Hydraulic characteristics and seepage modelling of clay pitchers produced in Jordan

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Abu-Zreig, M.M. and Atoum, M.F. 2004. **Hydraulic characteristics and seepage modelling of clay pitchers produced in Jordan.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **46**: 1.15-1.20. The use of clay pitchers for irrigation is gaining considerable interest in arid and semi-arid lands due to its simplicity and auto-regulative capabilities. The saturated hydraulic conductivity, Ks, of pitchers is considered the most important factor affecting the outflow rate from pitchers. The objectives of this study were to introduce a modified method of measuring Ks, survey hydraulic characteristics of locally produced pitchers, and develop a mathematical model that can predict seepage rate of pitchers from the pitcher's geometry and production temperature before field installation. A modified falling head method and a constant head method were used to measure the saturated hydraulic conductivity of 14 pitchers selected from local producers in Jordan, with varying size, shape, and production temperature. The two methods of measuring Ks were found to be accurate. However, the procedure of the falling-head method was faster and simpler. The hydraulic conductivity of pitchers was found to range between 0.219 and 2.37 mm/d. The values of Ks tended to increase with production temperature. Surface sanding of the pitcher wall was found to increase the value of Ks by about 30%. The seepage rate from the pitchers to the atmosphere ranged from 600 to 3700 mL/d, and was found to have a strong correlation with the pitcher's conductance. A mathematical conceptual model was developed to predict the seepage rates of pitchers from simple measurements and observations of the pitcher geometry. The model was first validated with measured conductance and other pitcher's properties in which the predicted seepage rate correlated very well with experimental data (R^2 = 0.97). The model prediction of seepage rate from the pitcher's volume, height, and predicted conductance, based on production temperature, was successful with R^2 = 0.56 and an average absolute error of 23%. This latter model can be used to estimate the pitcher's seepage rate before field installation. **Keywords**: pitcher irrigation, saturated hydraulic conductivity, falling head method, seepage rate.

L'utilisation de pots en argile pour l'irrigation connaît un gain de popularité dans les terres arides et semi-arides due à leur simplicité et leur capacités auto-régulatrices. La conductivité hydraulique saturée, Ks, des pots est considérée le facteur le plus important affectant le débit d'écoulement de ces pots. Les objectifs de cette étude étaient d'introduire une méthode modifiée pour mesurer Ks, de répertorier les caractéristiques hydrauliques de pots produits localement et de développer un modèle mathématique qui peut prédire le taux d'exfiltration des pots en fonction de leur géométrie et de la température de production avant leur installation au champ. Une méthode modifiée de charge hydraulique décroissante de même qu'une méthode sous charge hydraulique constante ont été utilisées pour mesurer la conductivité hydraulique à saturation de 14 pots sélectionnés chez des producteurs locaux en Jordanie et possédant différentes tailles, formes et températures de production. Les deux méthodes de mesure de Ks se sont avérées précises. Cependant, la procédure de la méthode sous charge hydraulique décroissante s'est révélée la plus rapide et la plus simple. La conductivité hydraulique des pots a varié entre 0,219 et 2,37 mm/j. Les valeurs de Ks avaient tendance à augmenter avec la température de production. Une surface sableuse des parois du pot augmentait la valeur de Ks d'environ 30%. Le taux d'exfiltration des pots à l'atmosphère variait de 600 à 3700 mL/j et présentait une forte corrélation avec la conductance du pot. Un modèle mathématique conceptuel a été développé pour prédire les taux d'exfiltration des pots à partir de simples mesures et observations de la géométrie des pots. Le modèle a été premièrement validé avec la conductance mesurée et d'autres propriétés des pots et le taux d'exfiltration prédit était très bien corrélé avec les données expérimentales (R^2 = 0,97). Le modèle de prédiction du taux d'exfiltration par le volume du pot, sa hauteur et sa conductance prédite, basé sur la température de production était précis avec un R^2 = 0,56 et une erreur absolue moyenne de 23%. Ce dernier modèle peut être utilisé pour estimer le taux d'exfiltration d'un pot en argile avant son installation au champ. **Mots clés**: irrigation par pot, conductivité hydraulique saturée, méthode de charge hydraulique décroissante, taux d'exfiltration.

INTRODUCTION

Pitcher irrigation is a traditional irrigation method that has been practised in many parts of the world such as India, Iran, Africa, and South America (Mondal 1974a, 1974b; Gischler and Jauregui 1984). Water is distributed from unglazed baked earthen pitchers buried in the soil. Pitchers gradually release water through their porous walls into the root zone by the action of static pressure and soil suction pressure. Pitcher irrigation is claimed to be a self-regulative system with a very high water saving potential and good capabilities for irrigation of various types of crops (Mondal 1978; Chigura 1994). Despite its apparent simplicity, factors affecting the system performance have not been well described and analyzed in the literature (Stein 1990). The authors of this work believe that the saturated hydraulic conductivity of clay pots is the key factor controlling the success of this irrigation method in the field.

Research efforts to understand the performance of pitcher irrigation and factors affecting water flow out of pitchers have been limited. The outflow of water is affected by many factors including the saturated hydraulic conductivity of the pitcher material, wall thickness, surface area, type of soil, type of crop, and rate of evapotranspiration. Stein (1997) conducted a laboratory experiment using 20 pitchers over a three month period to evaluate pitcher performance under different conditions. He found that the hydraulic conductivity and the surface area of the pitcher, amongst other factors, significantly affected the seepage rate from pitchers. He also found that

Table 1. Summary of physical characteristics of pitchers used in this study.

Pitcher name	Volume (mL)	Surface area (10^2 mm^2/d)	Height (mm)	Diameter† (mm)	Manufacturing temperature‡‡
A1	3360	1150	260	183	MH
A2	3060	1121	250	180	MH
A3	3150	1118	255	185	H
A4	3170	1123	265	180	H
A5	3210	1120	265	180	L
A6	3080	1120	265	180	H
A7	3090	1154	260	180	L
A8	3000	1194	240	183	ML
B1	6450	1665	300	205	H
B2	6400	1653	310	203	H
B3	5325	1569	275	195	ML
B4	6480	1692	330	200	ML
C1	6770	1835	270	245	L
C2	6820	1834	265	248	ML

† Maximum outside diameter
‡ Symbols for production temperature: L - low, M - medium, H - high

surface treatment, type of material and production process for the pitchers may cause variation in their saturated hydraulic conductivity by 18 orders of magnitude. Chigura (1994) reported that the seepage rate of some African and Ecuadorian pitchers were directly proportional to their saturated hydraulic conductivity.

Therefore, proper and accurate estimation of the saturated hydraulic conductivity of such clay pots is crucial. Unfortunately, there is no standard method found in the literature for evaluating the saturated hydraulic conductivity, Ks, of clay pots. Cliff-Hill (1985) and Usman (1986) used clay slabs constructed with similar materials and production processes as pitchers to estimate Ks of clay pots, while Stein (1990) and Chigura (1994) recommended that the whole pitcher should be used to measure Ks. They used a falling head permeameter to measure the saturated hydraulic conductivity; however, they did not explain the experimental procedure. It was not clear whether the whole pitcher was submersed in the water or how they estimated the surface area of the pitcher. Therefore, the objectives of our research were to establish a standard method for measuring the values of saturated hydraulic conductivity of various pitchers and to evaluate factors affecting those hydraulic conductivity values and therefore the seepage rate of pitchers.

The seepage rate of a pitcher has been shown to vary widely depending on geometry, materials and production process (Chigura 1994; Stein 1997). Estimation of the seepage rate of pitchers before field installation is necessary for successful application of a pitcher irrigation system. Therefore, another objective of this work was to develop a model that can predict daily seepage of pitchers before field installation.

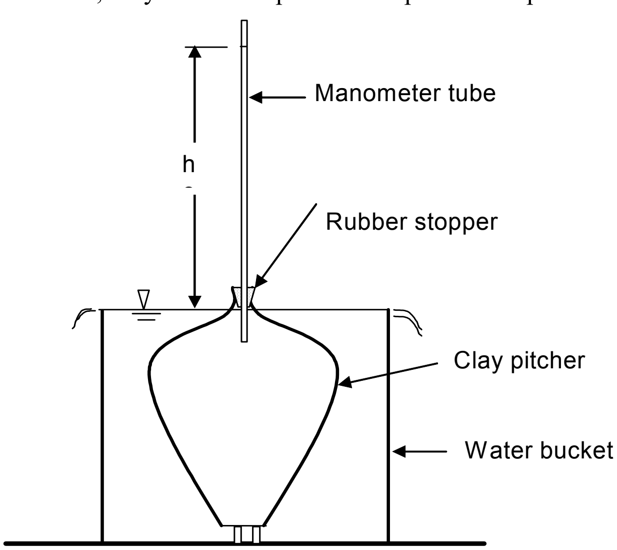

Fig. 1. Schematic diagram of the falling head permeameter used to measure the saturated hydraulic conductivity of the pitchers.

MATERIALS and METHODS

Fourteen pitchers of varying shape, volume, and production process were selected from local producers. The pitchers were categorized as A, B, and C depending on their general shape and water capacity. Type A pitchers are the most popular in Jordan while type B and C were chosen to test the influence of pitcher shape on its hydraulic performance. The pitcher volume varied from about 3 to 6.8 L. The average pitcher height and maximum outside diameter were about 270 and 200 mm, respectively. The average basal diameter of all pitchers was 100 mm. The production process is qualitatively categorized using production temperature as high, medium, and low. This division was based on personal contact with the producers and the colour of the pitcher. As the production temperature increased, the colour of pitchers turned from red to green. The physical descriptions of the fourteen pitchers are summarized in Table 1.

Falling head method

A modified falling head method was adapted to measure the saturated hydraulic conductivity of the whole pitcher using tap water. Pitchers were first submersed, with the pitcher full of water, in a tap water bath for three days for saturation. After that the pitcher, full of water, was submersed to its neck in a water bucket for the purpose of hydraulic conductivity measurement. The water level in the bucket was kept constant by means of overflow. A manometer tube was inserted into a rubber stopper and fitted tightly to the mouth of the pitcher. A schematic diagram of the experimental setup is shown in Fig. 1.

Changes in the water head, which is the height of water level in the manometer tube above the free water surface of the bucket, were monitored with time. The falling head equation for calculation of Ks is given by Eq. 1 (Stein 1990):

$$\ln\left(\frac{h}{h_o}\right) = \frac{AKs}{aL}t \qquad (1)$$

where:

h_o = original height of water level in manometer tube above free water surface (m),

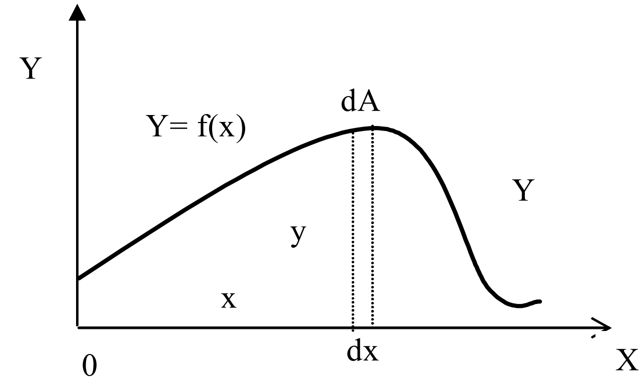

Fig. 2. Diagram showing the mathematical calculation of pitcher surface area. A is the surface area; Y is the outside radius; x is the depth of water.

h = height of water in manometer tube at time t (m),
A = surface area of pitcher (m^2),
a = cross-sectional area of manometer tube (m^2),
L = average wall thickness of the pitcher (m),
Ks = saturated hydraulic conductivity (m/s), and
t = cumulative time (s).

A plot of $\ln(h/h_o)$ versus time, t, gives a straight line. The Ks of pitchers can be calculated from the slope of the line if the other terms L, A, and a are known.

The thickness of the pitcher, L, was estimated by breaking up several pitchers and measuring the thickness of the fractured pieces with a calliper. The average thickness of pitchers varied from 6 to 7 mm. An average wall thickness of 6.5 mm was used to estimate saturated hydraulic conductivity in Eq. 1.

The most difficult parameter to estimate was the surface area of the pitchers. Two methods were used to estimate the surface area. The first method consisted of winding a nylon rope with a diameter of about 5 mm tightly around the pitcher and then measuring the length of the rope. The surface area was then equal to the length of the rope multiplied by its diameter plus the basal area. A second method was to draw a curve of the pitcher surface as a function of its height, as shown in Fig. 2. The external radius of the pitcher was then calculated for each incremental height. The surface area of each increment and therefore the whole pitcher surface area was calculated by surface integration using Eq. 2.

$$A_i = 2\pi Y_i \left(X_i - X_{i-1} \right)$$

$$A = \sum_{i=1}^{n} A_i + 2\pi r^2 \tag{2}$$

where:
A_i = incremental surface area (m^2),
A = total surface area of pitcher (m^2),
Y_i = external radius of ith segment (m),
X_i = height of ith segment above base of pitcher (m), and
r = radius of base of pitcher (m).

The two methods were applied on two different pitchers giving almost identical results with absolute differences ranging from 40 to 80 mm^2. However, estimating the incremental surface area as a function of height is necessary if a constant head method is to be used for measuring Ks as is explained in the following section.

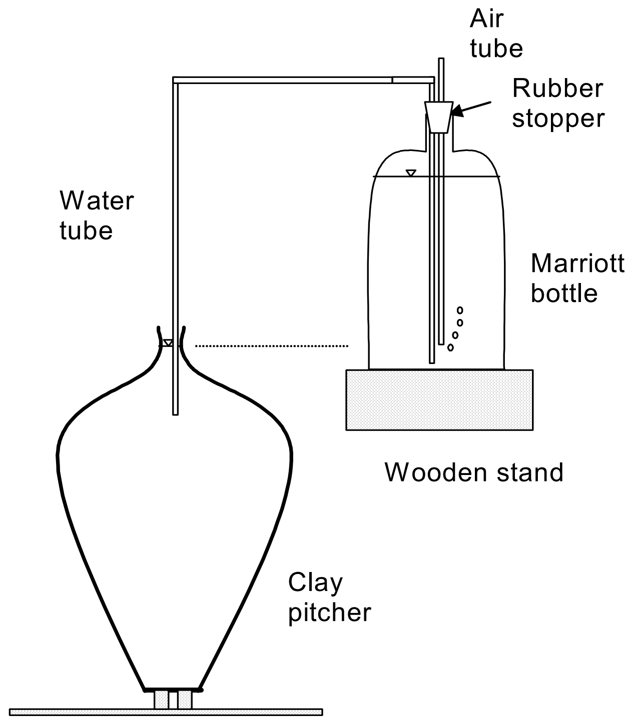

Fig. 3. Schematic diagram for measurements of saturated hydraulic conductivity of pitchers by constant head method.

Constant head method

A constant head approach was also used to measure the saturated hydraulic conductivity of the pitchers. In this method, a pitcher was placed in the atmosphere and the outflow rate of waterflow was measured under constant head condition. The constant head was maintained with a Marriott bottle arrangement, as shown in Fig. 3. The daily seepage volume out of a pitcher is equal to the decrease in water volume in the Marriott bottle. Constant head tests were done on four of the 14 pitchers (A5, A7, B4, and C2).

The saturated hydraulic conductivity was estimated by applying Darcy's law on the outflow rate of the pitcher at constant head condition. However, the head at the inner surface of the pitcher varied with water depth. Therefore, Darcy's law must be applied for each segmental area having a specific incremental head (Eq. 3).

$$Q = \frac{Ks}{L}\left[2\pi r^2 (H - hs) + \sum_{i=1}^{n} A_i \left(x_i - hs \right) \right] \tag{3}$$

where:
Q = seepage rate out of pitcher (m^3/s),
n = number of segments for a pitcher;
x_i = average pressure head for segment i, equal to the depth of water tocentre of ith segment (m),
hs = pressure head at outer surface of pitcher (m), and
H = total water depth in pitcher (m).

Table 2. Saturated hydraulic conductivity, conductance, and daily seepage of pitchers used in this study.

Pitcher name	Saturated hydraulic conductivity† (mm/d)	Conductance‡ (10^2 mm^2/d)	Daily free seepage§ (mL)
A1	0.914	161.96	1290
A2	0.539	92.97	960
A3	1.007	173.22	1300
A4	1.020	176.21	1350
A5	0.219 (0.201)¶	37.38	600
A6	0.952	164.02	13000
A7	1.171 (1.102)¶	207.87	1910
A8	1.678	308.17	2370
B1	2.220	568.54	3050
B2	2.370	602.86	3200
B3	0.817	197.25	2200
B4	0.713 (0.746)¶	185.60	2240
C1	0.442	124.78	1500
C2	0.858 (0.821)¶	262.11	3700

† Saturated hydraulic conductivity measured by falling head method
‡ Conductance equal to Ks x surface area/wall thickness of pitcher
§ Outflow volume when pitcher is filled with water and left in the air for 24 h
¶ Measured with constant head method

Surface sanding of pitchers

Surface sanding on the wall of two pitchers, C1 and C2, was performed to assess its influence on Ks. The pitchers were roughened with sand paper to remove the smooth surface that usually occurred during the production process. Removal of the smooth layer by sandpaper has negligible effect on the wall thickness of pitchers. The pitchers were then cleaned, re-saturated, and Ks was measured again with the falling head procedure.

Free seepage measurements

Another set of experiments was conducted using the same 14 pitchers to estimate the free seepage volume of pitchers under atmospheric pressure. The free seepage volume can be correlated to seepage volume of pitchers through soil under field conditions. Pitchers were filled with water and left in the atmosphere. After 24 hours, the amount of water that seeped from the pitcher was determined by measuring the volume of water required to fill the pitchers. This procedure was repeated several times and the average seepage volume was recorded. These experiments were designed to correlate outflow volume with the pitcher hydraulic parameters Ks and conductance. Conductance (CD) is equal to Ks multiplied by surface area and divided by the wall thickness of pitchers, thereby lumping together the effect of Ks, surface area, and wall thickness. The units of conductance (m^2/s), suggest that it has a similar effect to that of dispersion coefficient and it may correlate well with the seepage rate of the pitcher (Young and Sisson 2002).

RESULTS and DISCUSSION

The physical characteristics of pitchers used in this study are summarized in Table 1. Three types of pitchers that varied in surface area, volume, and maximum radius to height denoted by A, B, and C were used. The average volumes of A, B, and C pitchers were 3350, 6400, and 6800 mL, respectively, whereas the surface area varied from 1150 x 10^2 mm^2 for A pitchers to 1835 x 10^2 mm^2 for C class pitchers. The production temperature for each pitcher was also qualitatively specified and denoted by High (H), medium high (MH), Low (L), and medium low (ML). The production temperature is expected to have a significant influence on the saturated hydraulic conductivity of pitchers.

The saturated hydraulic conductivity of pitchers and conductance are shown in Table 2. The Ks varied from 0.219 mm/d to as high as 2.37 mm/d, whereas conductance of pitchers varied from 38 x 10^2 mm^2/d for the A5 pitcher to 653 x 10^2 mm^2/d for pitcher B2. The wide variations in Ks and conductance should result in wide variations of seepage volume of pitchers. This condition is a necessary requirement for studying the correlation between seepage volume of pitchers and their conductance.

Saturated hydraulic conductivity and conductance seemed to increase, qualitatively, with the production temperature. During the experiment, green coloured pitchers produced at high temperature always gave high Ks values compared to red ones, produced at low temperature. The average saturated hydraulic conductivity of all pitchers produced at low temperature, denoted by L and ML in Table 1, was 0.79±0.47 mm/d compared to 1.22±0.71 mm/d for the pitchers produced at high temperature, donated by H and MH.

The two methods of Ks measurement, falling and constant head, gave similar results for the four pitchers selected from each group, as shown in Table 2. The Ks of pitcher A5, A7, B4, and C2 measured with the falling head method were 0.22, 1.17, 0.71, and 0.86 mm/d compared to 0.20, 1.10, 0.75, and 0.82 mm/d for the constant head method, respectively. However, the falling head method was faster and simpler than the constant head method since measuring the outer surface of the pitcher as a function of height, required for the constant head method, was quite difficult. Nevertheless, the two procedures proved to be valid and accurate in Ks measurements.

The free seepage volume of the pitchers, under atmospheric pressure and falling head conditions (Table 2), varied from 600 to as high as 3700 mL/d. Seepage volume was directly and linearly proportional to pitcher conductance (CD) for all types of pitchers (Fig. 4). However, the linear relationship varied amongst each group. A linear regression between seepage rate, Q (mL/d), and conductance, CD (mm^2 x 10^2/d), was performed for A and B type pitchers only, since there were only two pitchers of type C. The results are shown in Eqs. 4 and 5, respectively, for A and B type pitchers.

$$Q = 6.7CD + 282 \qquad (R^2 = 0.95) \tag{4}$$

$$Q = 2.3CD + 1779 \qquad (R^2 = 0.99) \tag{5}$$

The standard errors of estimate (SE) for Eqs. 4 and 5 were 134 and 49 mL/d, respectively. This low SE with high R^2 values indicates a significant relationship between Q and CD within the

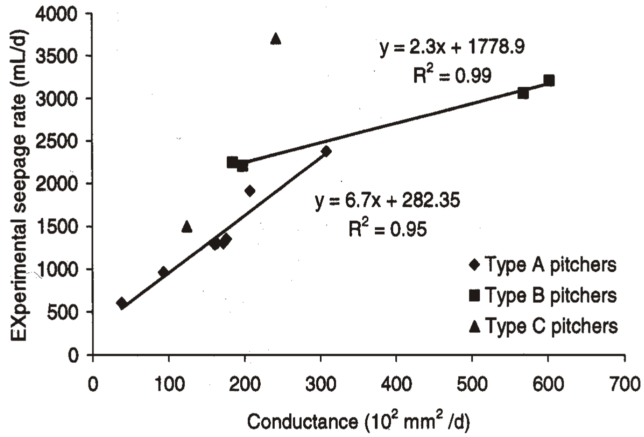

Fig. 4. Relationship between free seepage rate and conductance for pitchers used in this study.

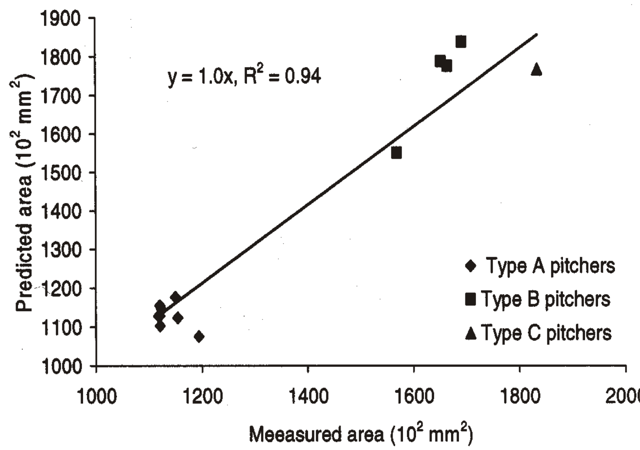

Fig. 6. Comparison of measured area of pitcher and predicted area based on pitcher volume and height.

range found in pitchers produced in Jordan. The regression coefficients for the A and B pitchers were 67 and 23 mm, respectively, have a dimension of length, and could be interpreted as the effective head driving water from the pitcher. These differences in effective head value may be attributed to the pitchers geometry and variation in wall resistance to flow. These equations should only be applied to pitchers of similar shape, wall thickness, and production method as described in this paper.

A physically based daily seepage model is proposed here. It is possible to predict daily seepage based on simple measurements of the pitcher's geometry including, volume, height, and wall thickness as well as manufacturing temperature. First, an index numbering system is assigned to manufacturing temperatures in which numerical values of 0, 1, 2, 3, and 4 are given to L, ML, M, MH, and H, respectively. This procedure is necessary in order to correlate hydraulic conductivities of pitchers to its manufacturing temperature. A weak but positive correlation between temperature and Ks_p exists (Fig. 5). The second step is to estimate the surface area of the pitchers from their volume and height. The estimated total surface area, As_p, is the sum of the side surface area ($As = 2\pi Reh$) and the basal area ($Ab = \pi Re^2$) where Re is the equivalent radius found from the equivalent cross sectional area, which is equal to pitcher volume divided by its height, h. A plot and regression analysis between the estimated surface area and measured values, shown in Fig. 6, gave good agreement; $As_p = 0.91As$ with $R^2 = 0.94$. Thirdly, the pitcher's conductivity values, CD_p, can be predicted using Ks_p (Fig. 5) and As_p (Fig. 6), from Eq. 6.

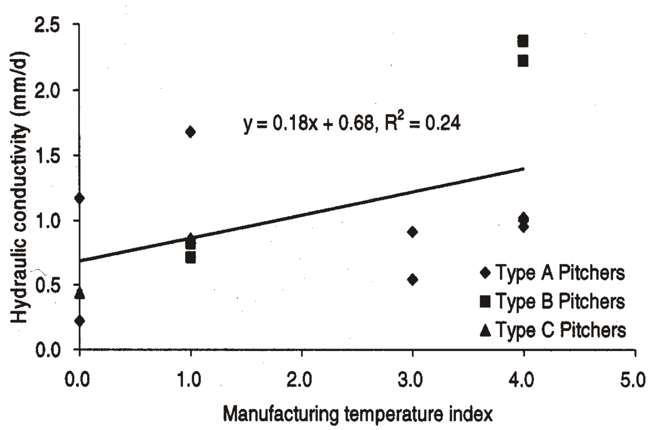

Fig. 5. Correlation between hydraulic conductivities and manufacturing temperature index of pitchers: L=0, ML=1, M=2, MH=3, and H=4.

$$CD_p = \frac{Ks_p As_p}{L} \tag{6}$$

where L = wall thickness of pitchers (6.5 mm). Finally, the pitcher's seepage is predicted from the previous data using::

$$Q_p = \frac{A_b}{As_p} CD_p h + \left[1 - \frac{A_b}{As_p}\right] CD_p h_{ep} \tag{7}$$

where h_{ep} = equivalent effective head that has to be predicted from the pitcher's geometry and is a fraction of the pitcher's height h; that is $h_{ep} = f\,h$. A best fit function has been found by taking f equal to 0.1, 0.2, and 0.3 for pitchers A, B, and C, respectively. The predicted daily seepage rates using Eq. 7, as plotted against measured rates, Q, are shown in Fig. 7. The linear correlation between Q_p and Q has an $R^2 = 0.56$, an equation of $Q_p .= 0.8Q + 147$, and a statistical analysis at 0.05 significant level showed that the line slope and intercept were not significantly different than 1 and 0, respectively. The absolute overall error between Q_p and Q was about 23% on average. Further simplification on seepage calculations can be done by taking an average value of f = 0.2 for all types of pitchers; this would increase the absolute average error to about 30% only.

The seepage rate of pitchers can be modified by simple roughening of the outer surface of pitchers to remove the smooth finish left by the production process. Surface roughening resulted in a 30% increase in the Ks value (Fig. 8). The increase in Ks resulting from sanding is likely due to removal of a more impermeable layer, composed of smaller pores, existing at the surface of the pitchers.

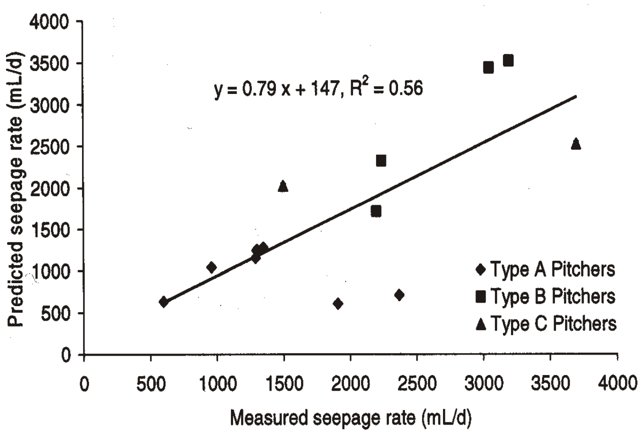

Fig. 7. Seepage rate of pitchers predicted from geometry and manufacturing temperature compared with experimental values.

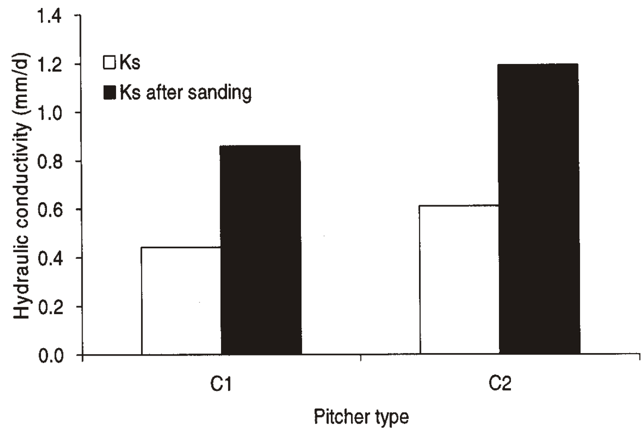

Fig. 8. Influence of surface roughening of pitchers on saturated hydraulic conductivity.

CONCLUSIONS

The saturated hydraulic conductivity (Ks) of 14 clay pitchers, with varying shape, volume, and production temperature, obtained from local producers in Jordan was measured with a modified falling head and constant head permeameters. Falling and constant head methods gave similar results but the falling head method was simpler and faster than the constant head method. The Ks of pitchers ranged from 0.219 to 2.37 mm/d. Accordingly, the free seepage rate of pitchers under atmospheric pressure ranged from 600 to 3700 mL/d. Seepage rates were directly and linearly related to the pitcher's conductance. The coefficient of determination (R^2) between seepage rate and conductance for A and B type pitchers were 0.95 and 0.99, respectively. Experimental observations showed that Ks tended to increase with the production temperature. The surface sanding of two pitchers resulted in a 30% increase in Ks.

A conceptual physically based model was developed to predict seepage rate of pitchers from conductance based on simple geometry and production temperature of pitchers. The model was successful considering the inherent variabilities in pitcher's material and manufacturing process with R^2 of 0.56 and average absolute error of 23%. The results presented herein can be used to estimate the seepage rate of a pitcher from its geometry and manufacturing temperature before installing it in the field.

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