VPLIV OBLIKE IN VELIKOSTI ZRN PESKOV NA HIDRAVLIČNO PREPUSTNOST

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Ključne besede

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Izvleček

Clij pričujoče študije je preiskati vpliv nekaterih fizikalnih lastnosti peskov (npr., velikost, oblika) na hidravlično prepustnost (k). Članek prikazuje rezultate obsežnih eksperimentalnih preiskav izvedenih z uporabo zrn peskov različnih velikosti in oblik. Preiskana so bila tri različna območja velikosti zrn (0.60 mm - 1.18 mm, 1.18 mm - 2.00 mm in 0.075 mm - 2.00 mm) peskov (i. drobljeni kamniti pesek, CSS; ii. pesek Trakya, TS; iii. pesek Narli, NS; iv. peleti elektrofiltrskega pepela, FAP; v. pesek Leighton Buzzard, LBS) z različnimi oblikami, vključno z okroglostjo, R, in sferičnostjo, S (R_i=0.15, S_i=0.55; R_{ii}=0.43, S_{ii}=0.67; R_{iii}=0.72, S_{iii}=0.79; R_{iv}=0.65, S_{iv}=0.89; R_v=0.78 S_v=0.65) v aparatu za določitev koeficienta prepustnosti s konstantno hidravlično višino pri relativni gostoti (D_r) okoli 35% in konstantno temperaturo prostora (20°C). Eksperimentalni rezultati so pokazali, da imajo peski z različnimi oblikami zrn (R, S) in enakih velikosti zrn ter granulometrije (c_c, c_u, D_{10}, D_{30}, D_{50}, D_{60}) različne vrednosti koeficientov hidravlične prepustnosti k. Fotografije posnete z vrstičnim elektronskim mikroskopom (Scanning Electron Microscope - SEM) kažejo fizikalne razlike / podobnosti med peski, ki so bili uporabljeni v tej preiskavi. Predstavljena je tudi primerjalna študija rezultatov preskusov in ocenjenih vrednosti hidravličnih prepustnosti z uporabo empiričnih enačb nekaterih raziskovalcev razvitih za oceno hidravlične prepustnosti tal.

EFFECTS OF THE PARTICLE SHAPE AND SIZE OF SANDS ON THE HYDRAULIC CONDUCTIVITY

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Keywords

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Abstract

This study aims to investigate the effects of some physical properties of sands (e.g., size and shape) on the hydraulic conductivity (k). The paper presents the results of an extensive series of experimental investigations performed using sands with different sizes and particle shapes. Three different particle size ranges (0.60- 1.18 mm, 1.18- 2.00 mm, and 0.075- 2.00 mm) of sands (i. Crushed Stone Sand, CSS; ii. Trakya Sand, TS; iii. Narli Sand, NS; iv. Fly Ash Pellets, FAP; v. Leighton Buzzard Sand, LBS) having distinct shapes, including roundness, R, and sphericity, S (R_i=0.15, S_i=0.55; R_{ii}=0.43, S_{ii}=0.67; R_{iii}=0.72, S_{iii}=0.79; R_{iv}=0.65, S_{iv}=0.89; R_v=0.78 S_v=0.65) were tested in a constant-head permeability testing apparatus at a relative density (D_r) of about 35% and constant room temperature (20°C). The experimental results showed that the sands having different shapes (R, S) with the same size and gradation characteristics (c_c, c_u, D_{10}, D_{30}, D_{50}, D_{60}) result in different k values. The scanning electron microscope (SEM) images indicate the physical differences/similarities among the sands used during this investigation. A comparative study of the tests results and the estimated hydraulic conductivity values using empirical equations previously developed for the hydraulic conductivity prediction of soils by certain researchers are presented.

1 INTRODUCTION

Water is free to flow through the pores between soil particles in accordance with the Darcy's empirical law (*q=Aki*). The hydraulic conductivity or coefficient of permeability (*k*) depends basically on the average size of the pores through the soil matrix and the temperature of the environment. It widely known that the hydraulic conductivity is related to the grain-size distribution of the soil grains [1]. In general, the smaller the soil grains, the lower is the coefficient of permeability. The presence of a fines content in a coarse-grained soil results in a *k* value significantly lower than that for the same soil without fines. The *k* value also changes with temperature, upon which the viscosity of the fluid (i.e., water) is dependent [2- 4]. From clay to gravels, the *k* value increases over many orders of magnitude. Typical *k* values for different soils are within the ranges shown in Table 1.

Because of its importance in some geotechnical problems, including the determination of seepage losses, settlement computations, and stability analyses [5], many field and laboratory investigations of permeability have been made [6- 19]. For example, Hazen [6, 7] developed an empirical formula ($k=cD_{10}^2$) for

Table 1. Coefficient of permeability, *k* (m/s) [13].

	Permeability (m/s)											
	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}
Drainage	Good							Poor		Practically impervious		
Soil Types	Clean gravel		Clean sands, cleansand & gravel mixtures			Very fine sands, organic & inorganic silts, mixtures of sand silt & clay, glacial till, stratified clay deposits, etc.				Impervious soils e.g., homogeneous clays below zone of weathering		
					"Impervious" soils modified by effects of vegetation & weathering							

predicting the hydraulic conductivity of saturated sands. Kozeny [8], and Carman [9, 10], who presented widely accepted derivations for permeability, developed a semi-empirical formula for predicting the permeability of porous media. Goktepe and Sezer [15] have recently proposed a new method for obtaining the shape coefficient for the Kozeny-Carman equation. Shepherd [17] conducted statistical power-regression analyses on 19 sets of published data on the hydraulic conductivity of unconsolidated sediments vs. grain size. Alyamani and Sen [19] proposed an equation based on an analysis of 32 samples incorporating the initial slope and the intercept of the grain-size distribution curve. Sperry and Peirce [20] developed a model for delineating the importance of particle size/shape, and porosity in explaining the variability of the hydraulic conductivity of a granular porous medium. They concluded that the Hazen equation provides the best estimate of the hydraulic conductivity of the media studied, except for the irregularly shaped particles. Ishaku et al. [21] have recently employed several empirical formulae to specify the hydraulic conductivity of aquifer materials in the field. They stated that the most accurate estimation of the hydraulic conductivity was found using the Terzaghi equation, followed by the Kozeny-Carman, Hazen, Breyer and Slitcher equations, respectively. Although many different techniques have been proposed to determine its value, including field methods (the pumping-of-wells test, the auger-hole test and the tracer test), laboratory methods (the falling-head test, the constant-head test), and calculations from the empirical formulae of Todd and Mays [22], an accurate estimation of hydraulic conductivity, particularly in the field, is inadequately quantified. Applications of these empirical formulae to the same porous medium material can yield different values of hydraulic conductivity due to the difficulty of including all possible variables in the porous media Vukovic and Soro [23].

It has long been understood that particle shape characteristics have a significant effect on the engineering properties of the soil matrix [24- 29]. Terzaghi [24] was one of the first engineers to make an investigation to understand the shape characteristics using flat-grained constituents. The observations made by Gilboy [25] that any system of analysis or classification of soil that neglects the presence and effect of the shape will be incomplete and erroneous. Numerous researches have carried out investigations, because of the importance of particle shape and its role in the behaviour of sands for practicing engineers and researchers in helping to estimate soil behaviour. Holubec and D'Appolinia [30] showed that the results of dynamic penetration tests in sands depend on the particle shape. Cornforth [31], and Holtz and Kovacs [32] demonstrated how particle shape impacts on the internal fiction angle (φ). Cedergren [33] pointed out that particle shape affects the permeability. Particle shape also plays a significant role in the liquefaction potential [34]. Wadell [35], Krumbein [36], Powers [37], Holubec and D'Appolinia [30], Youd [38], and Cho et al. [39] have introduced detailed explanations for the particle shape. Two independent properties are typically employed to describe the shape of a soil particle: (i) roundness is a measure of the extent to which the edges and corners of a particle have been rounded, and (ii) sphericity (form) describes the overall shape of a particle, since it is a measure of the extent to which a particle approaches the shape of a sphere. Wadell [35] proposed a simplified sphericity (S) parameter, ($D_{max\text{-}insc}/D_{min\text{-}circ}$), where $D_{max\text{-}min}$ is the diameter of a maximum inscribed circle and $D_{min\text{-}circ}$ is the diameter of a minimum sphere circumscribing a gravel particle. Wadell [35] defined the roundness (R) as $D_{i\text{-}ave}/D_{max\text{-}insc}$, where $D_{i\text{-}ave}$ is the average diameter of the inscribed circle for each corner of the particle. Figures 3-5 describe R, S and a chart for a comparison between them to determine the particle shape [36, 37].

A widely know aspect of hydraulic conductivity equations in the literature is the determination of an empirical relationship between the hydraulic conductivity and the porosity, the effective diameter, or a portion of the grain size distribution curve, etc. However, these parameters cannot yield consistent results with respect to the actual hydraulic conductivity values. Therefore, this paper attempts to relate the grain size, and in particular the shape parameters (i.e., roundness, sphericity), to hydraulic conductivity estimates. The major objectives of this study are, first, to conduct a number of permeability tests in the laboratory using sands artificially graded to certain size ranges to provide uniform specimens for classification purposes, and second, to relate the test results to hydraulic conductivity estimates.

2 EXPERIMENTAL STUDY

The materials used in the tests described in this study were Crushed Stone Sand (CSS), Trakya Sand (TS), Narli Sand (NS), Fly Ash Pellets (FAPs), Leighton Buzzard Sand (LBS) having distinct shapes and sizes falling between 0.60 mm and 1.18 mm, 1.18 mm and 2.00 mm, and 0.075 and 2.00 mm. Figure 1 indicates the particle size distribution of the sands used during the experimental study. Some properties (D_{10} , D_{30} , D_{60} , c_u, c_c , G_s , e_{max} , e_{min}) of the sands including roundness (R) and sphericity (S) estimations based on the study by Muszynski and Vitton [47] are listed in Table 2. Scanning electron microscope (SEM) images show the physical differences/similarities among the sands used during this investigation (Figure 2). The sands were tested using a constant-head permeability testing apparatus at a relative density (D_r) of about 35% and constant room temperature (20°C). The specimens, at the required

Table 2. Summary of the specimen data.

Sample	Gradation (mm)	USCS	G_s	e_{max}	e_{min}	especimen	dspecimen (g/cm^3)	R	S	k (cm/sec)
CSS	0.075-2.00	SW	2.66	0.787	0.435	0.664	1.599	0.15	0.55	0.189
	1.18-2.00	SP		0.900	0.604	0.796	1.481			1.259
	0.6-1.18	SP		1.013	0.668	0.892	1.406			0.418
TS	0.075-2.00	SW	2.65	0.744	0.450	0.641	1.615	0.43	0.67	0.173
	1.18-2.00	SP		0.874	0.627	0.788	1.483			1.231
	0.6-1.18	SP		0.931	0.679	0.843	1.438			0.375
NS	0.075-2.00	SW	2.68	0.581	0.335	0.495	1.793	0.72	0.79	0.139
	1.18-2.00	SP		0.720	0.506	0.645	1.629			1.097
	0.6-1.18	SP		0.795	0.543	0.707	1.570			0.296
FAP	0.075-2.00	SW	1.75	1.091	0.734	0.966	0.890	0.65	0.89	0.269
	1.18-2.00	SP		1.168	0.856	1.059	0.850			1.458
	0.6-1.18	SP		1.280	0.916	1.153	0.813			0.597
LBS	0.6-1.18	SP	2.65	0.842	0.525	0.731	1.531	0.78	0.65	0.323

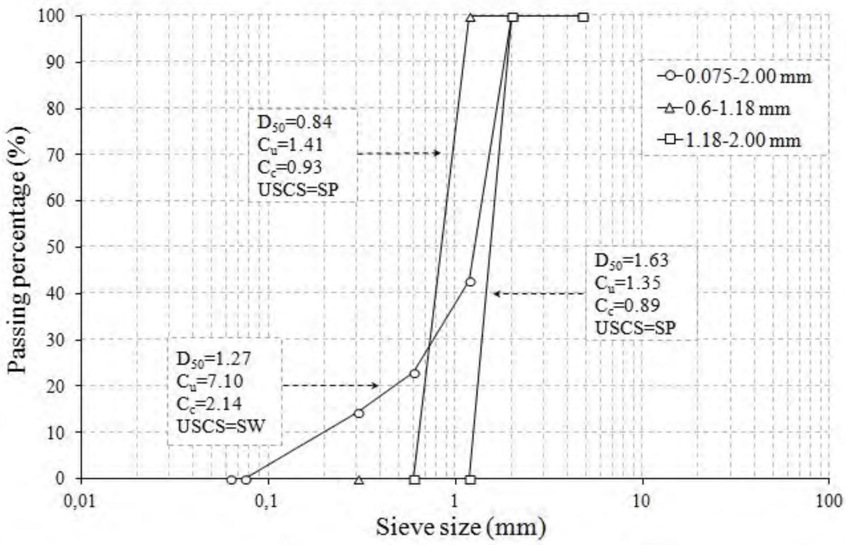

Figure 1. Particle size distribution for the sands used during the experimental study.

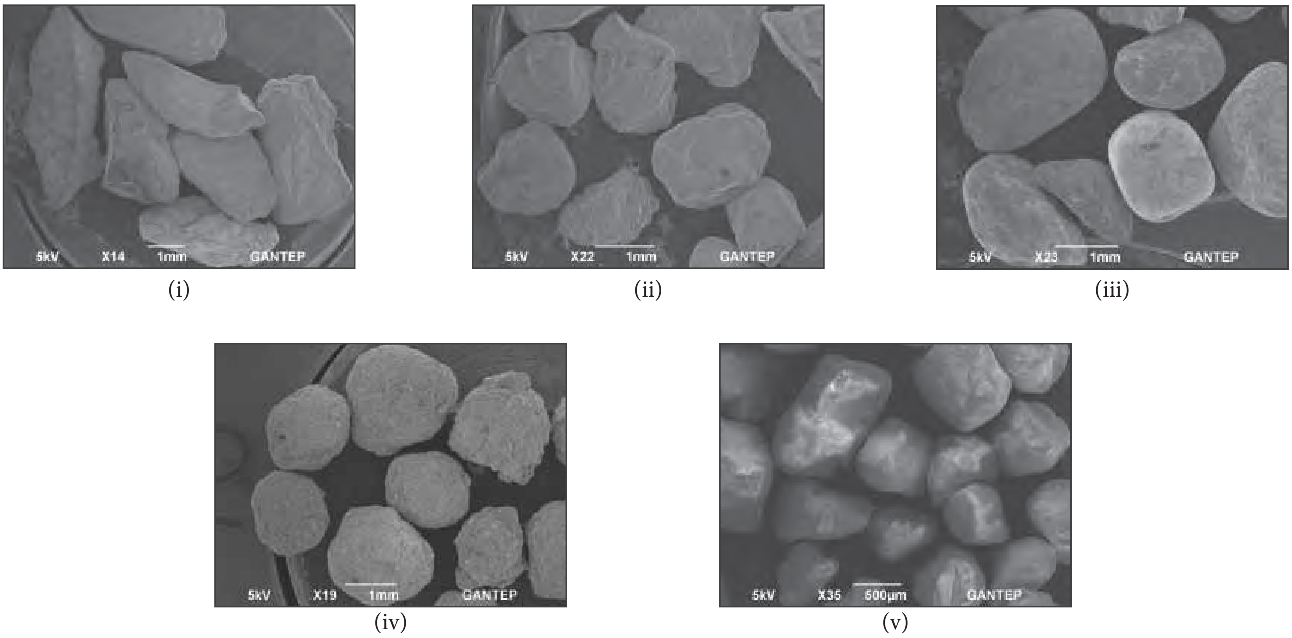

Figure 2. Scanning Electron Microscopy (SEM) images of the sands used during the experimental study (i- Crushed Stone Sand, ii. Trakya Sand, iii- Narli Sand, iv- Fly Ash Pellets, v- Leighton Buzzard Sand).

relative density (35%), are placed in a plexiglass cylindrical cell of about 50 cm^2 cross-sectional area (A). The specimens rest on a wire mesh at the bottom of the cell, which is a square grid of uniformly placed wires. The volume of the water (q) flowing during a certain time (t) is measured when a steady vertical water flow, under a constant head, is maintained through the soil specimen. Then, the k values of the specimens tested were calculated using Darcy's law ($k=ql/Ah$).

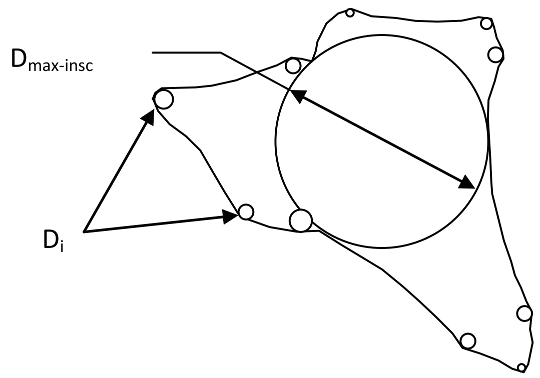

Figure 3. Graphical representation of roundness, *R* (redrawn from Muszynski and Vitton [47]).

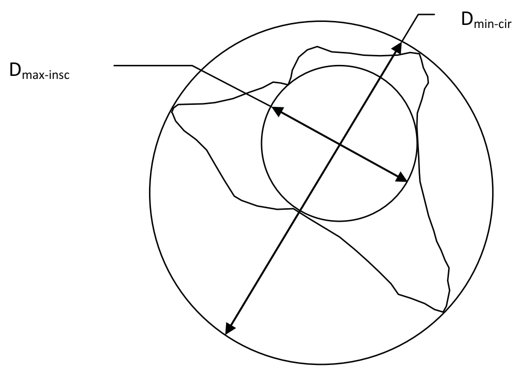

Figure 4. Graphical representation of sphericity, *S* (redrawn from Muszynski and Vitton [47]).

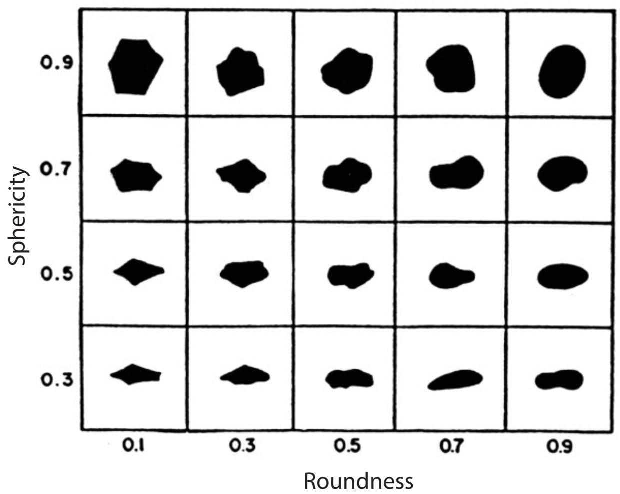

Figure 5. Comparison chart [49].

3 RESULTS AND DISCUSSION

Table 2 gives a summary of the specimens used in the tests reported here. The initial relative densities of all the specimens were around 35%. The specimens were loose to medium dense. Three different sizes of artificially graded CSS, TS, NS, FAP, and LBS sands, which have exactly the same gradation characteristics (D_{10} , D_{30} ,

Table 3. Empirical equations and their predictions on the sands tested in this paper.

Researcher/ Organization	Equation	Sample	k (cm/sec) 0.6-1.18 mm	k (cm/sec) 1.18-2.00 mm	k (cm/sec) 0.075-2.00 mm
Hazen	$k=6\times10^{-4}x\frac{g}{v}x\left[1+10\left(n-0.26\right)\right]x\left(d_{10}\right)^2$	LBS*	0.6349	-	-
		TS⁻	0.7196	2.5909	0.0545
		NS⁺	0.6151	2.1434	0.0404
		CSS[1]	0.7540	2.6162	0.0565
		FAP[2]	0.9087	3.2713	0.0783
Kozeny-Carman	$k=8.3\times10^{-3}x\frac{g}{v}x\left[\frac{n^3}{\left(1-n\right)^2}\right]x\left(d_{10}\right)^2$	LBS	0.7556	-	-
		TS	1.0872	3.4910	0.0525
		NS	0.6926	2.0844	0.0265
		CSS	1.2566	3.5916	0.0575
		FAP	2.3808	7.3642	0.1500
Terzaghi	$k=0.0084\,x\frac{g}{v}x\left[\frac{n-0.13}{\sqrt[3]{1-n}}\right]^2x\left(d_{10}\right)^2$	LBS	0.3229	-	-
		TS	0.4220	1.4208	0.0242
		NS	0.3022	0.9576	0.0135
		CSS	0.4676	1.4507	0.0260
		FAP	0.7181	2.3895	0.0525
Chapuis	$k=1.5x\left(d_{10}\right)^2x\frac{e^3}{1+e}x\frac{1+e_{max}}{\left(e_{max}\right)^3}$	LBS	0.4279	-	-
		TS	0.4776	1.7980	0.0408
		NS	0.4541	1.7625	0.0392
		CSS	0.4466	1.7176	0.0387
		FAP	0.4751	1.8385	0.0443
Slitcher	$k=1\times10^{-2}x\frac{g}{v}x\,n^{3.287}x\left(d_{10}\right)^2$	LBS	0.2372	-	-
		TS	0.3082	1.0403	0.0179
		NS	0.2224	0.7093	0.0104
		CSS	0.3408	1.0617	0.0192
		FAP	0.5175	1.7296	0.0381
USBR	$k=4.8\times10^{-3}x\frac{g}{v}x\left(d_{20}\right)^{0.3}x\left(d_{20}\right)^2$	LBS	0.2535	-	-
		TS	0.2535	1.0882	0.1048
		NS	0.2535	1.0882	0.1048
		CSS	0.2535	1.0882	0.1048
		FAP	0.2535	1.0882	0.1048
NAVFAC	$k=10^{1.291e-0.6435}x\left(d_{10}\right)^{10^{(0.5504-0.2937e)}}$	LBS	0.7593	-	-
		TS	1.1357	3.7613	0.0376
		NS	0.6953	2.5811	0.0166
		CSS	1.3549	3.8503	0.0426
		FAP	3.3791	7.7911	0.2052
Alyamani & Sen	$k=1300x\left[l_0+0.025\left(d_{50}-d_{10}\right)\right]^2$	LBS	0.5691	-	-
		TS	0.5691	2.1289	0.0418
		NS	0.5691	2.1289	0.0418
		CSS	0.5691	2.1289	0.0418
		FAP	0.5691	2.1289	0.0418
Breyer	$k=6\times10^{-4}x\frac{g}{v}x\log\left[\frac{500}{C_u}\right]x\left(d_{10}\right)^2$	LBS	0.6172	-	-
		TS	0.6172	2.3718	0.0437
		NS	0.6172	2.3718	0.0437
		CSS	0.6172	2.3718	0.0437
		FAP	0.6172	2.3718	0.0437

LBS*: Leighton Buzzard sand; TS⁻: Trakya sand; NS⁺: Narli sand; CSS[1]: Crushed stone sand; FAP[2]: Fly ash pellet

D_{60}, c_u, c_c) (Figure 1) within the specified ranges, were classified as 'well graded' (*SW*) and 'poorly graded' (*SP*) based on the Unified Soil Classification System (USCS). The specific gravity of the grains, apart from the FAP specimens, were found to be between 2.65 and 2.68. The specific gravity of the FAP was found to be 1.75. Fly Ash Pellets (FAPs), as lightweight aggregates, were produced from fly ash and cement mixing using the pelletization method. The crushing strength, specific gravity, water absorption, surface characteristics and shear strength properties of the manufactured aggregates were already evaluated. The researchers showed that these manufactured aggregates could be a good alternative in some civil-engineering applications. The specific-gravity values of the fly ash pellets change with the fly ash and cement type, and the mix ratio of the constituents [40, 41]. The FAP specimens have a lower density (ρ) and a higher void ratio (e) than the other specimens, because the specific gravity of the soil grains is used in calculating the void ratio. As can be seen from Table 2, the densities of the FAP specimens, calculated after obtaining the void ratios, are lower than the others, for all three gradation ranges. Based on the roundness criteria and the values proposed by Powers [37] and Youd [38] the specimens used during the experimental investigation vary from very angular (i.e., CSS) to well rounded (i.e., LBS).

Table 3 presents the empirical equations and their implications for the sands tested for hydraulic conductivity in this experimental investigation. Hazen, Kozeny- Carman, Terzaghi, Chapuis, Slitcher, USBR, NAVFAC, Alyamani and Sen, and Breyer's equations were considered in this study. The Hazen formula was developed for a prediction of the hydraulic conductivity of uniformly graded loose sand with cu less than 5, and an effective grain size (d_{10}) between 0.10 and 3.0 mm. It is clear from Table 3 that the hydraulic conductivity values (k) vary from 0.6151 cm/sec to 0.9087 cm/sec for the sands falling between 0.6 and 1.18 mm, from 2.1434 cm/sec to 3.2713 cm/sec for the sands falling between 1.18 and 2.00 mm, and from 0.0404 cm/sec to 0.0783 cm/sec for the sands falling between 0.075 and 2.00 mm. Based on the limitation of c_u specified, as expected, the formula does not give realistic prediction results for the sands falling between 0.075 and 2.00 mm (see Figure 6). The authors' interpretation is that the effect of the parameter c_u was neglected, and thereby the grain size distribution results yield the same cu for various sands. The Kozeny-Carman formula is one of the widely used derivations for hydraulic conductivity calculations. This equation is not applicable for either soil with an effective size above 3 mm, or for clayey soils [42]. The estimated hydraulic conductivity values (k) vary from 0.6926 cm/sec to 2.3808 cm/sec for the sands falling between 0.6 and 1.18 mm, from 2.0844 cm/sec to 7.3642 cm/sec for the sands falling between 1.18 and 2.00 mm, and from 0.0265 cm/sec to 0.1500 cm/sec for the sands falling between 0.075 and 2.00 mm. The predicted hydraulic conductivity values (k) using the Terzaghi formula vary from 0.3022 cm/sec to 0.7181 cm/sec for the sands falling between 0.6 and 1.18 mm, from 0.9576 cm/sec to 2.3895 cm/sec for the sands falling between 1.18 and

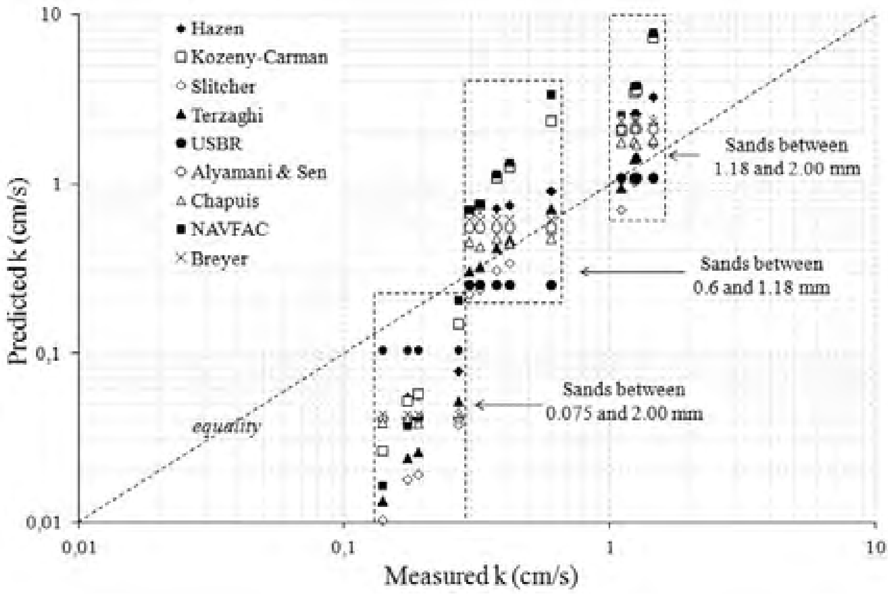

Figure 6. Predicted versus measured k values for the sands used during the during the experimental study.

Table 4. Empirical equations and their limitations for permeability estimates.

Researcher/ Organization	Equation	Limitations
Hazen	$k = 6\times10^{-4}\, x \frac{g}{v} x\left[1+10(n-0.26)\right] x (d_{10})^2$	$c_u < 5$ $0.1 < d_{10} < 3.0$
Kozeny-Carman	$k = 8.3\times10^{-3}\, x \frac{g}{v} x \left[\frac{n^3}{(1-n)^2}\right] x (d_{10})^2$	$0.5 < d_{10} < 4.0$
Terzaghi	$k = 0.0084\, x \frac{g}{v} x \left[\frac{n-0.13}{\sqrt[3]{1-n}}\right]^2 x (d_{10})^2$	-
Chapuis	$k = 1.5x(d_{10})^2\, x \frac{e^3}{1+e} x \frac{1+e_{max}}{(e_{max})^3}$	-
Slitcher	$k = 1\times10^{-2}\, x \frac{g}{v} x\, n^{3.287} x (d_{10})^2$	$0.1 < d_{10} < 5.0$
USBR	$k = 4.8\times10^{-3}\, x \frac{g}{v} x (d_{20})^{0.3}\, x (d_{20})^2$	$c_u < 5$
NAVFAC	$k = 10^{1.291e-0.6435}\, x (d_{10})^{10^{(0.5504-0.2937e)}}$	$2 < c_u < 12$ $0.1 < d_{10} < 2.0$ $0.3 < e < 0.7$ $1.4 < d_{10}/d_5$
Alyamani & Sen	$k = 1300x\left[l_0 + 0.025(d_{50} - d_{10})\right]^2$	-
Breyer	$k = 6\times10^{-4}\, x \frac{g}{v} x \log\left[\frac{500}{C_u}\right] x (d_{10})^2$	$0.06 < d_{10} < 0.6$ $1 < c_u < 20$

2.00 mm, and from 0.0135 cm/sec to 0.0525 cm/sec for the sands falling between 0.075 and 2.00 mm. Figure 6 presents a comparative study using all the formulae employed in this study. As can be seen from the Figure 6, Terzaghi's empirical equation has more accurate results than the other equations for the sands between 0.6 and 1.18 mm, and those between 1.18 and 2.00 mm. This equation, however, seems not to be appropriate for the soils between 0.075 and 2.00 mm, although it has no limitations reported (Table 4). Similarly, predicted *k* values using the Chapuis formula give us a relatively good correlation with the measured *k* values for the sands between 0.6 and 1.18 mm, and between 1.18 and 2.00 mm (Figure 6). Although there is no limitation for this approach as well, the estimated *k* values do not fit very well to the actual *k* values determined experimentally. The estimated hydraulic conductivity values (*k*) using the Chapuis approach vary from 0.4279 cm/sec to 0.4776 cm/sec for the sands falling between 0.6 and 1.18 mm, from 1.7176 cm/sec to 1.8385 cm/sec for the sands falling between 1.18 and 2.00 mm, and from 0.0387 cm/sec to 0.0443 cm/sec for the sands falling between 0.075 and 2.00 mm. The limitations of the empirical equation developed by Slitcher is that the d10 should be between 0.01 and 5.0 (Table 4). Figure 6 indicates that the Slitcher formula is the best fitted to the sands between 0.6 and 1.18 mm, and between 1.18 and 2.00 mm. However, the *k* predictions for the sand between 0.075 and 2.00 mm have no good agreement with the measured *k* values (Figure 6). Estimated *k* values using the Slitcher approach vary from 0.2224 cm/sec to 0.5175 cm/sec for the sands falling between 0.6 and 1.18 mm, from 0.7090 cm/sec to 1.7296 cm/sec for the sands falling between 1.18 and 2.00 mm, and from 0.0104 cm/sec to 0.0381 cm/sec for the sands falling between 0.075 and 2.00 mm. The US Bureau of Reclamation (USBR) formula estimates *k* values using the effective grain size (d_{20}), and it does not depend on the porosity (Table 4). The formula is most suitable for medium-grain sand with c_u less than 5 [43]. The estimated *k* values using the USBR formula are 0.2535 cm/sec for the sands falling between 0.6 and 1.18 mm, 1.0882 cm/sec for the sands falling between 1.18 and 2.00 mm, and 0.1048 cm/sec for the sands falling between 0.075 and 2.00 mm. The k values are same for each of three gradations due to the same d_{20}. The Alyamani and Sen equation, one of the well-known equations, considers both sediment grain sizes d_{10} and d_{50} as well as the sorting characteristics. Estimated k values using the Alyamani and Sen approach are 0.5691 cm/sec for the sands falling between 0.6 and 1.18 mm, 2.1289 cm/sec for the sands falling between 1.18 and 2.00 mm, and 0.0418 cm/sec for the sands falling between 0.075 and 2.00 mm. The k values are the same for each gradation of sands due to the same d_{10} and d_{50} values. Similarly, the Breyer equation gives the same k values for each gradation, 0.6172 cm/sec for the sands falling between 0.6 and 1.18 mm, 2.3718 cm/sec for the sands falling between 1.18 and 2.00 mm, and 0.0437 cm/sec for the sands falling between 0.075 and 2.00 mm, because of the same d_{10} value employed in this equation. The Naval Facilities Engineering Command design manual DM7 (NAVFAC) proposed a chart to predict the saturated k value of clean sand and gravel based on e and d_{10}. The limitations described in this approach are $0.3 < e < 0.7$, $0.10 < d_{10} < 2.0$ mm, $2 < c_u < 12$, and $d_{10}/d_5 < 1.4$. Estimated k values using NAVFAC vary from 0.6953 cm/sec to 3.3791 cm/sec for the sands falling between 0.6 and 1.18 mm, from 2.5811 cm/sec to 7.7911 cm/sec for the sands falling between 1.18 and 2.00 mm, and from 0.0166 cm/sec to 0.2052 cm/sec for the sands falling between 0.075 and 2.00 mm. The observed differences between the predicted and measured k values calculated using different equations (see Figure 6) could be because of some inaccuracies in the measured soil parameters, and some deficiencies in the predictive equations, as previously discussed. Finally, it also seems to be worth bearing in mind that the Vukovic and Soro [23] porosity (n) may be derived from the empirical relationship with the coefficient of grain uniformity (c_u) as n=0.255(1+0.83c_u). However, the porosity value (n) employed here in the empirical equations has been considered as equal to $e/e+1$, as described by Terzaghi and Peck [13], Craig [2], Powrie [4], and Das [3]. This is because, the approach by Vukovic and Soro [23] may not be applicable for the sands having the same c_u values as described here in this investigation.

Figure 7 shows the variation of the coefficient of permeability (k) values and the void ratio (e) for the sands tested, and the regression results for each of the three gradations. The results demonstrate that the higher e values cause higher k values for the measured type of sands. In general, if the void ratio is high, particles are free to rotate, which results in higher k values [44-45]. In densely packed soils with a low void ratio, a larger number of contacts per particle resulted in lower k values. Comparing the hydraulic conductivity values of CSS, TS, NS, and LBS, it is clear that the granular packing in more angular soil grain samples has a more open fabric than those in relatively rounded soil grain samples, resulting in higher k values in more angular sands with the G_s about 2.66. However, the FAP specimens with G_s about 1.75 exhibit much higher k values. The authors interpreted the reason could be attributed to the (i) the dispersion of fly ash particles on the pellet grains during the saturation phase and testing, or (ii)

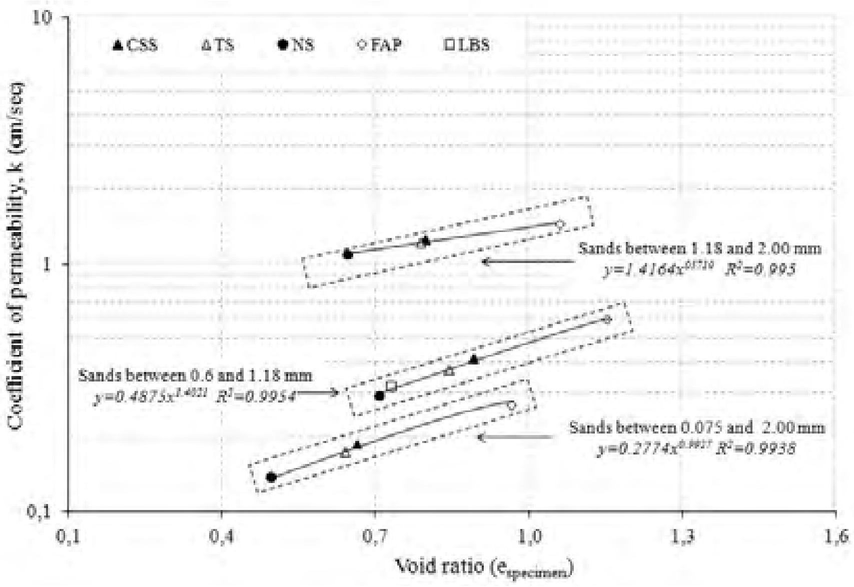

Figure 7. Graph of permeability against void ratio for the sands used during the experimental study.

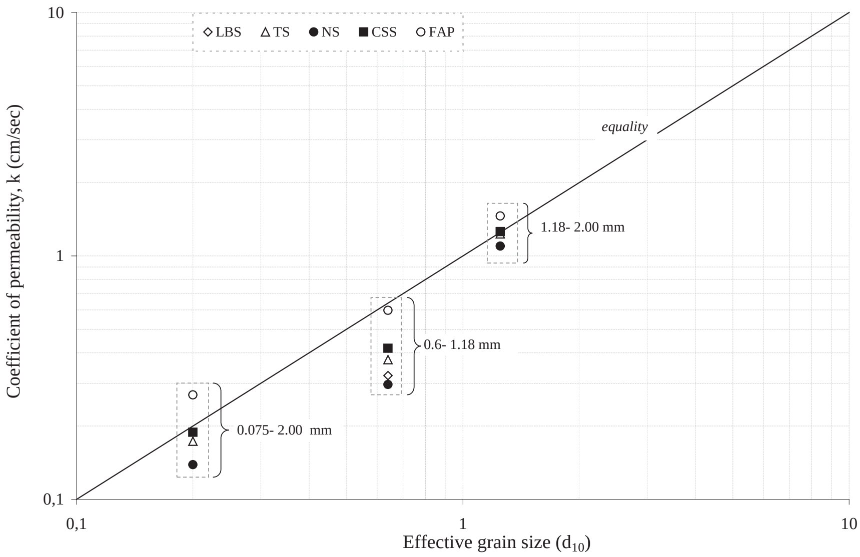

Figure 8. Plot of permeability against grain size for the sands used during the during the experimental study.

the lower specific gravity value of the FAP grains, which may cause a more open fabric because such grains are less likely to settle. Figure 8 illustrates a plot of hydraulic conductivity vs. grain size for the sands used in the experimental study. As can be seen, the measured k values are close to the each other for the sand specimens with d_{10} values about 1.20.

In this study, as an alternative approach, a stepwise regression (SR) model based on a laboratory study is proposed for the prediction of the hydraulic conductivity of the sands. In statistics, a SR contains regression models where the selection of predictive variations is conducted by a semi-automated process. The input variables in the developed SR models are the coefficient of uniformity (c_u), coefficient of curvature (c_c), specific gravity (G_s), porosity (n), roundness (R), and sphericity (S), while the output is k. As shown in Figure 9, comparing the results from the experiments and from the equation proposed here in this study, the accuricies of the proposed SR models are found to be quite satisfactory (R^2=0.9933). The results confirmed that the SR method can identify the k value effectively, while certain available methods result in an error. The developed model provides a way of expressing information to assess the contribution of each parameter (c_u , c_c , G_s , n, R, S) to the variance of the model output (k). The parameters c_u and c_c are more influential than the parameters R and S in Equation 1, and thereby changes in the hydraulic conductivity may be primarily due to the size of the grains. Evidently, the proposed SR model is also presented as a simple explicit mathematical function for further use by researchers. The SR equation (Eq. 1) is as follows:

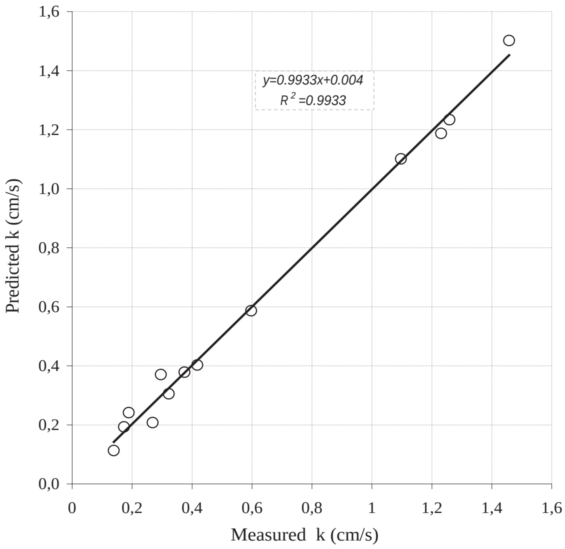

Figure 9. Comparison of the experimental results and predictions by proposed SR model.

$$k(cm/s) = 0.065 + 0.029 \cdot \frac{c_u}{c_c^{\,4} \cdot (G_s \cdot n)^2} - \frac{0.21R^2}{S} \qquad (1)$$

The hydraulic conductivity (k), roundness (R), and sphericity (S) relationship can be seen in the 3-D plot in Figure 10. The k value increases in a relatively linear pattern with a decrease in the roundness. However, it was realized that the sphericity value is not very effective for the k value, while the grains have a higher value of roundness. On the other hand, the k value exhibits an increasing trend at lower roundness values, while the sphericity increases.

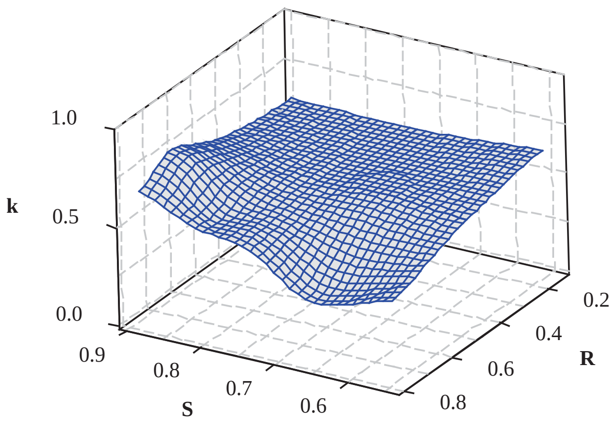

Figure 10. Surface plot of hydraulic conductivity (k) vs. roundness (R), sphericity (S).

4 CONCLUSIONS

In this investigation, three ranges of particle size (0.60-1.18 mm, 1.18-2.00 mm, and 0.075-2.00 mm) of five different sands (i. Crushed Stone Sand, CSS; ii. Trakya Sand, TS; iii. Narli Sand, NS; iv. Fly Ash Pellets, FAP; v. Leighton Buzzard Sand, LBS) having distinct shapes (R_i=0.15, S_i=0.55; R_{ii}=0.43, S_{ii}=0.67; R_{iii}=0.72, S_{iii}=0.79; R_{iv}=0.65, S_{iv}=0.89; R_v=0.78 S_v=0.65) were tested in a constant-head permeability testing apparatus at a relative density (D_r) of about 35%. Also, already available empirical permeability equations were briefly discussed for an estimation of the coefficient of permeability values (k). The tests reported in this paper indicate three new facets of behaviour:

1. Sands having different shapes (R, S) with the same grading characteristics (c_u, c_c, D_{10}, D_{30}, D_{50}, D_{60}) result in different k values.
2. Relatively rounded sand grains have lower k values than the angular sand grains with the exception of the FAP specimens. This could be due to (i) the dispersion of fly ash particles on the FAP grains during the saturation phase and testing, or (ii) the lower specific gravity value of the FAP grains.
3. Empirical equations by Terzaghi and Slitcher give more accurate results than the other equations [6, 8, 19, 46, 51] employed to predict the k values of the sand specimens tested in this investigation.

This suggests that the already-available methods employed here are capable of, but not sufficient for, an accurate prediction of the k values. Therefore, it is obvious that further investigations of the microstructural behavior of the soil matrix are required in order to gain an insight regarding the shape and size effects on permeability.

REFERENCES

[1] Freeze, R. A., Cherry, J.A. 1979. Groundwater. Prentice Hall Inc., Englewood Cliffs, New Jersey.
[2] Craig, R.F. 1997. Craig's Soil Mechanics, 2nd ed. Taylor and Francis, London.
[3] Das, B.M. 2008. Advanced Soil Mechanics, 3rd ed. Taylor and Francis, London.
[4] Powrie, W. 2004. Soil Mechanics Concepts & Applications, 2nd ed. Taylor and Francis, London.
[5] Boadu, F.K. 2000. Hydraulic Conductivity of Soils from Grain-Size Distribution: New Models. Journal of Geotechnical and Geoenvironmental Engineering 126, 8, 739-746. http://dx.doi.org/10.1061/(ASCE)1090-0241(2000)126:8(739)
[6] Hazen, A. 1892. Some Physical Properties of Sands and Gravels, with Special Reference to their Use in Filtration. 24th Annual Report, Massachusetts State Board of Health, Pub. Doc. 34, 539-556.
[7] Hazen, A. 1911. Discussion: dams on sand foundations. Transactions of the American Society of Civil Engineers 73, 199–203.
[8] Kozeny, J. 1927. Uber Kapillare Leitung Des Wassers in Boden. Sitzungsber Akad. Wiss. Wien Math. Naturwiss. Kl., Abt.2a, 136, 271-306 (In German).
[9] Carman, P.C. 1937. Fluid Flow through Granular Beds. Trans.Inst.Chem. Eng. 15,150.
[10] Carman, P.C. 1956. Flow of Gases through Porous Media. Butterworths Scientific Publications, London.
[11] Krumbein W.C., Monk G.D. 1942. Permeability as a function of the size parameters of unconsolidated sand. American Institute of Mining and Engineering, Littleton, CO. Tech. Pub. 153-163.
[12] Harleman D.R.F., Melhorn P.F., Rumer, R.R. 1963. Dispersion-permeability correlation in porous media. Am. Soc. Civ. Eng. (NY) 89, 67-85.
[13] Terzaghi, K., Peck, R.B. 1964. Soil Mechanics in Engineering Practice. Wiley, New York.
[14] Masch, F.D., Denny, K.T. 1966. Grain-size distribution and its effect on the permeability of unconsolidated sands. Water Res. 2, 665-677.
[15] Goktepe, A.B., Sezer, A. 2010. Effect of particle shape on density and permeability of sands. Proceedings of the Institution of Civil Engineer-Geotechnical Engineering 163 (6), 307-320.
[16] Wiebega, W.A., Ellis, W.R., Kevi, L. 1970. Empirical relations in properties of unconsolidated quartz sands and silts pertaining to water flow. Water Res., 6, 1154-1161.
[17] Shepherd, R.G. 1989. Correlations of permeability and Grain-size. Groundwater 27(5), 663-638.
[18] Uma, K.O., Egboka, B.C.E., Onuoha, K.M. 1989. New statistical grain-size method for evaluating the hydraulic conductivity of sandy aquifers. J. Hydrol. 108, 143-366.
[19] Alyamani, M.S., Sen, Z. 1993. Determination of Hydraulic Conductivity from Grain-Size Distribution Curves. Groundwater 31(4), 551-555.

[20] Sperry, M.S., Peirce, J.J. 1995. A model for estimating the hydraulic conductivity of granular material based on grain shape, grain size and porosity. Ground Water, 33(6), 892- 898. doi: 10.1111/j.1745-6584.1995.tb00033.x

[21] Ishaku, J.M., Gadzama, E.W., Kaigama, U. 2011. Evaluation of empirical formulae for the determination of hydraulic conductivity based on grain-size analysis. Journal of Geology and Mining Research, 4, 105-113

[22] Todd, D.K., Mays, L.W. 2005. Groundwater Hydrology. John Wiley & Sons, New York.

[23] Vukovic, M., Soro, A. 1998. Determination of Hydraulic Conductivity of Porous Media from Grain-Size Composition. Water Resources Publications, Littleton, Colorado.

[24] Terzaghi, K. 1925. Erdbaumechanik auf bodenphysikalischer grundlage. Deuticke, Leipzig/Vienna.

[25] Gilboy, G. 1928. The compressibility of sand–mica mixtures. Proceedings of the ASCE 2, 555- 568.

[26] Lees, G. 1964. A new method for determining the angularity of particles. Sedimentology, 3, 2-21.

[27] Olson, R.E., Mesri, G. 1970. Mechanisms controlling the compressibility of clay. Journal of the Soil Mechanics and Foundations Division, ASCE 96 (SM6), Proc. Paper 7649, 1863-1878.

[28] Abbireddy, C.O.R., Clayton, C.R.I., Huvenne, V.A. 2009. A method of estimating the form of fine particulates. Geotechnique 59 (6), 503- 511. http://dx.doi.org/10.1680/geot.2008.P.009

[29] Clayton, C.R.I., Abbireddy, C.O.R., Schiebel, R. 2009. A method of estimating the form of coarse particulates. Geotechnique 59(6), 493-501. doi:10.1680/geot.2007.00195

[30] Holubec, I., D'Appolonia, E. 1973. Effect of particle shape on the engineering properties of granular soils. Evaluation of relative density and its role in geotechnical projects involving cohesionless soils. ASTM, STP523, West Conshohocken, PA, 304- 318.

[31] Conforth, D.H. 1973. Prediction of drained strength of sands from relative density measurements. Evaluation of relative density and its role in geotechnical projects involving cohesionless soils. Special technical publication 523, ASTM, West Conshohoken, PA, 281-303

[32] Holtz, R.D., Kovacs, W.D. 1981. An introduction to geotechnical engineering. Prentice-Hall, Englewood Cliffs, NJ, 517.

[33] Cedergren, H.R. 1989. Seepage, drainage, and flownets. 3rd ed., Wiley, New York, 26.

[34] Kramer, S.L. 1996. Geotechnical earthquake engineering. Prentice Hall, Upper Saddle River, NJ, 653.

[35] Wadell, H. 1932. Volume, shape, and roundness of rock particles. J. Geol., 40(5), 443- 451.

[36] Krumbein, W.C. 1941. Measurement and geological significance of shape and roundness of sedimentary particles. J. Sediment. Petrol., 11(2), 64- 72.

[37] Powers, M.C. 1953. A new roundness scale for sedimentary particles. Journal of Sedimentary Petrology 23(2), 117-119.

[38] Youd, T.L. 1973. Factors controlling maximum and minimum densities of sands, Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils. ASTM STP 523, 98-112

[39] Cho, G.C., Dodds, J.S., Santamarina, J.C. 2006. Particle shape effects on packing density, stiffness and strength: Natural and crushed sands. J. Geotech. Geoenviron. Eng. 132(5), 591- 602. http://dx.doi.org/10.1061/(ASCE)1090-0241(2006)132:5(591)

[40] Doven. A.G. 1996. Lighweight fly ash aggregate production using cold bonding agglomeration process. PhD thesis, Bogazici University, Turkey.

[41] Arslan, H., Baykal, G. 2006. Utilization of fly ash as engineering pellet aggregates. Environ. Geol. 50, 761-770. doi: 10.1007/s00254-006-0248-7

[42] Carrier, W.D. 2003. Goodbye Hazen: Hello. Kozeny-Carman. J. Geotech. Geoenviron. Eng. 129,11, 1054-1056. http://dx.doi.org/10.1061/(ASCE)1090-0241(2003)129:11(1054)

[43] Cheng, C., Chen, X. 2007. Evaluation of Methods for Determination of Hydraulic Properties in an Aquifer- Aquitard System Hydrologically Connected to River. Hydrogeology Journal, 15, 669-678. doi: 10.1007/s10040-006-0135-z

[44] Zelasko, J. S., Krizek, R. J., Edil T. B. 1975. Shear Behavior of Sands as a Function of Grain Characteristics. Proc. Istanbul Conference on Soil Mechanics and Foundation Engineering, Turkish National Committee of Soil Mechanics and Geotechnical Engineering, Istanbul, Turkey, 55-64.

[45] Sukumaran, B., Ashmawy, A. K. 2001. Quantitative characterisation of the geometry of discrete particles. Geotechnique 51(7), 619-627. doi: http://dx.doi.org/10.1680/geot.2001.51.7.619

[46] Chapuis, R.P. 2004. Predicting the Saturated Hydraulic Conductivity of Sand and Gravel Using Effective Diameter and Void Ratio. Can. Geotech. J., 41, 787-795.

[47] Muszynski, M.R., Vitton, S.J., 2012. Particle shape estimates of uniform sands: visual and automated methods comparison. J. Mater. Civ. Eng. 24(2), 194-206. 10.1061/(ASCE)MT.1943-5533.0000351

[48] NAVFAC, 1974. Soil mechanics, foundations, and earth structures. Naval Facilities Engineering Command (NAVFAC) design manual DM7. U.S. Government Printing Office, Washington, D.C.

[49] Santamarina, J.C., Cho, G.C. 2004. Soil behaviour: The role of particle shape. The Skempton Conference, Thomas Telford, London, 604- 617.

[50] Slichter, C.S. 1898. Theoretical investigation of the motion of ground waters. 19th Annual Report. U.S. Geology Survey.

[51] USBR 1990. Earth Manual-Part 2, U.S. Department of the Interior Bureau of Reclamation, Denver, 1270 p.