

Technical Note

Investigation on the effect of carpet fiber inclusion on hydraulic conductivity of clean sand using laboratory and random finite element analysesM. B. Esfandiari S.S¹, R. Jamshidi C^{2,*}

Received: May 2012, Accepted: July 2012

Abstract

Soil reinforced with fiber shows characteristics of a composite material, in which fiber inclusion has a significant effect on soil permeability. Concerning to the higher void ratio of carpet fibers, at first stages it may be expected that an increase in fiber content of the reinforced soil would result in an increase in permeability of the mixture. However, the present article demonstrates that fiber inclusion will decrease the permeability of sand-fiber composite.

A series of constant head permeability tests have been carried out to show the effects and consequently, a new system of phase relationships was introduced to calculate the dry mass for the sand portion of the composite.

Monte Carlo simulation technique adopted with finite element theory was employed to back calculate the hydraulic conductivity of individual porous fibers from the laboratory test results. It was observed that the permeability coefficient of the porous fibers are orders of magnitude less than the skeletal sand portion due to the fine sand particle entrapment and also the fiber volume change characteristics.

Keywords: Reinforced sand, Carpet fiber, Constant head, Monte Carlo, Random finite element analysis.

1. Introduction

The crisis of municipal waste disposal has been receiving substantial public attention recently and some policy makers and environmentalists have advocated the recycling of wastes, particularly non-decaying materials, into practical products as a possible solution. One potential reuse of these materials lies in soil reinforcement as reported in the literature, Wang (1997) studied the utilization of carpet waste fibers in soil reinforcement [1]. The study showed an increase in shear strength of sandy soil reinforced with waste carpet fibers. It was further confirmed by Ghiassian et al. (2004), that randomly distributed synthetic strips affect the shear strength characteristics and constitutive behavior parameters of fine sand significantly [2]. Poorebrahim (2004) performed an extensive amount of experiments on sand material reinforced with waste carpet fibers [3]. He also discussed the durability and mechanical properties of the single fibers and emphasizes a promising reuse of this kind of waste materials. Mirafteb and Lickfold (2008) report that

inclusion of as much as 10% carpet waste fibers can be well mixed with substandard soil to enhance the internal friction angle of the soil as well as its cohesion intercept [4].

Dynamic characteristics of fiber reinforced soils have also been studied to investigate the response of these soils under lateral and vertical cyclic excitations [5-9].

The above mentioned studies are all confirming that carpet fiber inclusion will improve the shear strength of the mixture; however the hydraulic performance of the mixture is not very well established. The hydraulic properties of soils, especially fine grained sands are significantly important when seismic loading is applied to the saturated reinforced soil.

In line with previous studies on the utilization of carpet wastes in soil reinforcement, Jamshidi and Shahbazi (2011) investigated the effect of carpet fiber inclusion on seepage and permeability properties of granular soils [10]. Constant head permeability test scheme was adopted to measure the hydraulic properties of sands of different relative densities reinforced with carpet waste strips.

Carpet and geotextile fibers were explained on the one hand to be porous materials subject to volume change due to the effective stress increase. Fine grained sand particles entrapment within the porous spaces of the fibers on the other hand embodies extra reduction in permeability of reinforced sand. For the reasons explained by Jamshidi and Shahbazi (2011), fibers mixed with sands especially fine grained particles show a dramatic drop in hydraulic

* Corresponding author: jamshidi_reza@yahoo.com

¹ M.Sc Graduated, Faculty of Engineering, The University of Guilan, Rasht, Guilan, Iran

² Assistant Professor, Faculty of Engineering, The University of Guilan, Rasht, Guilan, Iran

conductivity of the composite which generally becomes even less permeable than plain sand while preserving the skeletal relative density. The outcome of this effect is that the equivalent permeability of sand-fiber composite decreases with the increase in fiber weight fraction. The equivalent permeability is however affected by randomness of fiber distribution within soil fiber mixture. A comprehensive study can be conducted by replicating the mixture several times with the same fiber content in order to capture the stochastic hydraulic behavior of the mixture. However this is not practical due to its cost and time intensiveness. Current study employs random field theory adopted with finite element formulation in order to back calculate the hydraulic conductivity of individual fibers filled with fine sand particles, through modeling the seepage problem in Monte Carlo simulations. Monte Carlo simulation takes random sampling of probability distribution functions as model inputs in order to produce hundreds or thousands of possibility outcomes instead of a

few discrete scenarios. Parametric studies are then conducted to show the effect of different reinforcement parameters on discharge capacity of reinforced sand.

2. Materials

2.1. Soil

In this study two types of soil with different effective particle sizes were used. Both of them are classified as SP in unified classification system. First soil sample, Q_1 was acquired from the city of Anzali in north of Iran. The second sample acquired from the same source is Q_2 sand which bears greater effective size than Q_1 . Properties of these two soils are illustrated in Fig. 1 along with the gradation curve for the Q_1 and Q_2 sands respectively.

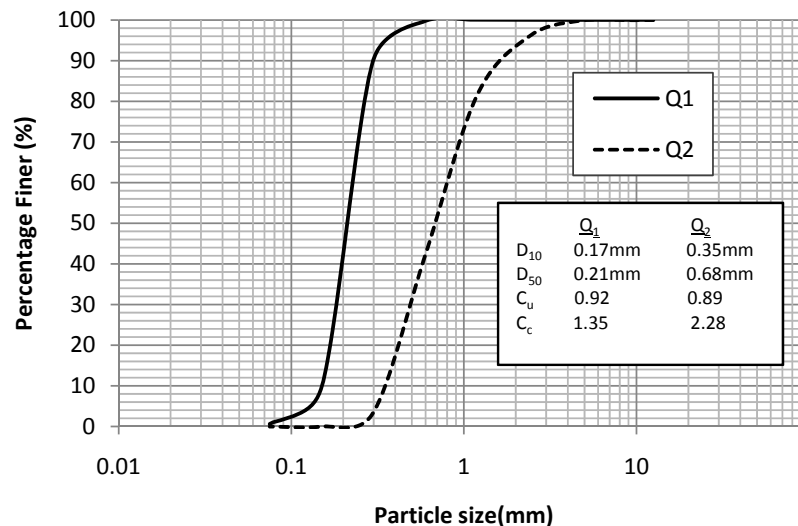


Fig. 1 Grain size distribution of Q_1 and Q_2 sands

2.2. Reinforcement element

Carpet waste strips, the essential reinforcing fibrous materials, were cut into short elements with $5 \times 5 \text{mm}^2$ square cross section and lengths of 5, 15, 25, 35 and 45mm corresponding to the aspect ratios (A_R , length/width) of 1, 3, 5, 7 and 9 respectively. The specific gravity of strips (G_{sf}) is 1 as reported by the carpet company. To get strip content or weight fraction (w_f), defined as the weight of strips to the dry weight of sand, as 0%, 0.2%, 0.4%, 0.5%, 0.6%, 0.8% and 1% respectively, different amounts of strips were added to the soil.

3. Laboratory Test Study

3.1. Sample preparation

Dry tamping method was adopted as part of the sample

preparation for sand reinforced with carpet fiber. Samples were compacted in 7 layers into a 100 mm (4 inch) diameter and 210 mm (8.4 inch) high cylindrical mold, with different target skeletal relative densities. Skeletal sand density was estimated for the sand part only according to the new phase relationships and the weight of fibers was not taken into consideration. Calculations provided by Jamshidi and Shahbazi (2011) shows that when the fibers are not included in dry mass calculations for sand portion, it will make a big difference and impose great effect on results.

3.2. New phase relationships

In order to isolate the coupled effects of sand skeletal density and fiber inclusion on mechanical and hydraulic properties of reinforced soil, it is needed to maintain the relative density of free sand portion constant for various fiber contents.

Volume change characteristics and also sand particle

entrapment potential make the sand skeletal density estimation complicated and approximated. New phase definition and diagram provided in Fig. 2 renders a clear

understanding of the mentioned effects and the way they are encompassed by different affecting parameters.

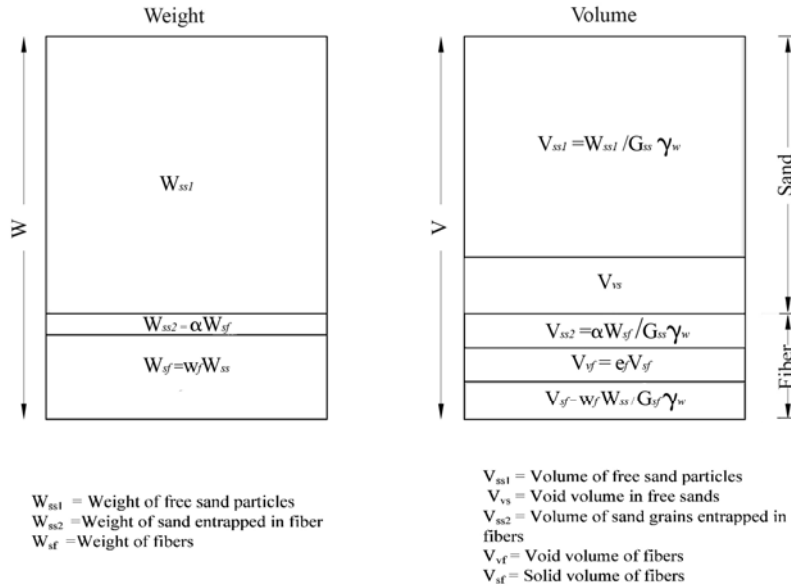


Fig. 2 Phase diagram for reinforced sand (modified after Jamshidi and Shabbazi 2011)

Fiber void ratio, e_f is a new and important terminology cased in the study, which is subject to variation due to the stress level changes during compaction. Sand entrapment factor, α coined in this study is another terminology used to define the amount of fine sand particles absorbed by the porous fibers. Having taken these effects into account, Equation 1 can be used to obtain sand dry mass.

$$W_{ss} = \frac{V_m}{\left[e_{50\%} \left(\frac{1}{G_{ss} \gamma_w} - \frac{\alpha w_f}{G_{sf} \gamma_w} \right) + \left(\frac{1}{G_{ss} \gamma_w} + \frac{(1 + e_f) w_f}{G_{sf} \gamma_w} \right) \right]} \quad (1)$$

Where:

$$e_{50\%} = e_{\max} + D_r (e_{\max} - e_{\min}) \quad (2)$$

Other parameters are listed in Table 1 for Q_1 and Q_2 sands.

4. Laboratory Test Results

Reinforced sand models of different fiber contents, aspect ratios, effective size and skeletal relative densities were tested upon constant head permeability. Fig. 3 and 4 illustrate how the equivalent hydraulic conductivity (permeability) of reinforced sand is affected by the fiber content for Q_1 and Q_2 sands respectively.

Table 1: Input parameters for the new phase relationships

Properties of soil	Q1 sand	Q2 sand
Relative density	$D_r = 25\%$ and 50%	$D_r = 25\%$ and 50%
Maximum void ratio	$e_{\max} = 0.815$	$e_{\max} = 0.6$
Minimum void ratio	$e_{\min} = 0.667$	$e_{\min} = 0.34$
Specific gravity of sand grain	$G_{ss} = 2.65$	$G_{ss} = 2.42$
Specific gravity of fiber solids	$G_{sf} = 1$	$G_{sf} = 1$
Sand entrapment factor	$\alpha = 1$	$\alpha = 1$
Fiber void ratio	$e_f = 2.68$	$e_f = 1.91$
Mold volume	$V_m = 1400 \text{ cm}^3$	$V_m = 1400 \text{ cm}^3$

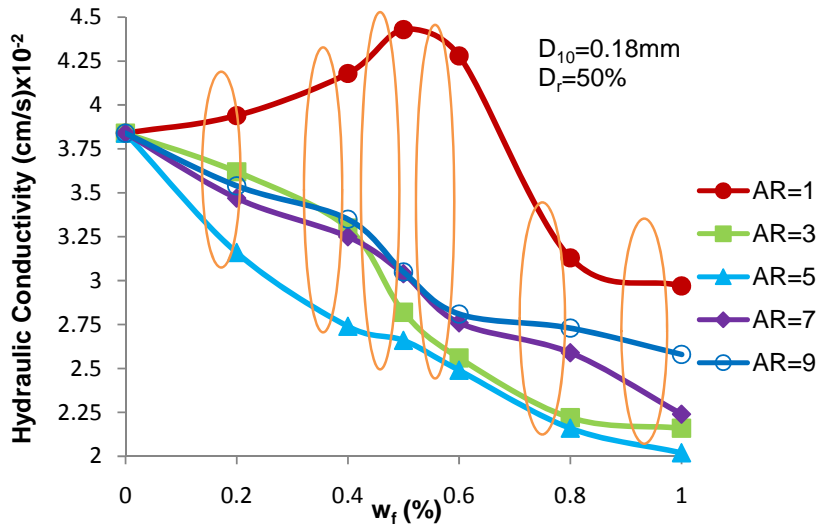


Fig. 3 Hydraulic conductivity of Q_1 sand reinforced with carpet fiber

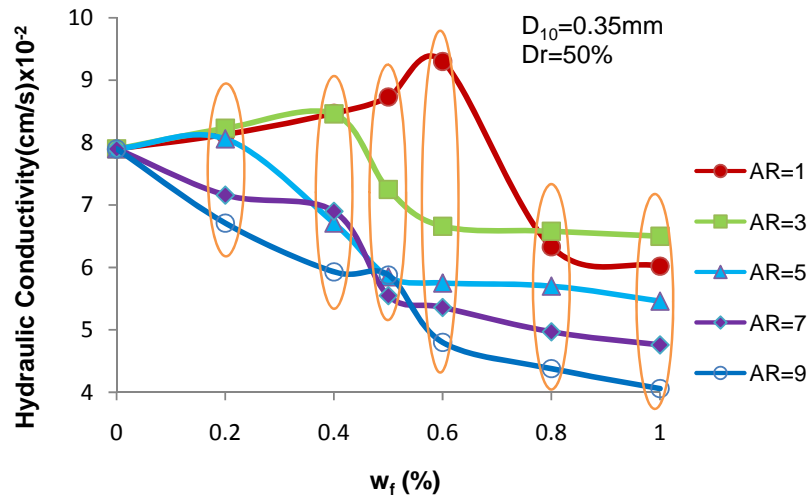


Fig. 4 Hydraulic conductivity of Q_2 sand reinforced with carpet fiber

It is unexpectedly observed that the equivalent permeability of the reinforced sand decreases as the fiber weight content increases. This is in contrary to the normal expectation since the hydraulic conductivity of plain Q_1 sand was measured to be an order of magnitude less than that measured for clean and uncompressed individual fibers. The fact behind this observation is that fine grained sands are entered into the porous spaces within fibers and entrapped there leading to a significant reduction in hydraulic conductivity of the fiber which itself induces a decrease in equivalent hydraulic conductivity of composite and this can partially explain the extraordinary hydraulic behavior of reinforced sand.

5. Random Finite Element Model

In order to compute the discharge of granular soils reinforced with waste carpet fibers, a two-dimensional linear elastic finite element model with an axisymmetric

geometric idealization was used in MATLAB code. The overall dimensions of this model are held fixed at $L = 10\text{cm}$ in length By $D = 9\text{cm}$ in width, according to Fig. 5.

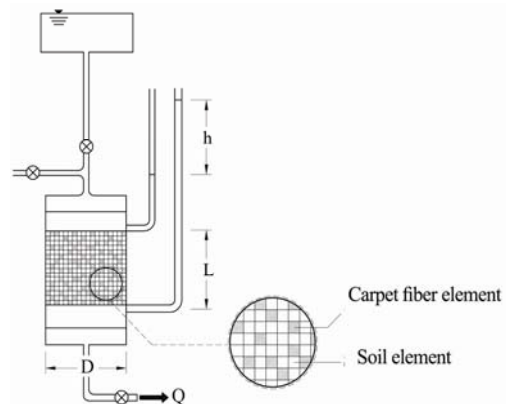


Fig. 5 Geometry of the numerical model used for soil-carpet fiber mixture

The top and bottom faces of the finite element model are hydrostatically fixed. The soil mass is discretized into different mesh density patterns depending on the aspect ratio for carpet fibers. Two major types of materials are considered for numerical modeling of this problem; sand and carpet fibers. Sands of two different compaction levels of 25 and 50% are taken into account while a single carpet fiber type is considered herewith.

5.1. Monte Carlo simulation

The randomization process in MATLAB code which is adopted in this study is of pseudo-random number generation type. A sensitivity analysis was conducted to select an optimum number of analysis in Monte Carlo simulation scheme. Results indicate that compromising on 1000 realizations for different input parameter sets (w_f , A_R and D_r) makes sense in both views of accuracy sought and the cost which is directly proportional to the run time.

5.2. Back analysis

Numerous realizations considering different weight fractions and aspect ratios were performed in order to back calculate the permeability of porous carpet fibers. Permeability of the individual carpet fibers were assumed

0.001 to 100 times of the permeability of sand portion considered in each analysis set. As a large number of realizations were performed in the Monte Carlo simulation, instead of the calculated discharge for each single analysis, mean values obtained from 1000 realizations were employed for back analysis. The discharge ratio, Q_{ratio} is defined by the ratio of the calculated discharge from the finite element model to the discharge measured from the laboratory and the permeability ratio, and k_{ratio} is also defined by the ratio of the fiber permeability assumed in finite element analysis to the permeability of sand grains which was measured to be $7.9 \times 10^{-2} \text{cm/s}$. It was achieved that the K_{ratio} of 0.01 as defined earlier will render a Q_{ratio} of 1 (Fig. 6). This means that the permeability coefficient for the porous individual fibers is 0.01 times the permeability of the sand grains. This small figure ($7.9 \times 10^{-4} \text{cm/s}$) is 1000 times smaller than the permeability coefficient for the clean and uncompressed carpet fibers in the laboratory scale. This difference is due to the fine sand particles entrapment within porous fibers and the fibers volume compression due to the effective stress increase in composite model and it leads to the formation of impermeable pockets of carpet fibers.

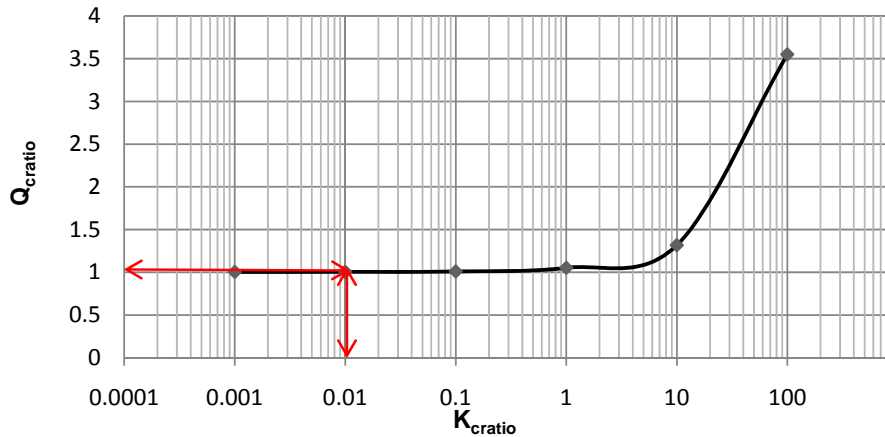


Fig. 6 Back calculation process to calculate the hydraulic conductivity of the single fibers

5.3. Parametric study

The back calculated values, for the carpet fiber permeability are utilized in subsequent stochastic Monte Carlo analyses. The effects of different reinforcing parameters namely the fiber weight fraction and the fiber aspect ratio on stochastic discharge parameters are then investigated.

In Fig. 7, a typical histogram of the discharge, estimated from 1000 realizations is presented for $A_R=3$, $w_f=0.4\%$ and $D_r=50\%$ for Q_1 sand. Regarding the condition that discharge should be strictly non-negative, the shape of histogram suggests a lognormal distribution. A fitted lognormal distribution with parameters given by

m_{lnD} and σ_{lnD} (which are the estimators of the mean and standard deviation of log-discharge, respectively) in the line key is superimposed on the histogram.

At least visually, the fit appears reasonable. For identification of the reasonableness of the assumed distribution for discharge, a Chi-Square goodness-of-fit test was used and yields a p-value to compare various distributions' fitness. Large p-values (up to 1.0) support the hypothesis distribution. As it is shown in Fig. 8, the p-values of distribution indicate that the lognormal distribution matches the output results and it definitely seems reasonable. So the lognormal distribution is usually a close approximation to the distribution of the simulated discharge data, normally at least as good as seen in Fig. 7.

Recognizing the lognormal distribution as a sensible fit to the simulation results, estimation of distribution

parameters as functions of the input parameters (w_f , and A_R) would be the next step. Distribution parameters includes first and second moments namely, mean and variance of the discharge values. Stochastic analyses confirm that the coefficient of variation of the discharge capacity of reinforced sand (standard deviation/mean value) bears very low value as appears from line key of Fig.7. For this reason the mean discharge is believed to be a good representative of the stochastic hydraulic behavior.

It's shown in Fig. 9 how the carpet fibers content affects the mean discharge for different fiber aspect ratios.

It is observed that the mean discharge decreases with the increase in fiber weight fraction and numerical analysis can predict the laboratory discharge through granular soils efficiently. Superimposed on the graph are the results of experimental results acquired from constant head permeability test scheme. It is emphasizing that the discharge prediction using random finite element theory and adoption of a proper value for the hydraulic conductivity of fibers is in clear conformity to the laboratory measurements.

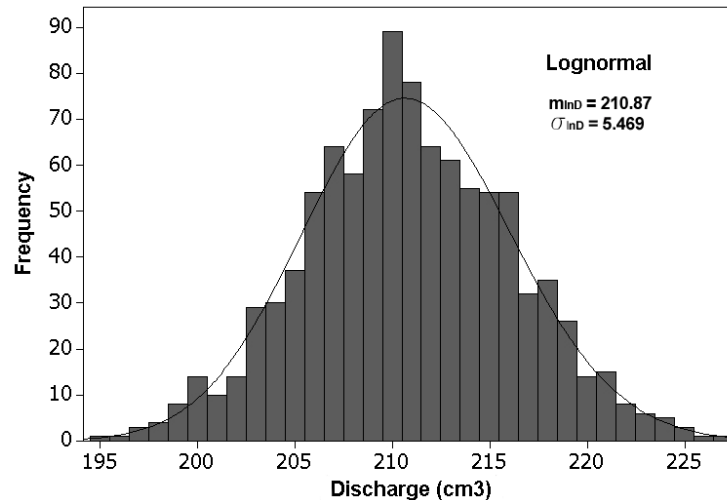


Fig. 7 Typical frequency plot and fitted lognormal distribution of discharge

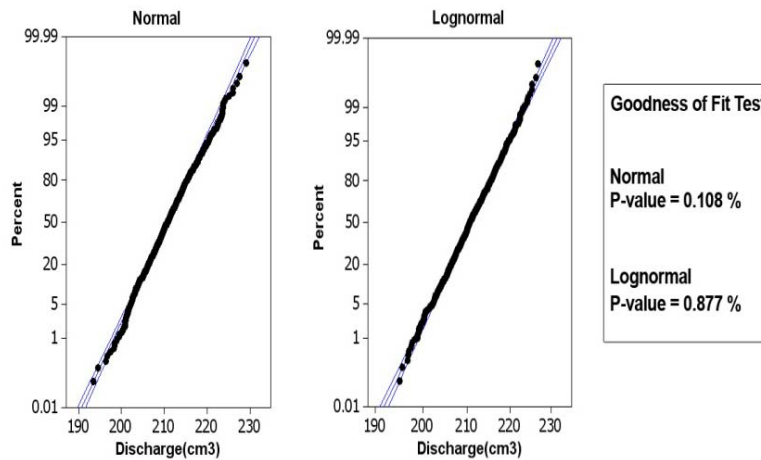


Fig. 8 Chi-Square goodness-of-fit test result for $A_R=3$ and $w_f=0.4\%$

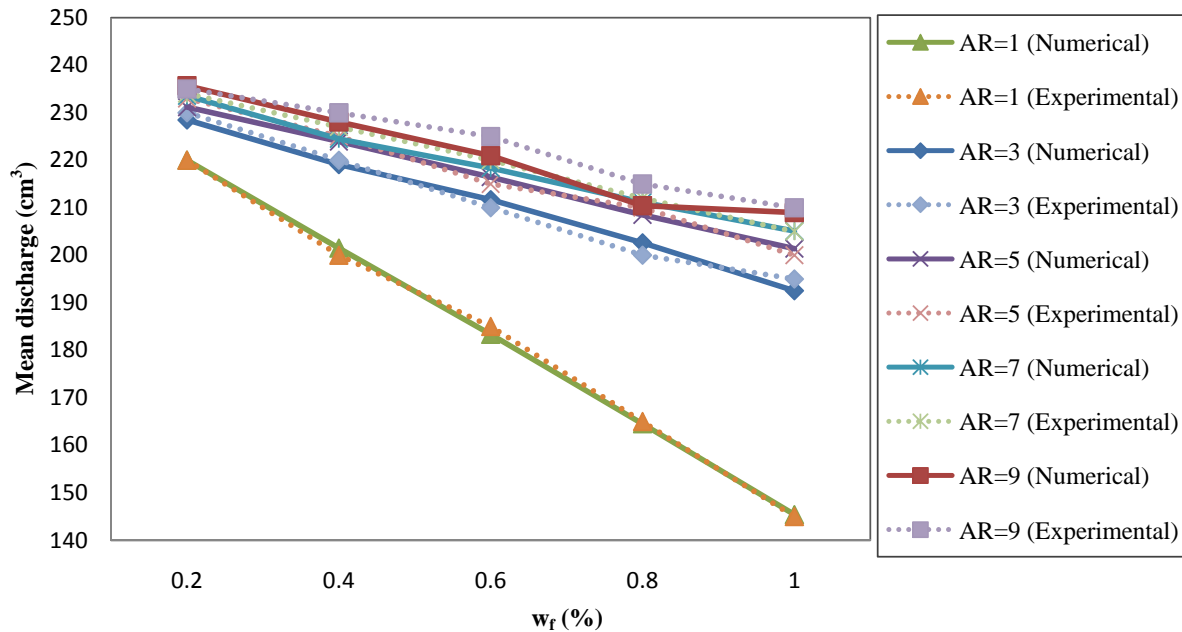


Fig. 9 Effect of carpet fiber weight fraction on mean discharge for Q₁ sand

6. Conclusion

This paper looked into the effect of carpet fiber inclusion on hydraulic conductivity (permeability) of fine grained sands. For this purpose, the coupled effect of skeletal relative density and porous fiber inclusion were first pointed out and a new phase relationship was introduced. Employing the new phase diagram enabled isolation of the aforesaid effects and then, dry sand solid weight was calculated to focus on the effect of fiber content on hydraulic properties of reinforced sand while maintaining the skeletal relative density fixed for different reinforced models.

In order to investigate the effect of different reinforcement parameters namely, fiber weight content and aspect ratio on equivalent permeability of sand-fiber composite, constant head permeability test was conducted. The individual carpet fiber permeability was back calculated using finite element modeling adopted with random field theory. Consequently, following results were obtained:

1. The composite permeability decreases despite the fact that clean plain porous fibers are more permeable than plain sand. This is due to the fine sand particles entrapment within porous fibers and volume change characteristics of fibers due to compaction.
2. Mean discharge shows decreasing with the increase in fiber weight fraction and the results are consistent with the laboratory measurements.
3. Minor coefficients of variation of the discharge capacity of reinforced sand for different fiber weight fractions show that the Monte Carlo simulation can predict the discharge through granular soils efficiently, in case that the proper values of permeability are adopted.

The concluding remark is that fiber reinforcement has a mixed effect on performance of granular soils. On the one hand it will improve the shear strength of the soil by rendering intercept cohesion to the mixture and this effect gets more highlighted when the effective stress level is higher. On the other hand it induces a decrease in hydraulic conductivity of the mixture due to the fine grained particles entrapment and fibrous media to be squeezed. The combined effect of the mentioned effects is that the hydraulic performance of the mixture (liquefaction potential for example) is an interaction of the effects of reinforcement elements and permeability of the porous medium. It means that this type of reinforcements shall be used with caution in cases the mixture is in saturation condition. However it can be used in dry condition like backfill reinforcement for sheet piles or gravity walls as highlighted earlier.

References

- [1] Wang Y. Carpet waste for soil stabilization, Proceedings of Second Conference on Recycling of Fibrous Textile & Carpet Waste, Atlanta, GA, 1997.
- [2] Ghiassian H, Poorebrahim G. R, Gray D. H. Soil reinforcement with recycled carpet wastes, Journal of Waste Management and Research (WMR), International Solid Waste Association (ISWA), 2004, No. 2, Vol. 22, pp. 108-114.
- [3] Poorebrahim G. Soil reinforcement with carpet wastes, PhD dissertation, Iran University of Science Technology, Tehran, Iran, 2003.
- [4] Mirafteb M, Lickfold A. Utilization of carpet waste in reinforcement of substandard soils, Journal of industrial textiles, 2008, Issue 2, Vol. 38, pp. 167-174.
- [5] Ghiassian H, Jamshidi C. R, Tabarsa A. R. Dynamic performance of Toyoura sand reinforced with randomly

- distributed carpet waste strips, 4th Decennial Geotechnical Earthquake Engineering and Soil Dynamics Conference: Sacramento, California, USA, 2008.
- [6] Ghiassian H, Jamshidi C. R, Shahnazari H, Tabarsa A. Dynamic performance of Toyoura sand reinforced with randomly distributed carpet waste strips using a laminar box on shaking table, *Journal of Seismology and Earthquake Engineering*, 2009, Vol. 10, Special Farsi Issue.
- [7] Shahnazari H, Ghiassian H, Noorzad A, Shafiee A, Tabarsa A.R, Jamshidi C. R. Shear modulus of silty sand reinforced by carpet waste strips, *Journal of Seismology and Earthquake Engineering*, Tehran, Iran, 2009, No. 3, Vol. 11.
- [8] Jamshidi C. R. Towhata I, Ghiassian H, Tabarsa A. Experimental evaluation of dynamic deformation characteristics of sheet pile retaining walls with fiber reinforcement backfill, *Journal of Soil Dynamics and Earthquake Engineering*, 2010, Issue 6, Vol. 30, pp. 438-446.
- [9] Ghiassian H, Shahnazari H, Tabarsa A, Jamshidi C. R. Damping ratio of silty sand reinforced with carpet fibers. Amirkabir, *Journal of Science and Technology*, Tehran, Iran, 2010.
- [10] Jamshidi C. R, Shahbazi F.H. *Fiber Reinforced Composites*, Nova Science Publisher, Inc, 2011.