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ARTICLE

Feldspathic sandstone addition and its impact on hydraulic properties of sandy soil

Junchao Jia, Pingping Zhang, Xiaofeng Yang, and Xingchang Zhang

Abstract: Feldspathic sandstone could be used as an effective conditioner to improve the physical quality of sandy soil, and increase the crop yield there. To determine the effects of feldspathic sandstone content on soil hydraulic properties in a sandy soil, the present study added 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% (no sandy soil) of feldspathic sandstone to sandy soil. Changes in hydraulic parameters were investigated and the results showed addition of feldspathic sandstone increased saturated water content by 37%–61% and field capacity by 29%–44%, and decreased saturated hydraulic conductivity from 10.19 to 0.58 cm h^{-1} of the sandy soil. Further data analysis demonstrated that with increasing content of feldspathic sandstone, the parameter n of soil water retention curve in Van Genuchten model dropped from 1.807 to 1.333. The same decreasing trend is detected in parameter a of infiltration rate (3.841–0.703) in Kostiakov formula ($i = at^{-b}$) and parameter a_1 of wetting front (6.901–1.174) in the empirical equation ($X = a_1t^{b1}$). In terms of hydraulic parameters, 40% feldspathic sandstone and 60% sandy soil, optimally matching indices of loess soil, were the best mixing ratio for sandy land restoration.

Key words: feldspathic sandstone content, sandy lands, hydraulic properties.

Résumé : On pourrait utiliser du grès feldspathique pour améliorer la texture des sols sablonneux et augmenter le rendement des cultures poussant sur ce type de terre. Pour préciser les effets d'un tel amendement sur les propriétés hydrauliques d'un sol sablonneux, les auteurs y ont ajouté 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, ou 100 pour cent (aucun sable) de grès feldspathique. Ensuite, ils ont examiné comment les paramètres hydrauliques étaient modifiés et ont noté que le grès accroît la teneur en eau au point de saturation de 37 à 61 pour cent et la capacité de rétention du sol de 29 à 44 pour cent; ils ont aussi observé une baisse de la conductivité hydraulique au point de saturation, qui est passée de 10,19 à 0,58 cm h^{-1} dans le sol sablonneux. Une analyse plus poussée des données révèle que le paramètre n de la courbe de rétention de l'eau du modèle de Van Genuchten baisse de 1,807 à 1,333 quand la proportion de grès feldspathique augmente. Une tendance à la baisse analogue a été observée pour le paramètre a du taux d'infiltration (de 3,841 à 0,703) dans la formule de Kostiakov ($i = at^{-b}$), ainsi que pour le paramètre a_1 du front d'humectation (de 6,901 à 1,174) dans l'équation empirique ($X = a_1t^{b1}$). En ce qui concerne l'hydraulique, un mélange composé de 40 % de grès feldspathique et de 60 % de sol sablonneux, dont les indices reproduisent de façon optimale ceux du lœss, serait l'idéal pour restaurer les terres sablonneuses. [Traduit par la Rédaction]

Mots-clés : teneur en grès feldspathique, terres sablonneuses, propriétés hydrauliques.

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J. Jia* and X. Yang. State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, People's Republic of China; University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China.

P. Zhang.* State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, People's Republic of China; Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, People's Republic of China; State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, Shaanxi 710075, People's Republic of China.

X. Zhang. State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, People's Republic of China; Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, People's Republic of China.

Corresponding author: Xingchang Zhang (email: zhangxc@ms.iswc.ac.cn).

*These authors contributed equally to this work.

Introduction

Cultivating sandy soil is a promising suggestion to overcome the fight against hunger in the word (Reuter 1994; Ismail and Ozawa 2007). The main problem of sandy soil is its deficiency in water and nutrients. To better use sandy lands, soil ameliorants like mulches, sewage-sludge compost, polyacrylamide, and biochar have been applied to improve the sandy soil throughout the years (Tester 1990; Andry et al. 2009; Young et al. 2009; Głąb et al. 2016). These materials can achieve good results in water and nutrients use efficiency and crop yield, but they have some disadvantages including high cost, limited availability, the potential to cause pollution (Han et al. 2012). Compared with the above ameliorants, some natural water retaining materials, such as clay minerals and soft rocks, which are inexpensive, readily available, and environmentally friendly, are better suited to improve sandy soil on a large scale.

The research area, Jin–Shaan–Meng energy circle in northwest China, has a total area of 5.44×10^4 km^2 and consists of mainly loessial soil and the sandy soil. One-third of this area is covered by loose rock known as feldspathic sandstone (Zhen et al. 2016) formed in the Permian, Triassic, Jurassic, and Cretaceous and having a low degree of diagenesis, sand cementation, and poor structural strength (Wang et al. 2007). The loose rock is very hard when dry but becomes loose when wet. Feldspathic sandstone contains a large percentage of montmorillonite (Ma and Zhang 2016), which has a high cation exchange capacity and water-holding capacity. These properties indicated that feldspathic sandstone has potential application in land reclamation for the soil with poorer structure and coarser texture. Several authors have found that feldspathic sandstone could be selected as a sandy soil amendment to improve the soil texture and pore structure and increase corn yields (Chai et al. 2013; Fu et al. 2013). More than 1600 hm^2 new arable lands have been added by incorporating feldspathic sandstone into sandy soil by Shaanxi Provincial Land Engineering Construction Group (Han et al. 2012). However, few if any studies have monitored the change of hydraulic properties in different treatments with various mixture ratios, which are important soil index for land restoration.

In this study, sandy soil and feldspathic sandstone were mixed to investigate the soil hydraulic property changes through determining its saturated water content (SWC), field capacity (FC), and saturated hydraulic conductivity (SHC), and analyzing soil water retention curve (SWRC), infiltration rate (IR), and wetting front (WF) of the mixture. Furthermore, some empirical formulas were proposed to describe the relationship between hydraulic parameters and feldspathic sandstone addition. The purpose of this study was thus to determine the effect of feldspathic sandstone on hydraulic characteristics when mixed with sandy soil and to provide scientific information for the large scale application in sandy land control on the Loess Plateau.

Materials and Methods

Sampling site

Soil samples were collected from the towns of Dalu (111°22′6.4″E, 40°2′45.7″N) and Nuanshui (110°34′34.3″E, 39°44′23.6″N), in Jungar Banner, the Inner Mongolia Autonomous Region in northwest China in October 2016. Located in an arid and semi-arid continental monsoon climate, the sampling site has an average annual precipitation of 426.3 mm, of which about 77% occurs from June to September (Su and Pan 2006). The average annual evaporation is 1943.6 mm, the relative humidity is 58%, and the annual average temperature is 7.2 °C (Huang et al. 2015).

The particle size distribution and mineral compositions of sandy soil and feldspathic sandstone were determined by laser diffraction using a Master-sizer 2000 (MS-2000, Malvern, Britain, UK) and X-ray power diffraction (D/MAX-2600pc), respectively, and the results were shown in Table 1.

Experimental instruments

The air-dried sandy soil and feldspathic sandstone samples were crushed and sieved through a 2 mm mesh, and then they were thoroughly mixed to obtain 11 different volumetric contents of feldspathic sandstone.

To determine SWC, FC, SHC, and SWRC, the well-mixed soil substrates were packed into 100 cm^3 stainless steel cylinders (about 4 cm height). In addition, Plexiglas columns (length: 50.0 cm^3 and inner diameter: 6.0 cm) were prepared to measure IR and WF. The sandy soil, feldspathic sandstone, and mixtures were packed manually, and the bulk density (BD) is shown in Table 2. Three replicates were conducted for each treatment.

Moisture retention and SHC

The water content of packed samples which saturated from the bottom up for 48 h was SWC. Field capacity was commonly defined as the water content when free drainage has practically ceased (about 24 h) after saturation (Warrick 2002).

The constant-head ($H = 5$ cm) method (Klute and Dirksen 1986) was employed to measure SHC (K). The packed samples were slowly saturated from the bottom up for 48 h. The water flow (V) through the stainless steel cylinders was measured every 20 min (t) after being constant. Together with the height (L) and cross-sectional area (A) of the soil column, the SHC in the mixed soil column could be calculated by eq. 1 according to Darcy's law (Liu and Birkholzer 2012):

$$(1) \qquad K = \frac{VL}{tAH}$$

Table 1. Particle (American classification system) and mineral composition of the samples.

Soil	Particle-size distribution (%)			Mass percentage of mineral composition (%)						
	Sand	Silt	Clay	Quartz	Kaolinite	Montmorillonite	Feldspar	Calcite	Dolomite	Amphibole
Sandy soil	96.8	2.53	0.67	82	4	0	10	2	0	2
Feldspathic sandstone	28.95	59.41	11.64	57	0	30	10	0	3	0

Table 2. Designed mixing ratio and bulk density of each treatment.

Treatment	Volume fraction		Bulk density ($g\ cm^{-3}$)
	Sandy soil (%)	Feldspathic sandstone (%)	
S0	100	0	1.65
S1	90	10	1.63
S2	80	20	1.60
S3	70	30	1.58
S4	60	40	1.55
S5	50	50	1.53
S6	40	60	1.50
S7	30	70	1.48
S8	20	80	1.45
S9	10	90	1.43
S10	0	100	1.40

Soil water retention curves

Soil water retention curves were measured using the centrifuge method (Nimmo and Akstin 1988). The stainless steel cylinders (100 cm^3 in volume), packed with homogeneous substrates following the BD shown in Table 2, were saturated with water by capillary rise for about 48 h and then equilibrated step-wise to matric potentials of 0, 10, 100, 200, 400, 600, 800, 1 000, 2 000, 4 000, 6 000, 8 000, and 10 000 cm with a high speed centrifuge (CR21G, made in Japan) at about 20 °C. At the end of the experiment, the gravimetric water content was determined after oven-drying the soil samples equilibrated at 105 °C for 24 h. The volumetric water contents of the different pressure heads were obtained by multiplying the dry BD with mass water content. Consequently, the SWRCs for various treatments were expressed by the pressure head (h) and the volumetric water content (θ).

For θ–h data, Van Genuchten's equation (Van Genuchten 1980) parameters describing SWRCs of soil mixtures were determined by the computer program RETention Curve (RETC). Van Genuchten's equation is presented as eq. 2:

$$(2)\qquad \frac{\theta-\theta_r}{\theta_s-\theta_r}=\frac{1}{[1+(\alpha h)^n]^m}$$

where θ_s is the SWC; θ_r is the residual water content; h is the pressure head; α, n, and m are empirical parameters affecting the shape of the retention curve.

Infiltration

The method of horizontal one-dimensional infiltration (Mao et al. 2007; Sayah et al. 2016) was employed to explore the soil water infiltration in laboratory. Based on the water balance and the assumption of Green-Ampt distribution of soil moisture content in the infiltrating horizontal soil column (Green and Ampt 1911), Mao et al. (2007) proposed a simplified mathematic model to obtain infiltration properties accurately and quickly with horizontal method. In the ideal piston model, there were only two soil contents — the saturation and initial water content in the horizontal infiltration process, and the WF was the dividing line. The relationship between cumulative infiltration and the distance of WF migration in soil column was obtained by water balance principle. And the equation can be written as

$$(3)\qquad I=(\theta_s-\theta_i)X$$

The cumulative infiltration and IR have the following relation:

$$(4)\qquad i=\frac{dI}{dt}$$

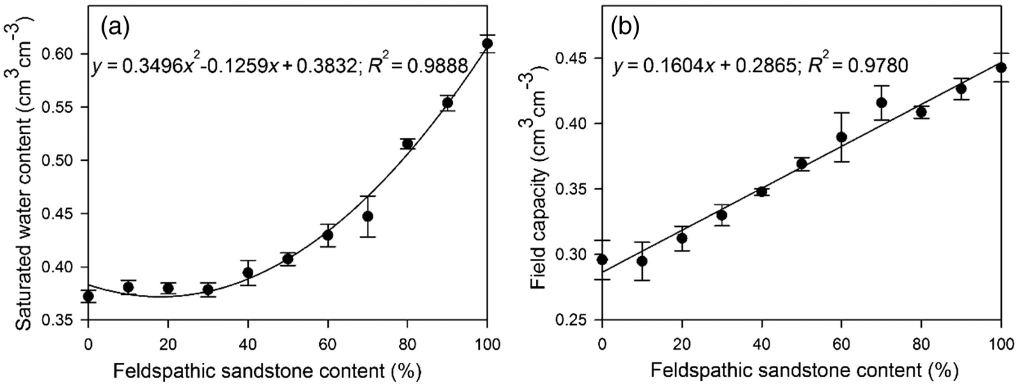
Substituting eq. 3 into eq. 4, the relationship between the IR and the velocity of soil WF is as follows:

$$(5)\qquad i=(\theta_s-\theta_i)\frac{dX}{dt}$$

where θ_s is the SWC; θ_i is the initial water content; X is the distance of the WF migration; t is the time.

The experimental device included a mariotte bottle and a horizontal soil column. A mariotte bottle was used to supply water for the horizontal soil column under a constant water head to ensure the soil to be saturated at the inlet side and also to avoid the gravity flow. The given amount of mixed soil samples (initial water content: sandy soil: 0.0022 v/v; feldspathic sandstone: 0.0753 v/v) was packed into the plexiglass tubes and hammered for targeted BD (Table 2). The distances from the WF to the water source and time were recorded.

Fig. 1. Relationship between feldspathic sandstone content and saturated water content (*a*), field capacity (*b*).



Best mixing ratio

A comparative study of the hydraulic features, especially the SHC, SWC, and SWRC, among different treatments were conducted. Then, the results were contrasted with those features of loess soil, the most adaptable soil type for vegetation in the research area, to select the best mixing ratio for land restoration of sandy soil.

Results and Discussion

Soil particle

Table 1 shows that feldspathic sandstone had much higher proportion of silt and clay than the sandy soil, and addition of feldspathic sandstone into sandy soil might increase the overall composition of clay which could improve the void and increase absorption capacity (Gupta and Larson 1979; Rawls and Brakensiek 1982), leading to higher water retention.

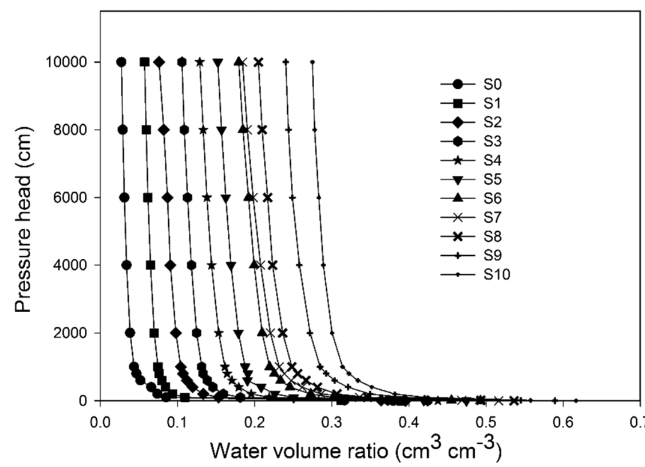
Moisture retention

As two important soil hydraulic parameters, the SWC is the maximum water content following saturation and FC is the water content of a saturated soil at which internal drainage becomes essentially negligible (Veihmeyer and Hendrickson 1931; Nemes et al. 2011).

As seen in Fig. 1, SWC increased from 0.37 to 0.67 (*v*/*v*) and FC increased from 0.29 to 0.48 (*v*/*v*) when feldspathic sandstone content increased from 0% to 100% by volume. Moreover, the dosage of 30% feldspathic sandstone in the sandy soil divided a slow rise and a sharp increase of SWC, a marking point not witnessed in FC change. Based on the previous study of Yi et al. (2013) and trend variation of figures, a quadratic equation and a linear equation were curve-fitted and applied to decode the relationship between SWC and feldspathic sandstone content, and the relationship between FC and feldspathic sandstone content, as were shown in Fig. 1.

The higher degree of fitting ($R^2 = 0.9888$ in SWC; $R^2 = 0.9780$ in FC) demonstrated that the two regression equations might be extended to calculate SWC and FC based on the content of feldspathic sandstone.

Fig. 2. Soil water retention curves fitted by Van Genuchten model.



Soil water retention curves

Figure 2 illustrated the SWRCs in different treatments. The SWRCs of treatments generally moved right with the addition of feldspathic sandstone, representing overall increase of water retention at same pressure head. The soil moisture contents of CK groups (only sandy soil or feldspathic sandstone) outlined the variation range of that in all treatments. The soil moisture content increased as the feldspathic sandstone was added at the same pressure head, especially at the lower suction. This is caused by the higher clay content in feldspathic sandstone which consequently changed of pore size distribution by reforming more small pores and less large pores (Dexter et al. 2012; Ding et al. 2016). In addition, the feldspathic sandstone had a larger surface area which absorbed higher amount of water. Therefore, there revealed an increase in volumetric water content at each soil water pressure head with increasing feldspathic sandstone content.

It was also observed that the SWRCs were steep at pressure head of above 300 cm, and then became flat when the pressure head was below 300 cm. The lower

Table 3. Parameters from the Van Genuchten model fit ($m = 1 - 1/n$).

Treatment	θ_r ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	α	n	R^2
S0	0.0316	0.3812	0.0768	1.8072	0.9972
S1	0.0621	0.3904	0.0922	1.8074	0.9986
S2	0.0854	0.3991	0.0575	1.7735	0.9961
S3	0.1096	0.4258	0.0759	1.6704	0.9979
S4	0.1262	0.4389	0.0910	1.5086	0.9981
S5	0.1481	0.4758	0.0889	1.4948	0.9981
S6	0.1651	0.4943	0.0690	1.4260	0.9990
S7	0.1537	0.5154	0.0749	1.3516	0.9987
S8	0.1783	0.5365	0.0706	1.3777	0.9997
S9	0.2089	0.5891	0.0657	1.3777	0.9998
S10	0.2335	0.6149	0.0884	1.3326	0.9993

the content of feldspathic sandstone was added, the smoother the curves became, indicating significant increasing of water retention in each treatment below the pressure head of 300 cm. In lower pressure head, water inside large pores in the mixed soil was drained out, a minor increase of pressure head might lead to an evident decrease of water retention. In higher pressure head, residual water saved in small pores was drained and the significant increase of suction will cause little decrease of water retention (Li et al. 2009). More steep and flat SWRCs can be evidently detected in soil with higher sand grain content.

The fitted parameters in Van Genuchten's equation (eq. 2) are listed in Table 3.

The θ_s and θ_r increased with higher feldspathic sandstone content. The value of θ_s following the S0 to S10 treatments increased from 0.3812 to 0.6149 because the soil total porosity increased with the increase of clay. And the value of θ_r following the S0 to S10 treatments increased from 0.0316 to 0.2335. This is because the higher content of clay had larger surface areas for water retention, resulting in a higher θ_r for feldspathic-sandstone-rich soils. It could be concluded that the SWC and residual water content significantly correlated with soil texture.

Based on the similar fitting research and the present study, formulas were linearly fitted to predict θ_s and θ_r by feldspathic sandstone content (x), the equations were as below:

$$(6)\qquad \theta_s = 0.2373x + 0.3596,\ R^2 = 0.9723$$

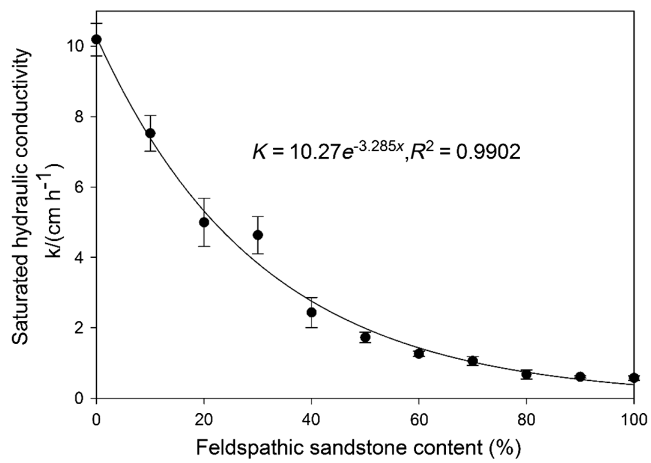
$$(7)\qquad \theta_r = 0.1821x + 0.0455,\ R^2 = 0.9688$$

The parameter n, which controls the curvature of the SWRC, is the essential parameter to predict the relative hydraulic conductivity (Costabel and Yaramanci 2013). Table 3 showed that the highest n is from the sandy soil and the value of n decreased with increasing feldspathic sandstone content. There was a significant correlation between n and particle size distribution (Schaap and Bouten 1996; Haverkamp et al. 2005). Minasny and Mcbratney (2007) suggested that the value of n increased with increasing sand content. Feldspathic sandstone content increase in mixture can equate to sand content decrease. And the relationship between feldspathic sandstone content (x) and n could be described through an exponential function. The formula of n can be written as

$$(8)\qquad n = 1.8205e^{-0.035x},\ R^2 = 0.9142$$

where the parameter n can be predicted by feldspathic sandstone content.

Fig. 3. Effect of feldspathic sandstone addition on saturated hydraulic conductivity.



Changes in SHC

Figure 3 showed relationship between SHC and feldspathic sandstone content. Experimental results indicated that SHC decreased from 10.19 to 0.58 cm h^{-1} as feldspathic sandstone increased from 0% to 100% by volume. Vereecken (1995) has noted that particle size distribution powerfully affects the pore geometry and thereby the SHC. Table 1 showed that 96.80% of the sandy soil was sand grains, and that in feldspathic sandstone was only

Table 4. Fitted results of infiltration.

Treatment	Infiltration rate, i	R^2	Wetting front, X	R^2
S0	$i = 3.841t^{-0.57}$	0.971	$X = 6.901t^{0.54}$	0.997
S1	$i = 3.429t^{-0.62}$	0.984	$X = 5.912t^{0.50}$	0.999
S2	$i = 3.403t^{-0.52}$	0.965	$X = 4.278t^{0.60}$	0.995
S3	$i = 2.137t^{-0.51}$	0.996	$X = 3.997t^{0.58}$	0.992
S4	$i = 2.000t^{-0.57}$	0.960	$X = 3.329t^{0.50}$	0.998
S5	$i = 1.911t^{-0.55}$	0.917	$X = 2.988t^{0.51}$	0.999
S6	$i = 1.201t^{-0.48}$	0.976	$X = 2.241t^{0.50}$	0.997
S7	$i = 1.136t^{-0.52}$	0.982	$X = 2.105t^{0.48}$	0.999
S8	$i = 1.007t^{-0.57}$	0.966	$X = 1.699t^{0.46}$	0.999
S9	$i = 0.903t^{-0.56}$	0.979	$X = 1.616t^{0.45}$	0.994
S10	$i = 0.703t^{-0.52}$	0.950	$X = 1.174t^{0.48}$	0.997

Note: Infiltration rate was fitted by Kostiakov formula ($i = at^{-b}$), and wetting front by empirical equation ($X = a_1t^{b1}$).

28.95%, indicating more large pores in sandy soil and more small pores in the feldspathic sandstone. Furthermore, nearly 30% of the feldspathic sandstone was montmorillonite (Ma and Zhang 2016) which swells up when wet and closes up the channel between large pores. In addition, it was observed that the increase of feldspathic sandstone led to a sharp decrease of SHC when feldspathic sandstone was below 50%, and this tendency slowed down beyond this threshold, similar to the work by Yamada et al. (2011). It was assumed that when adding 50% of feldspathic sandstone, the clay would separate the sand grains and reduce the number of large pores in the soil significantly. Similar findings were concluded by Komine and Ogata (1999) and Sivapullaiah et al. (2000) after studying the mixing of sandy soil and bentonite and the lower threshold percentage, 20%, could be due to the higher content of montmorillonite in bentonite than in feldspathic sandstone.

To quantify the SHC in process of conditioning, Belkhatir et al. (2013) proposed linear relations between log(K) and clay content. A similar equation relating SHC and feldspathic sandstone content (x) was proposed here:

$$(9) \qquad K = 10.27e^{-3.285x}, \; R^2 = 0.9902$$

This empirical relation provided a simple and relatively accurate model to estimate the change of SHC with feldspathic sandstone addition from 0% to 100%. Therefore, this evaluation method can be used for designing the feldspathic sandstone content to achieve appropriate permeability.

Soil infiltration

The IR declined from a higher value dramatically at the beginning to a lower number after a period of time. Mazaheri and Mahmoodabadi (2012) proposed that the soil texture heavily influenced behavior of infiltration, and clay and silt percent increase significantly decreased the IR of the soil. The present study simulated IR with Kostiakov's infiltration function ($i = at^{-b}$), and the results in Table 4 displayed that the parameter a decreased with the increase of feldspathic sandstone and the parameter b was around 0.55. Feldspathic sandstone content (x) and parameters a matched an exponential function relationship, which can be written as

$$(10) \qquad a = 4.0528e^{-1.75x}, \; R^2 = 0.9719$$

This can be used for predicting the parameter a of Kostiakov's infiltration function at any feldspathic sandstone content.

Determining the migration distance (X) of the WF with the time (t) found that feldspathic sandstone delayed the forward speed of WF, indicating a significant inverse correlation between the migration rate of WF and the content of feldspathic sandstone. A power function was applied to describe the relationship between the forward distance and the time of WF depending on the previous research (Fok and Bishop 1965), and the equation was as follows:

$$(11) \qquad X = a_1t^{b1}$$

in which, X was the forward distance of WF (cm); t was time in minutes; a_1 and b_1 were function parameters of WF. The equation was then used to fit on the change of infiltration distance of WF with time in each treatment (Table 4) and the data revealed that feldspathic sandstone addition decreased the value of a_1. Meanwhile, feldspathic sandstone content and parameters a_1 met a very significant exponential function relationship:

$$(12) \qquad a_1 = 6.6333e^{-1.618x}, \; R^2 = 0.9883$$

This can be used for predicting the parameter a_1 of WF at any feldspathic sandstone content.

Best mixing ratio

Due to that loess is the main soil type for most vegetation in the research area, the present study cited the critical hydraulic parameters of the loess soil and compared them with those of the mixed soil in 11 treatments to select the optimized mixing ratio between sandy soil and feldspathic sandstone. SHC and SWC of the mixture in S4 almost matched that of loess ($K = 0.37$ mm min^{-1}; SWC = 0.38 cm^3 cm^{-3}; Zhao et al. 2016), and parameters θ_s, n, and α of SWRC in S4 and S5 were quite close to that of loess ($\theta_s = 0.479$; $n = 1.4$; $\alpha = 0.06$; Wang et al. 2015), indicating that treatment including 40% feldspathic sandstone resembled loess soil in terms of hydraulic features and could be the most optimal strategy in land restoration through addition of feldspathic sandstone into sandy soil.

Conclusion and Prospects

The addition of feldspathic sandstone into sandy soil increased clay content in the mixed sample. Further analysis revealed that feldspathic sandstone addition exhibited a positive correlation with SWC and FC, and a negative correlation with SHC and IR. In addition, the SWRC moved right with increasing of feldspathic sandstone and water retention in lower suction decreased dramatically. Several regression models were proposed to estimate the relationship between hydraulic parameters and the content of feldspathic sandstone. Feldspathic sandstone addition about 40%, optimally matching indices of loess soil, could be the most adaptive mixing strategy for sandy soil improvement in the research area.

This study affirmed that feldspathic sandstone could be used as physical soil conditioner to improve water-holding capacity of sandy soil. Knowledge of the effect of feldspathic sandstone on the hydraulic characteristics in the sandy soil can facilitate the management of sandy land control on the Loess Plateau.

Nevertheless, the present study only studied the change of soil hydraulic properties with addition of feldspathic sandstone, and did not take into consideration the hydraulic influence caused by different BD in various treatments. Also important is the study of swell–shrink characteristics of feldspathic sandstone and its role in establishing and applying the developed equations. Furthermore, the findings of this and similar studies must be transferred to the field.

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