_d - \Theta_w)d\psi$, practically this method is used with log (ψ) as the independent variable in the integrand (Maqsoud et al., 2004; Yang et al., 2004; Shvarov and Koreneva, 2008). This index basically depends not only on the deviation between the drying and wetting curves but also (perhaps to a larger degree) on the range of water potential extend by the soil retention curves. As a result, fine grained soils, for which several order of magnitude of water potential are typically measured; tend to have higher H_t, even with marginal real deviation. Moreover, numerical integration of this index shows that the integral converges very slowly for n > 2 and fails to converge to a finite value when n 2.

The second approach defines the degree of hysteresis as the maximum deviation in effective saturation between the drying and wetting curves H_d = max (H_d = max ($\Theta_d - \Theta_w$)) (Zhuang et al., 2008; Konyai et al., 2009). To the best of our knowledge, the logical basis behind this index and its universality has not been explored enough. At first brief look, this index seems to be weak as it represents deviation at only one although significant value of pressure head.

The effect of hysteresis comes in the equation of unsaturated flow through the hydraulic capacity function C(ψ) = dΘ/dψ:

$$C_d(\psi) = \frac{d\Theta_d}{d\psi} = -\frac{mn}{\psi}(\alpha_d\psi)^n\{1 + (\alpha_d\psi)^n\}^{-(1+m)} \quad (3)$$

$$C_w(\psi) = \frac{d\Theta_w}{d\psi} = -\frac{mn}{\psi}(\alpha_w\psi)^n\{1 + (\alpha_w\psi)^n\}^{-(1+m)} \quad (4)$$

The shift between the drying and wetting curves (which reflects the difference between the corresponding α values) signifies the need for a relatively higher energy state during wetting. H defines as the hysteretic mismatch along with pressure head:

$$H = \frac{1}{2}\left\{\int_{-\infty}^{\psi*}(C_d - C_w)d\psi + \int_{\psi*}^{0}(C_w - C_d)d\psi\right\} \quad (5)$$

$\psi*$ is the water potential at curves intersect (C$_d$ = C$_w$) and the $\frac{1}{2}$ is added to limit the range of H in 0 ≤ H ≤ 1. Note that the H index is by definition, a dimensionless quantity and equation [5] leads to the same values regardless of the units used to describe water pressure head. Then, substituting equations [3 & 4] into [5], simplifying using equations [1 & 2] leads to:

$$H = \Theta_d(\psi^*) - \Theta_w(\psi^*) \quad (6)$$

Note that at the intersection C$_d$(ψ^*) = C$_w$(ψ^*):

$$\frac{d}{d(\psi)}(\Theta - \Theta)|_{\psi=\psi*} = 0 \quad (7)$$

The maximum difference in effective saturation occurs at $\psi = \psi^*$. This means that the H index in terms of a concept represents the entire range of hydraulic capacity, is numerically identical to the index based on the maximum water content deviation (H_d) (Zhuang et al., 2008; Konyai et al., 2009).

At the intersection water potential ($\psi = \psi^*$) equations [3 & 4] can be rewritten as:

$$\frac{C_d(\psi^*)}{C_w(\psi^*)} = \left(\frac{\alpha_d}{\alpha_w}\right)^n \left\{\frac{1 + (\alpha_d \psi^*)^n}{1 + (\alpha_w \psi^*)^n}\right\}^{-(1+m)} \quad (8)$$

Solving Eq. [6] for ψ^* and take the place of it in equation [6] leads to:

$$H \simeq \left(\frac{\alpha^n - 1}{\alpha^{\frac{n(n-1)}{2n-1}} - 1}\right)^{(1/n)-1} - \left(\frac{\alpha^n - 1}{\alpha^n - \alpha^{\frac{n^2}{2n-1}}}\right)^{(1/n)-1} \quad (9)$$

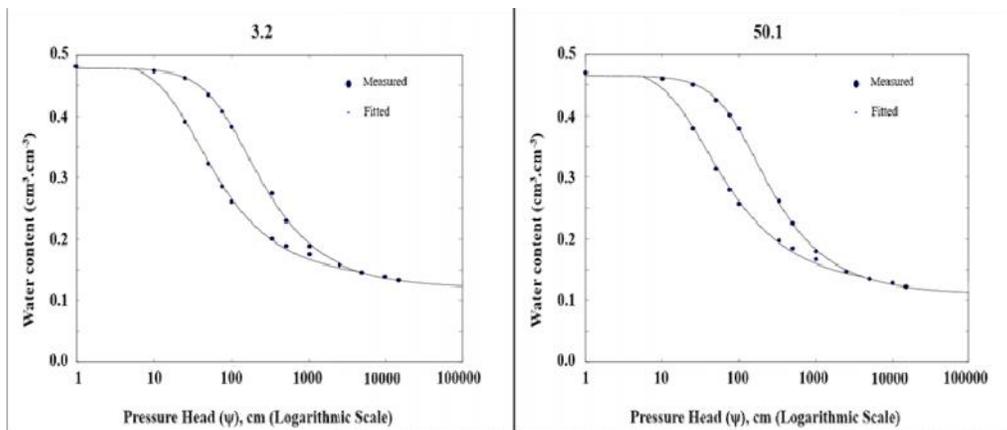where $\alpha = \alpha_d/\alpha_w$.

RESULTS AND DISCUSSION

Fig. 1 shows soil water retention curves (SWR) of soil samples with different carbonate content for drying and wetting curves. Hysteretic water retention curves for 9 soils with varying degrees of hysteresis. The solid line in the fig. 1 refer to the best fitting of data of pressure head (ψ) against effective saturation (Θ) according to van Genuchten (1980). The highest SWR was soil sample with 3.2 g.kg^{-1} carbonate, following by (high to low) 50.1,103, 152, 203, 251, 205, 334 and 352 g.kg^{-1} carbonate in soil. Volumetric moisture content of the soil has varied by the variation of contents of the soil samples of carbonate for each pressure head upon them which led to increasing of carbonic minerals within the soil samples from 3.2 to 352 g.kg^{-1} to a significant decrease of the moisture content to 6.31% by pressure head change from 1 to 100 cm, as for the pressure head change to 15000 cm, the remaining volumetric moisture content Θ_r decreased with increasing of carbonate content, as well as water holding capacity increased with decreasing of carbonate content. Fig.2

showed corresponding hydraulic capacity functions, the area of intersection region between drying and wetting curves corresponds to the used index for hysteresis.

The results showed that the mismatch between the hydraulic capacity functions of the primary drying and wetting curves can serve as generalized index for degree of hysteresis (H). Moreover, we showed that hysteresis indices of a wide range of carbonate in soil are polynomial (order 3) related with the van Genuchten n parameter (R^2 = 0.948) (fig. 3) which corresponding hydraulic capacity functions, the area of intersection region between drying and wetting curves corresponds to the used index for hysteresis, the result of soil water retention parameters and hysteresis index H shown in table 2. The highest H value was in soil sample with 352 g.kg^{-1} carbonate (highest n), and the lowest value was with soil sample with 3.2 g.kg^{-1} (lowest n). Also, the results showed that the relation between degree of hysteresis index (H) and carbonates contents in soil are polynomial (order 3) (R^2 = 0.9031) (fig. 4).

TABLE 2. Water retention parameters and hysteresis index H of example soils with wide range of carbonate content

| Carbonate Minerals Content (g.kg^{-1})	Parameters					
	α_d	α_w	n	Θ_s	Θ_r	H
3.2	0.0110	0.0469	1.6637	0.4808	0.1330	0.0394
50.1	0.0101	0.0507	1.6825	0.4697	0.1221	0.2190
103	0.0098	0.0523	1.6918	0.4575	0.1160	0.2277
152	0.0098	0.0527	1.6947	0.4484	0.1099	0.2292
203	0.0090	0.0505	1.7414	0.4308	0.0883	0.2447
251	0.0093	0.0511	1.7443	0.4197	0.0780	0.2429
305	0.0096	0.0456	1.7823	0.4119	0.0711	0.2337
334	0.0099	0.0495	1.7272	0.4007	0.0666	0.2283
352	0.0087	0.0508	1.7864	0.3787	0.0592	0.2616
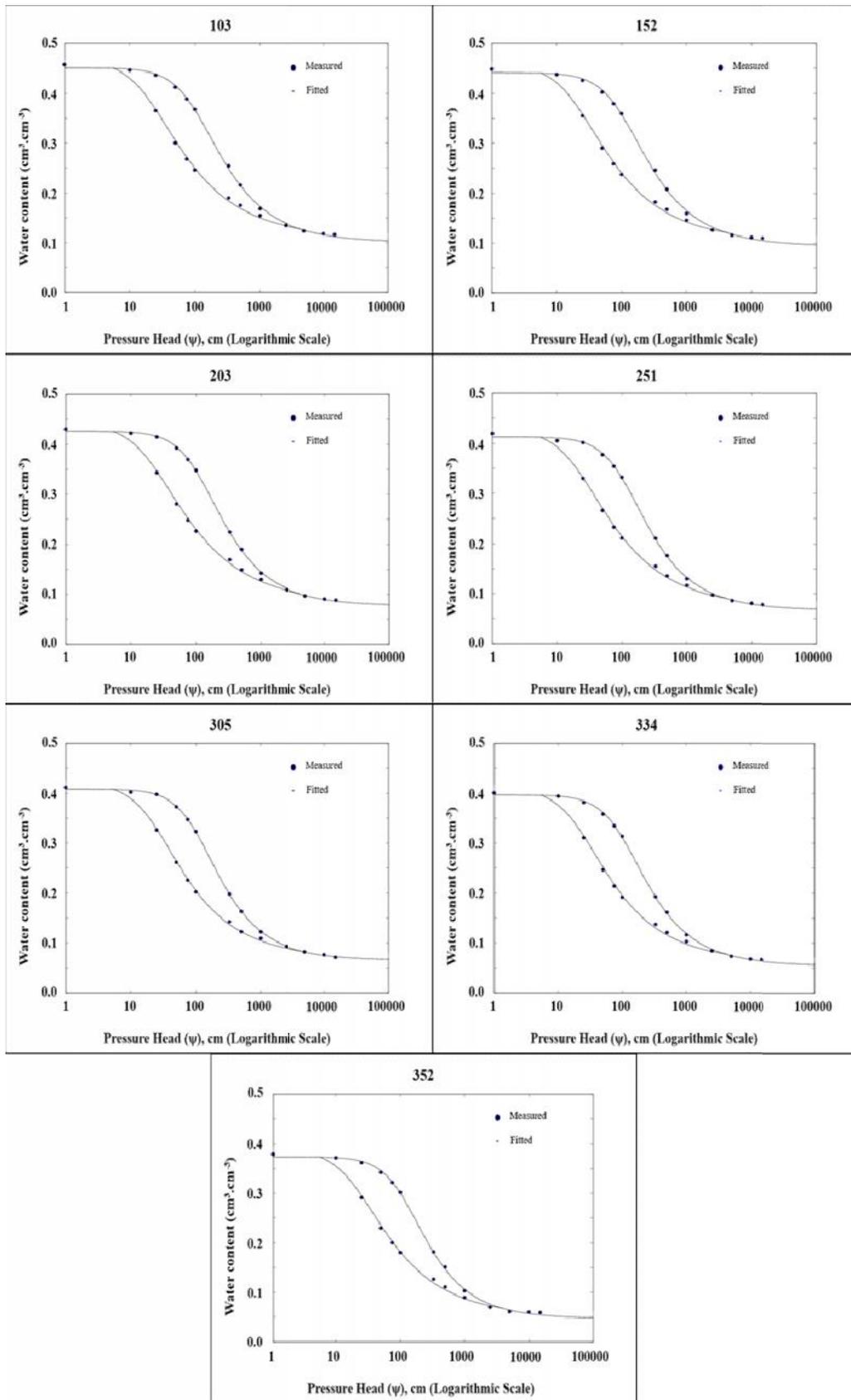
FIGURE 1: soil water retention curves (SWR) of soil samples with different carbonate content for drying and wetting curves
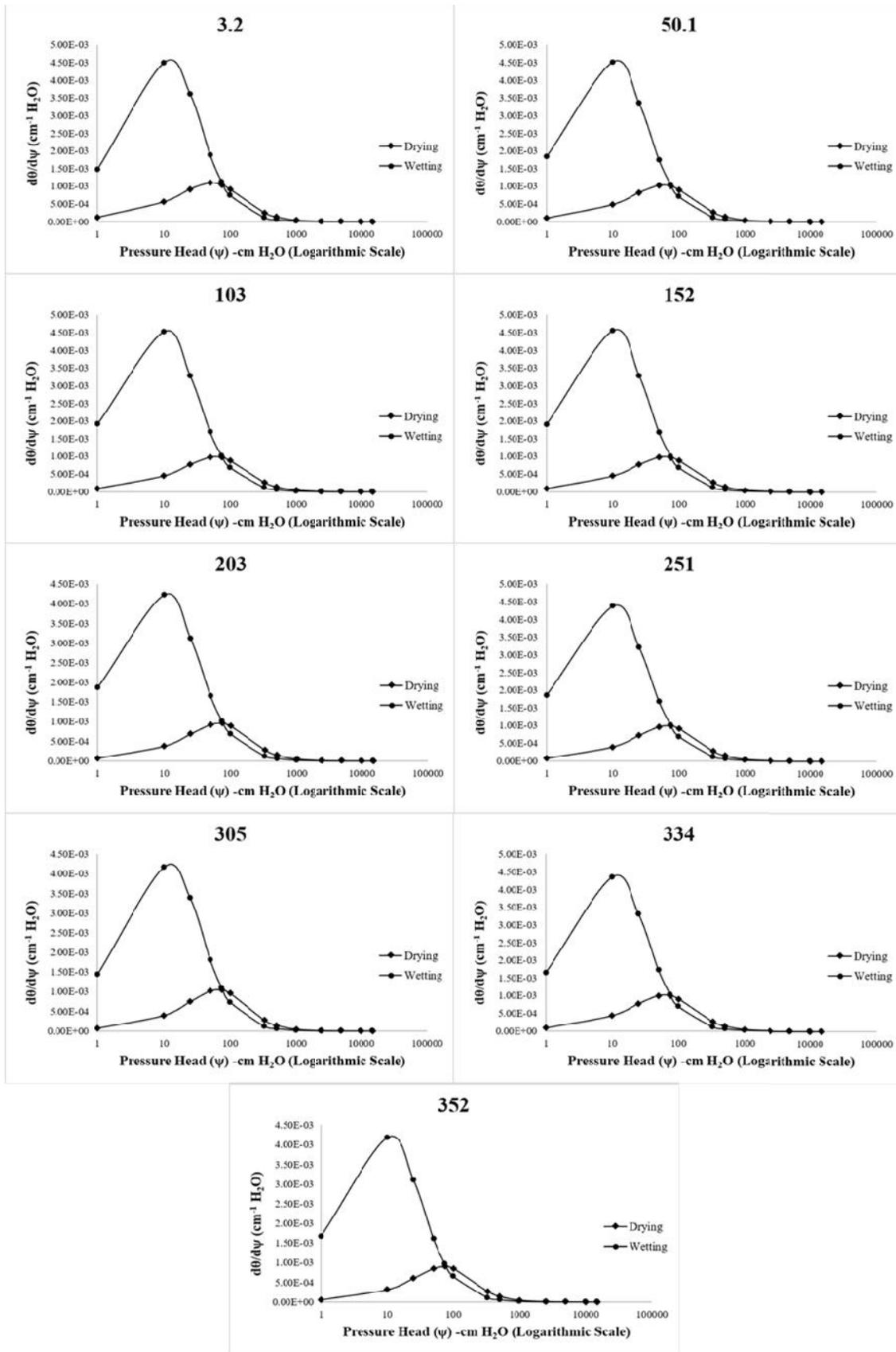
FIGURE 2. hydraulic capacity d /d with different carbonate content for drying and wetting curves

$$H = 715.91n^3 - 3732.1n^2 + 6483.9n - 3753.9$$
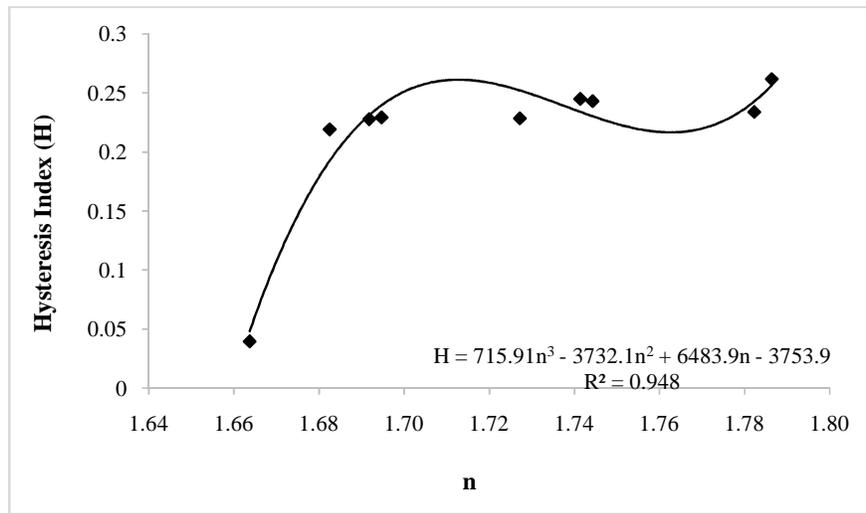$$R^2 = 0.948$$

FIGURE 3. Degree of hysteresis as a function of the van Genuchten n parameter: curves are theoretical hysteresis curves for 9 different values of $\quad = \quad_d/\quad_w$
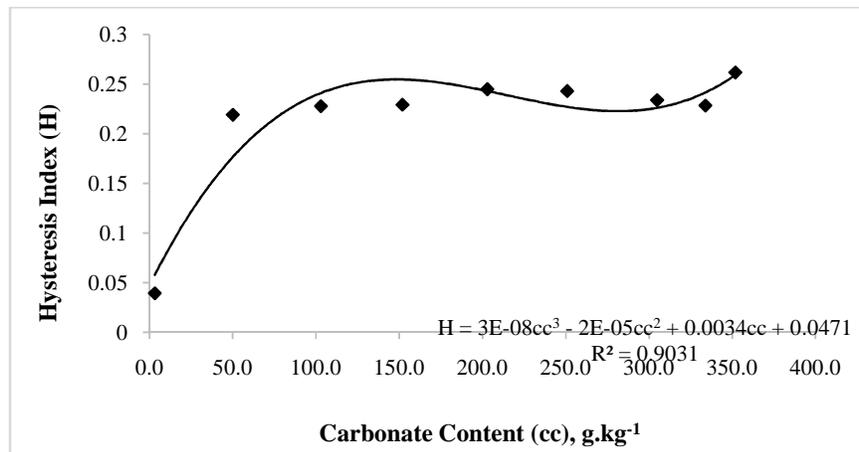

$$H = 3E\text{-}08cc^3 - 2E\text{-}05cc^2 + 0.0034cc + 0.0471$$
$$R^2 = 0.9031$$

FIGURE 4. Relation between degree of hysteresis index (H) and carbonates contents

CONCLUSION

Soil samples mismatch between the hydraulic capacity functions of the primary drying and wetting curves have affected by carbonate minerals content so that an increase occurred in hysteresis index H with the increasing of carbonate content in the sample of 352 gm kg^{-1} carbonate with highest with the van Genuchten n parameter.

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