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## Research Article

# Evaluation of an analytical method for relationship between soil hydraulic diffusivity and sorptivity under zeolite application

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**ABSTRACT-** Zeolite is used to improve the soil hydraulic properties, i.e., soil hydraulic diffusivity (D) and sorptivity (S) that should be determined. A simple method that relates S to D was evaluated by horizontal water absorption experiment in sandy loam, loam and silty clay soils and zeolite application rates of 0, 4, 8, and 12 g $kg^{-1}$ soil. Results indicated that zeolite application was not effective on the a and b values of hydraulic diffusivity function (D=aEXP(bθ), θ is the soil water content, $cm^3\ cm^{-3}$), while maximum value of a and b in sandy loam and silty clay soils, respectively occurred by zeolite application of 8 g $kg^{-1}$ soil. The values of a and b for loam soil were not influenced by zeolite application rates. Sorptivity for sandy loam soil was reduced by zeolite application rate, while minimum value of S for loam and silty clay soils occurred at zeolite application rate of 8 g $kg^{-1}$ soil. It is indicated that indirect determination of S for different soil textures and zeolite application rates were closely similar to the direct determination of S. Therefore, by determination of S value by simple horizontal absorption test at two different initial soil water contents or two different absorption suction heads in tension infiltrometer the values of $D_s$ and α for hydraulic diffusivity function ($D=D_s\theta^{\alpha}$) can be estimated.

## INTRODUCTION

Soil and water are known as the main natural resources in agriculture. Soil conditions and water supply can be improved by using different methods. Soil conditions can be improved by using soil conditioners that affect the water and solute movement in soil. One of the inorganic soil conditioners that have recently been considered is zeolite. Zeolites are crystalline, hydrated aluminosilicates of alkali and alkaline earth cations that possess infinite, three-dimensional crystal structures. However, they are different from other silicate minerals due to the spacious pores and channels within their crystal structures. They are further characterized by their abilities to hydrate and dehydrate reversibly and to exchange some of their constituent cations, both without major change of structures. Along with quartz and feldspar, zeolites are tectosilicates. They consist of three-dimensional frameworks of $SiO_4^{4-}$ tetrahedral in which all O's of each tetrahedron are shared with adjacent tetrahedral. This arrangement reduces the overall O/Si ratio to 2:1, and if each tetrahedron was to contain Si as its central cation, the structure would be electrically neutral, as in quartz ($SiO_2$). In zeolite structures, however, some of the quadrivalent Si is replaced by trivalent Al, giving rise to a deficiency of positive charge in the framework. This charge is balanced by monovalent and divalent cations, principally $Na^+$, $K^+$, $Ca^{2+}$ and $Mg^{2+}$ elsewhere in the structure (Ming and Mumpton, 1989). Application of zeolite as a soil conditioner improves the physical and chemical properties of soil and confirms the long-term stability of crop productivity in irrigated agriculture.

Water and solute flow in soil is one of the important components in hydrologic cycle and different mathematical models are used to simulate the water and solute flow in soil (Perrier et al., 1996). Accuracy of these models depends on the roboustness of the soil hydraulic parameters such as soil hydraulic conductivity, hydraulic diffusivity (D) and sorptivity, S (Wang et al., 2006; Bohne et al., 1995; Wei et al., 2011). Application of soil conditioners such as bentonite reduces infiltration rate and improves irrigation application efficiency ($E_a$) in coarse textured soils (Taleb-Nejad and Sepaskhah, 2013). They indicated that maximum reduction in infiltration equation coefficient and final infiltration rate occurred by 2 g bentonite $L^{-1}$ and its effect on design of furrow irrigation in a field with loamy sand soil indicated that in first irrigation after field plowing and seed planting, longer furrow length, lower deep percolation and higher $E_a$ were obtained.

Soil conditioners have been used in many investigations to study their effects on soil hydraulic properties (Ibrahim-Saeedi and Sepaskhah, 2013). Xiubin and Zhanbin (2001) studied the effect of zeolite on soil properties. In this study mordinite powder (a type of zeolite) was mixed with fine-grained calcareous loess soil and some parameters were measured under field and laboratory conditions. Xiubin and Zhanbin (2001) observed that applying zeolite increased infiltration by 7-30 % in the gentle slope and by 50 % in the steep slope. Furthermore, runoff and erosion were low with zeolite application and the sediments decreased by 85 % in the gentle slope and 50 % in the steep slope. In general, in treatments containing zeolite compared with the natural soil, values of soil moisture and cation exchange capacity **(**CEC**)** were increased. Sepaskhah and Yousefi (2007) evaluated the effect of different rates of calcium- potassium zeolite on pore velocity of water in soil and leaching of ammonium and nitrate that were applied as ammonium-nitrate fertilizer in a loam soil under saturated conditions. They reported that application of 4 and 8 g zeolite $kg^{-1}$ soil increased the pore water velocity in soil by 35 and 74 %, respectively. They claimed that because of high ion exchange ability of zeolite, using 2 g zeolte $kg^{-1}$ soil is sufficient to prevent ammonium leaching in a loam soil. Also applying 8 g zeolite $kg^{-1}$ soil could decrease ammonium leaching considerably. Therefore, zeolite application can decrease the groundwater pollution with increasing detention of nitrate and ammonium in soil by trapping nitrate in zeolite pores and adsorption of ammonium by negative charge of zeolite. Yasuda et al. (1998) reported that zeolite application increased the soil water holding capacity and alleviated the harmful effect of saline water on plant growth. Gholizadeh-Sarabi and Sepaskhah (2013) indicated that by increasing the zeolite application rates in heavy textured soils, the saturated hydraulic conductivity increased and it decreased in light textured soils. Further, they reported that interaction of salinity and zeolite application rates should be considered in determination of optimum zeolite application rates. They also indicated that at a given level of salinity of water, increasing zeolite application rates reduced the values of sorptivity.

Water flow in soil mostly occurs in unsaturated condition that is more complicated than the saturated conditions. Determination of unsaturated hydraulic properties, i.e., sorptivity and hydraulic diffusivity are difficult, costly and time consuming. Therefore, theoretical principles should be used for their determination. Wang et al. (2006) proposed a simple method to relate sorptivity and hydraulic diffusivity. However, their method should be evaluated for different soil textures especially under different application rates of soil conditioners such as zeolite.

The objectives of this study were to determine the soptivity and hydraulic diffusivity in different soil textures in horizontal soil column under different zeolite application rates. Further, the simple method to estimate sorptivity from hydraulic diffusivity for different soil textures and zeolite application rates was evaluated.

## THEORETICAL PRINCIPLE

The flow of water in one-dimensional horizontal soil column and boundary conditions are given as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial X}\right] \quad (1)$$

$$\Theta(X, 0) = \theta_i \;:\; X \geq 0, t = 0 \quad (1a)$$

$$\Theta(0, t) = \theta_s \;:\; X = 0, t > 0 \quad (1b)$$

$$\Theta(\infty, t)=\theta_i \quad : X=\infty,\ t>0 \quad (1c)$$

where $D(\theta)$ is the unsaturated hydraulic diffusivity ($cm^2$ $min^{-1}$), $\theta$ is the volumetric soil water content ($cm^3$ $cm^{-3}$), $t$ is the time (min), $X$ is the horizontal distance (cm), $\theta_i$ is the initial water content ($cm^3$ $cm^{-3}$), $\theta_s$ is the saturated soil water content at the beginning soil column where water enters into the soil column ($cm^3$ $cm^{-3}$).

Equation (2) is used as Boltzmann transformation to transform Eq. (1) into an ordinary differential equation as follows:

$$\lambda = X\, t^{-\frac{1}{2}} \quad (2)$$

$$-\frac{\lambda}{2}\frac{d\theta}{d\lambda} = \frac{d}{d\lambda}\left[D(\theta)\frac{d\theta}{d\lambda}\right] \quad (3)$$

where $\lambda$ is a coefficient.

Equation (3) can be written as follows:

$$X = \lambda\, t^{\frac{1}{2}} \quad (4)$$

Cumulative volume of entered water per unit surface area at X=0 and time t is as follows (Philip, 1957):

$$I= \int_{\theta_i}^{\theta_s} X\, d\theta \quad (5)$$

where $I$ is the cumulative infiltration (cm). By substitution of Eq. (2) in Eq. (5):

$$I = t^{\frac{1}{2}} \int_{\theta_i}^{\theta_s} \lambda(\theta)\, d\theta = S\, t^{\frac{1}{2}} \quad (6)$$

where

$$S = \int_{\theta_i}^{\theta_s} \lambda(\theta)\, d\theta = I/t^{\frac{1}{2}} \quad (7)$$

where $S$ is the soil water soptivity (cm $min^{-1/2}$). It is difficult to theoretically relate $S$ to $\lambda$, therefore $S$ in Eq. (7) is usually estimated from experimental infiltration data in a horizontal infiltration test.

In order to relate the sorptivity to diffusivity, the assumption of Parlange (1971) is used in Eq. (1) as follows:

$$\frac{\partial X}{\partial t} + \frac{\partial}{\partial \theta}\left[\frac{D}{\left(\frac{\partial X}{\partial \theta}\right)}\right] = 0 \quad (8)$$

where $D$ is the soil water diffusivity ($cm^2$ $min^{-1}$).

Integrating Eq. (8) results:

$$\int_{\theta}^{\theta_s} \frac{\partial X}{\partial t} d\theta + D(\theta_s)\left[\frac{\partial \theta}{\partial X}\right]_{X=0} - D(\theta)\frac{\partial \theta}{\partial X} = 0 \quad (9)$$

where $D(\theta_s)$ is the saturated soil water diffusivity ($cm^2$ $min^{-1}$). By equating $\theta$=$\theta_i$, Eq. (7) is changed to:

$$\int_{\theta_i}^{\theta_s} \frac{\partial X}{\partial t} d\theta + D(\theta_s)\left[\frac{\partial \theta}{\partial X}\right]_{X=0} = 0 \quad (10)$$

where $\theta$ is the soil volumetric water content ($cm^3$ $cm^{-3}$), $\theta_s$ is the saturated soil water content, and $D(\theta_s)$ is the saturated soil water diffusivity. Parlange (1971) assumed that the first term of Eq. (9) is negligible; therefore Eq. (9) is changed to:

$$D(\theta_s)\left[\frac{\partial \theta}{\partial X}\right]_{X=0} \approx D(\theta)\frac{\partial \theta}{\partial X} \quad (11)$$

By considering infiltration rate ($i$) as follows:

$$i = -D(\theta)\frac{\partial\theta}{\partial x} \approx -D(\theta_s)\left[\frac{\partial\theta}{\partial x}\right]_{X=0} \quad (12)$$

Where $i$ is the infiltration rate (cm min$^{-1}$) and $\frac{\partial\theta}{\partial x}$ is the soil water content gradient. Integrating Eq. (12) results in:

$$X_i = \int_{\theta_i}^{\theta_s} D(\theta)d\theta \quad (13)$$

Combining Eqs. (13), (12), and (9) results in:

$$i^2 = \frac{\int_{\theta_i}^{\theta_s} \theta D(\theta)d\theta}{2t} \quad (14)$$

or

$$i = \frac{1}{\sqrt{2}}\sqrt{\int_{\theta_i}^{\theta_s} \theta D(\theta)d\theta}\, t^{-\frac{1}{2}} \quad (15)$$

Derivation of Eq. (6) results in:

$$i = \frac{1}{2} st^{-\frac{1}{2}} \quad (16)$$

Combining Eqs. (15) and (16) results in:

$$S = \sqrt{2}\sqrt{\int_{\theta_i}^{\theta_s} \theta D(\theta)d\theta} \quad (17)$$

Equation (17) shows the relationship between sorptivity and hydraulic diffusivity. Hydraulic diffusivity can also be shown as follows:

$$D(\theta) = D_s\theta^{\alpha} \quad (18)$$

where $D_s$ is the saturated hydraulic diffusivity and $\alpha$ is an empirical constant. By substitution of Eq, (18) in Eq. (17) following equation is obtained:

$$S = \frac{\sqrt{2}}{\sqrt{\alpha+2}}\sqrt{D_s({\theta_s}^{\alpha+2} - {\theta_i}^{\alpha+2})} \quad (19)$$

In case where $\theta_i$ is negligible Eq. (19) is changed to:

$$S = \frac{\sqrt{2}}{\sqrt{\alpha+2}}\sqrt{D_s({\theta_s}^{\alpha+2})} \quad (20)$$

Equation (20) indicated that sorptivity is determined as a function of $D_s$ and $\alpha$. Further, sorptivity increases with increasing $D_s$ and it decreases with increasing $\alpha$. By given values of $D_s$ and $\alpha$ and using Eq. (20), the value of $S$ is estimated.

The proposed method by Meyer and Warrick (1990) was used to determine $D$. This method is described by using Eq. (3) as follows:

$$D(\theta) = -\frac{1}{2}\frac{d\lambda}{d\theta}\int_{\theta_i}^{\theta} \lambda\, d\theta \quad (21)$$

We used a rational function that is a nonlinear function formed from the ratio of two polynomials similar to that presented by Miller (1981) as follows:

$$\theta = \frac{A_1 + A_3\lambda}{1 + A_2\lambda} \quad (22)$$

where $\lambda$ is the independent variable and $\theta$ is the dependent variable. Combining Eqs. (21) and (22) results in:

$$\int_{\theta_i}^{\theta} \lambda\, d\theta = f(\theta_i, \theta) \quad (23)$$

$$\text{where: } f(\theta_i, \theta) = \int_{\theta_i}^{\theta} \left(\frac{\theta - A_1}{A_3 - A_2\theta}\right) d\theta \quad (24)$$

By integration of Eq. (24) it results:

$$f(\theta_i, \theta) = -(1/A_2)(\theta - \theta_i) + \left[(A_1A_2 - A_3)/{A_2}^2\right]\ln\left[\frac{\theta - (A_3/A_2)}{\theta_i - (A_3/A_2)}\right] \quad (25)$$

By taking derivative of Eq. (22) and inserting it in Eq. (21) it results in:

$$D(\theta) = -0.5\left(\frac{A_3 - A_1A_2}{(A_3 - A_2\theta)^2}\right) f(\theta_i, \theta) \quad (26)$$

For determination of $A_1$, $A_2$ and $A_3$ by multiple regression analysis Eq. (22) is rearranged as follows:

$$\theta = A_1 + A_3\lambda - A_2\lambda\theta \quad (27)$$

By substitution of $A_1$, $A_2$ and $A_3$ in Eqs. (25), and (26), the values of $D$ for different $\theta$ are determined. Furthermore, according to Gardner and Mayhugh (1958) the relationship between $D$ and $\theta$ was determined as follows:

$$D(\theta) = a\, e^{b\theta} \quad (28)$$

where a, and b are the constants.

## MATERIALS AND METHODS

### Hydraulic Diffusivity

Hydraulic diffusivity was determined in horizontal soil column with timely measured horizontal infiltration and soil water profile at the end of infiltration measurement as described by Bruce and Klute (1956). The measurements were made in three soil textures as sandy loam, loam, and silty clay with three replicates. The physical properties of soils are depicted in Table 1. Soil samples were collected from soil surface (0-30 cm) and air dried and passed through sieve with 2 mm screen diameter. The sieved soils were mixed with zeolite. The application rates were 0, 4, 8, and 12 g zeolite kg$^{-1}$ soil. The treated soils were packed in plexiglass cylinder with internal diameter of 64 mm and 210 mm length. The plexiglass cylinder was constructed by attaching different rings with various lengths, one ring with 40 mm, three rings with 20 mm, and eleven rings with 10 mm length.

**Table 1.** Physical properties of the soils used in the experiment of this study

| Soil texture | Sand (%) | Silt (%) | Clay (%) | Bulk density (g cm$^{-3}$) | Initial soil water content (cm$^3$ cm$^{-3}$) | Geometric mean (mm) | Geometric standard deviation (mm) |
|---|---|---|---|---|---|---|---|
| Sandy loam | 70.0 | 18.0 | 12.0 | 1.47 | 0.008 | 11.51 | 0.230 |
| Loam | 40.0 | 47.0 | 13.0 | 1.15 | 0.028 | 10.85 | 0.074 |
| Silty clay | 10.6 | 45.4 | 44.0 | 1.07 | 0.049 | 9.38 | 0.009 |

Water infiltrated in soil column by a Marriott bottle with water entrance located at the center of soil column, therefore the average suction at the entrance was kept at zero cm. The volume of water entered into soil column at different times was measured volumetrically in the Marriott bottle. At the time when the wetting front reached the ring before the last one, water entry was stopped by disconnecting the entry tube. Then, different rings were separated and the soil water contents in rings were determined by gravimetric procedure. Volumetric soil water contents in rings were determined by multiplying the gravimetric soil water content by soil bulk density. The soil water content at the first ring was considered as saturated soil water content ($\theta_s$) and the water content in the last ring with no entrance of the wetting front was considered as initial soil water content ($\theta_i$).

Using the obtained data, i.e., soil water profile, and Eqs. (21)-(26), hydraulic diffusivity as a function of soil water content was determined (Meyer and Warrick, 1990).

### Sorptivity

Sorptivity was determined by direct and indirect (simple) methods. In direct method, Eq. (7) was used to determine sorptivity for different soils, zeolite application rates and replicates. In this procedure, cumulative infiltration was related to the square root of elapsed time and slope of this relationship was considered as sorptivity. In indirect method, Eq. (18) was used. In this method the relationship between $D$ and $\theta$ (in the horizontal infiltration) and their parameters ($D_s$ and $\alpha$) was determined. Then by using Eq. (20) and saturated soil water content ($\theta_s$) the values of $S$ were determined.

## RESULTS AND DISCUSSION

### Hydraulic Diffusivity (Exponential Function)

Hydraulic diffusivities [$D(\theta)$] were determined based on Eq. (21) for different zeolite application rates and soil textures. Then, Eq. (28) was fitted to the data and its coefficients were determined and presented in Table 2. In general, the values of b for different soil textures are not very different. The value of b was highest at zeolite application rate of 8 g kg$^{-1}$ soil for silty clay soil. However, the value of a was higher for sandy loam than those for loam and silty clay soils, respectively at different zeolite application rates. In general, the value of a was highest in sandy loam soil and it was decreased at loam and silty clay soils. Zeolite application rate of 8 g kg$^{-1}$ soil in sandy loam increased significantly the value of a. However, higher zeolite application rate (12 g kg$^{-1}$ soil) decreased the value of a. Application of 8 g zeolite kg$^{-1}$ soil might have influenced the soil structure and resulted in increasing the value of a and b in sandy loam and silty clay soils, respectively.

### Hydraulic Diffusivity (Power Function)

Hydraulic diffusivities [$D(\theta)$] were determined based on Eq. (21) for different zeolite application rates and soil textures. Then, Eq. (18) was fitted to the data and coefficients of Eq. (18) were determined and presented in Table 3. The values of $D_s$ for medium and light textured soils were reduced by zeolite application rate of 4 g kg$^{-1}$ soil and higher. However, for heavy texture soil, the value of $D_s$ increased up to zeolite application rates of 8 g kg$^{-1}$ soil and then it decreased at zeolite application rate of 12 g kg$^{-1}$ soil. Similar results were occurred for $\alpha$ in sandy loam and silty clay soils, however the value of $\alpha$ decreased at zeolite application rate of 8 g kg$^{-1}$ soil for medium texture soil.

**Table 2.** Mean values of a and b in $D(\theta)=a\mathrm{EXP}(b\theta)$ for different soil textures and zeolite application rates

| Zeolite application rate (g kg$^{-1}$) | Sandy loam | | Loam | | Silty clay | |
|---|---|---|---|---|---|---|
| | a | b | a | b | a | b |
| 0 | 2.3bcd* | 23.2abc | 0.70cd | 19.3c | 0.30d | 20.3bc |
| 4 | 4.3abc | 21.8bc | 0.53d | 19.7bc | 0.02d | 25.4ab |
| 8 | 6.6a | 18.3c | 0.93cd | 17.8c | 0.01d | 27.9a |
| 12 | 5.0ab | 21.2bc | 0.80cd | 18.2c | 0.05d | 25.4ab |

*Means followed by the same letters in each column are not significantly different at 5% probability level by Duncan multiple range test.

**Table 3.** Mean values of coefficients in $D(\theta)=D_s\theta^{\alpha}$ for different soil textures and zeolite application rates.

| Coefficient | Zeolite application rate (g kg$^{-1}$) | Sandy loam | Loam | Silty clay |
|---|---|---|---|---|
| $D_s$ (cm$^2$ min$^{-1}$) | 0 | 4219.6a* | 740.9a | 493.3b |
| | 4 | 401.1b | 468.7b | 1505.4ab |
| | 8 | 443.3b | 416.1b | 2394.1a |
| | 12 | 481.8b | 458.2b | 618.3b |
| $\alpha$ | 0 | 4.98a | 5.12a | 5.69b |
| | 4 | 3.15b | 4.81ab | 6.82ab |
| | 8 | 3.37b | 4.66b | 7.18a |
| | 12 | 3.38b | 4.67b | 5.75b |

*Means followed by the same letters in each column are not significantly different at 5% level of probability by Duncan multiple range test.

In general, for 0 application rate of zeolite the values of $D_s$ are higher in light texture soil and it decreased as soil texture becomes heavier. However, zeolite application rates (4-12 g kg$^{-1}$soil) decreased the values of $D_s$ for sandy loam and loam soils with no significant difference between $D_s$ for these application rates and soils.

Furthermore, zeolite application rates of 4-8 g kg$^{-1}$ soil increased the $D_s$ values for silty clay soil and this increase was higher in zeolite application rate of 8 g kg$^{-1}$ soil. In general, for 0 application rate of zeolite, the values of $\alpha$ are not different for different soil textures. However, zeolite application rates (4-12 g kg$^{-1}$ soil) decreased the values of $\alpha$ for sandy loam and loam soils with significant difference between $\alpha$ values for these soils. Zeolite application rates of 4-12 g kg$^{-1}$ soil increased the values of $\alpha$ for silty clay soil, and the values of $\alpha$ in this soil is higher than those in sandy loam and loam soils.

## Sorptivity

### Direct Method

A sample of relationship between cumulative infiltration and root squared of elapsed time for different soil textures is shown in Fig. 1. The slope of this relationship is soil water sorptivity. The values of sorptivities for different soil textures and zeolite application rates are presented in Table 4. In general, the value of sorptivity is higher for loam and it is lower for sandy loam and silty clay soils.

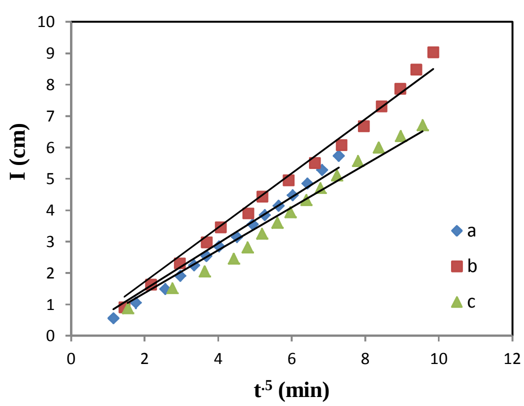


**Fig. 1.** Relationship between cumulative infiltration (I) and squared elapsed time ($t^{0.5}$) for different soil textures: (a) Sandy loam, (b) Loam, (c) Silty loam

Sorptivity differences between soil textures are higher in higher zeolite application rates. In sandy loam soil, zeolite application decreased the value of S by increasing zeolite application rates. However, for loam and silty clay soils, decrease in the value of S occurred up to zeolite application rate of 8 g kg$^{-1}$ soil and then by increasing zeolite application rate, the value of S increased. Decrease in value of S might have been as a result of soil structure improvement by zeolite application to a certain extent and at higher zeolite application rate, the pore size distribution might have been reduced that might have resulted in increasing in the value of S.

Variation of logarithm of S in different soils and application of zeolite can be presented as a multiple regression and variation of soil type in this equation is included by geometric mean and geometric standard deviation of soil particles diameter (Table 1). The obtained regression equation is as follows:

$$\text{Log}(S)=0.001Z^2-0.025Z+0.120\sigma_g-1.099d_g-1.228 \quad (29)$$

$R^2$=0.87, SE=0.03, n=12, p=0.003

where $S$ is the sorptivity (cm min$^{-1/2}$), $Z$ is the zeolite application rate (g kg$^{-1}$ soil), $d_g$ is the geometric mean of soil particle diameter (mm) and $\sigma_g$ is the geometric standard deviation of soil particle diameter (mm). Equation (29) indicated that by increasing diameter of soil particles and decreasing standard deviation, the value of $S$ is decreased. This equation can be used as a pedo-transfer function to estimate the optimum zeolite application rate for different soil textures. For each texture, by knowing the $d_g$ and $\sigma_g$, Eq. (29) is changed to a quadratic equation of LogS and by taking derivative of this quadratic equation and equating to zero, the optimum value of $Z$ for decreasing value of $S$ is obtained.

### Indirect Method

Using the measured hydraulic diffusivity at different soil water contents in Eq. (18) the values of $D_s$ and $\alpha$ were determined. Then by using these values in Eq. (20) the values of $S$ were determined. This procedure was used for different soil textures and zeolite application rates. Results of determined $S$ are given in Table 4 as values of $S$ in indirect method. Variation pattern of indirect $S$ for different soil textures and zeolite application rates was similar to that of direct $S$ values. It is indicated that indirect $S$ is highest for loam soil and it is lower for sandy loam and silty clay soils. Similar to direct $S$, the values of indirect $S$ was decreased as zeolite application rate increased to 8 g kg$^{-1}$ soil and then increased at higher zeolite application rates.

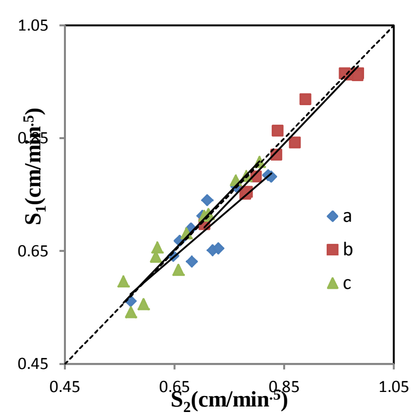


**Fig. 2.** Relationship between direct sorptivity ($S_1$) and indirect sorptivity ($S_2$) for different soil textures: (a) Sandy loam, (b) Loam, (c) Silty clay

**Table 4.** Mean values of sorptivity (cm $min^{-1/2}$) determined by direct and indirect methods for different soil textures and zeolite application rates.

| Method | Zeolite application rate (g $kg^{-1}$) | Sandy loam | Loam | Silty caly |
|---|---|---|---|---|
| Direct | 0 | 0.776a* | 0.963a | 0.788a |
| | 4 | 0.714b | 0.815b | 0.689b |
| | 8 | 0.646c | 0.734c | 0.571c |
| | 12 | 0.623c | 0.915a | 0.644b |
| Indirect | 0 | 0.803 | 0.980 | 0.782 |
| | 4 | 0.696 | 0.835 | 0.677 |
| | 8 | 0.748 | 0.755 | 0.607 |
| | 12 | 0.626 | 0.896 | 0.615 |

*Means followed by the same letters in each column are not significantly different at 5% level of probability by Duncan, multiple range test.

**Table 5.** Statistical parameters to compare the linear relationship between direct sorptivity ($S_1$) and indirect sorptivity ($S_2$) to 1:1 line by F-test.

| Soil texture | Slope | Intercept | $R^2$ | F for slope | F for intercept |
|---|---|---|---|---|---|
| Sandy loam | 0.83 | 0.09 | 0.77 | $1.35^{ns}$ | $3.59^{ns}$ |
| Loam | 1.01 | -0.02 | 0.95 | $0.079^{ns}$ | $2.79^{ns}$ |

Relationship between direct $S$ ($S_1$) and indirect $S$ ($S_2$) for different soil textures is shown in Fig. 2. Linear relationships between $S_1$ and $S_2$ are compared with the 1:1 line by statistical F-test. Results are shown in Table 5. The slope and intercept of these linear relationships are close to 1.0 and 0 statistically ($p$<0.05). Further, the values of $R^2$ for different soils were high and indicated a high correlation between $S_1$ and $S_2$. Furthermore, there was no significant difference between the slopes and intercepts between different soils ($p$<0.05). Therefore, it is indicated that by knowing the values of $D_s$ and $\alpha$ for different soils and zeolite application rates, accurate values of $S$ can be estimated. On the other hand, it is obvious that the values of $D_s$ and $\alpha$ are different at different initial soil water contents. Therefore, by knowing the values of $S$ for different initial soil water contents in horizontal water absorption experiment or two different suction heads in tension infiltrometer test and using Eq. (20) the values of $D_s$ and $\alpha$ can be estimated.

## CONCLUSIONS

Results indicated that zeolite application was not effective on the a and b values of hydraulic diffusivity function (D=aEXP(bθ)), while maximum value of a and b in sandy loam and silty clay soils, respectively occurred by application of 8 g zeolite $kg^{-1}$ soil. The values of a and b for loam soil were not influenced by zeolite application rates. Sorptivity for sandy loam soil reduced by zeolite application rate, while minimum value of S for loam and silty clay soils occurred at zeolite application rate of 8 g $kg^{-1}$ soil. It is indicated that indirect determination of S for different soil textures and zeolite application rates were closely similar to the direct determination of S. Therefo determination of S value by simple horizontal absorption test at two different initial soil water contents or two different absorption suction heads in tension infiltrometer the values of $D_s$ and α for hydraulic diffusivity function ($D=D_s\theta^{\alpha}$) can be estimated.

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**مقاله علمی- پژوهشی**

# ارزیابی یک روش تحلیلی برای رابطه بین ضرایب پخشیدگی هیدرولیکی و جذب همراه با کاربرد زئولیت

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***واژه‌های کلیدی:***

ضریب پخشیدگی هیدرولیکی

ضریب جذب

پارامترهای هیدرولیکی خاک

اصلاح کننده های خاک

زئولیت

**چکیده-** از زئولیت برای بهبود خواص هیدرولیکی خاک مانند ضریب پخشیدگی هیدرولیکی(D) و ضریب جذب (S) استفاده می شود که بایستی تعیین شوند. یک روش ساده که مقدار S را به D ارتباط می دهد با آزمایش جذب افقی آب در خاک شنی لومی ، لومی و سیلتی رسی و کاربرد زئولیت به میزان صفر، ۴، ۸ و ۱۲ گرم بر کیلوگرم خاک ارزیابی شد. نتایج نشان داد که کاربرد زئولیت بر روی ضرایب a و b تابع ضریب پخشیدگی هیدرولیکی $\left[D = a\exp(b\theta)\right.$، $\theta$ مقدار حجمی آب خاک $\left.(cm^3 cm^{-3})\right]$ موثر نبود در حالیکه بیشترین مقدار a و b در خاک های شنی لومی و سیلتی رسی در مقدار کاربرد ۸ گرم بر کیلوگرم خاک اتفاق افتاد. مقدار a و b برای خاک لومی تحت تأثیر میزان کاربرد زئولیت قرار نداشت. ضریب جذب برای خاک شنی لومی با کاربرد زئولیت کاهش یافت در حالیکه حداقل مقدار S برای خاک لومی و سیلتی رسی در میزان کاربرد زئولیت ۸ گرم بر کیلوگرم اتفاق افتاد. نتایج نشان داد که روش غیر مستقیم تعیین S برای بافت های مختلف خاک و مقادیر مختلف کاربرد زئولیت تقریباً شبیه روش مستقیم تعیینS بود. بنابراین با تعیین مقدار S در روش ساده آزمایش جذب افقی آب در دو مقدار مختلف آب اولیه خاک یا دو مقدار مختلف بار آبی جذب آب در نفوذ سنج مکشی، مقادیر $D_s$ و $\alpha$ برای تابع ضریب پخشیدگی هیدرولیکی ($D= D_s \Theta^{\alpha}$) می تواند بدست آید.