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Use of Taguchi Method to Evaluate the Hydraulic Conductivity of Lignocellulosic Fibers-Reinforced Soil

A. Moslemi[1], A. Tabarsa[1*], S.Y. Mousavi[1], M.H. Aryaie Monfared[2]

[1] Faculty of Civil Engineering, Golestan University, Gorgan, Iran.

[2] Department of Paper Sciences and Engineering, Faculty of Wood and Paper Engineering, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran.

ABSTRACT: Population growth and the subsequent need for the development of infrastructures along with lack of lands with appropriate geotechnical properties have made soil improvement more common. This is while the use of traditional materials in civil engineering projects has raised questions over their environmental impacts. Lignocellulosic fibers, considered as an eco-friendly and renewable source, can be suitable materials to replace traditional additives. In this investigation, three types of lignocellulosic fibers including softwoods bleached pulp (S.W.), old containers pulp (O.C.), and wheat straw soda high yield pulp (W.S.) were used as reinforcement materials. Moreover, Taguchi's design of experiment (DOE) was used to determine the optimum conditions corresponding to three curing times. The Taguchi analysis indicated 2 percent of 1 mm-long S.W. fibers would lead to the lowest hydraulic conductivity while 1 percent of 1.5 mm-long O.C. fibers and 1 percent of 0.5 mm-long W.S. fibers would contribute to the lowest hydraulic conductivity coefficients among 7 and 14 day-cured specimens, respectively. Furthermore, according to the analysis of variance (ANOVA), fiber content was the most effective parameter on the hydraulic conductivity coefficients of 1 and 14 day-cured specimens. This is while fiber length was the most influential one on the hydraulic conductivity of 7 day-cured specimens. The results of this paper indicated the high potential applications of such statistical methods in geotechnical engineering.

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1- Introduction

The development of urbanization has led to increasing demand for lands with poor geotechnical properties. Thus, using effective stabilization techniques in such soils is inevitable [1]. Compressibility reduction, improving soil strength, decreasing hydraulic conductivity to restrict groundwater flow or increasing it for drainage purposes as well as mitigating the risk of liquefaction are among the major objectives of soil improvement. Therefore, soil improvement can be considered a technique to change the properties of soil to enhance the performance of a specific project. To this end, a wide range of materials such as cement and lime, fly ash and furnace slag, polymers and resins, natural or synthetic fibers as well as waste materials are used as admixtures [2]. Though cement is the most common additive used in soil improvement projects [3], environmental problems have led to an increasing tendency towards more eco-friendly approaches [4].

As eco-friendly materials, biopolymers are synthesized by biological organisms. These biopolymers can be categorized into three main groups including polynucleotides, polypeptides, and polysaccharides. However, polysaccharides-based biopolymers have found more applications [5]. Xanthan gum, as an anionic polysaccharide, is produced by Xanthomonas Campestris bacteria and has a significant effect on the viscosity of water [6]. Besides, guar gum, as a neutral polysaccharide, is extracted from the seeds of Leguminous shrub [7]. It is a water-soluble biopolymer and can increase viscosity, significantly [8]. Gellan gum, produced by Sphingomonas Elodea bacteria, is another polysaccharides-based biopolymer. At low temperatures, it has poor water-solubility but high viscosity [9]. Furthermore, Starpol 136, as modified starch and corn-based biopolymer, is a non-anionic polysaccharide. It is highly soluble in water, forming high viscose solutions at room temperature [10]. Sodium alginate, as another type of biopolymer and the product of unprocessed sugar, is also used to increase the viscosity of liquids in the food industry [11]. Moreover, chitosan, derived from crustacean shells of foodstuff, is a low-cost biopolymer [12]. Lignocellulosic fibers can also be considered biopolymers made up of cellulose, hemicellulose, and lignin [13]. Cellulose is a polysaccharide consisting of glucose units. Cellulose has a crystalline structure while hemicellulose has an amorphous structure as well as less strength compared to cellulose. The other component of the cell wall is lignin which binds different layers of a cell wall [14]. Wood, agricultural residues, water plants, grasses, and other plant substances are the main sources of lignocellulosic

*Corresponding author's email: a.tabarsa@gu.ac.ir

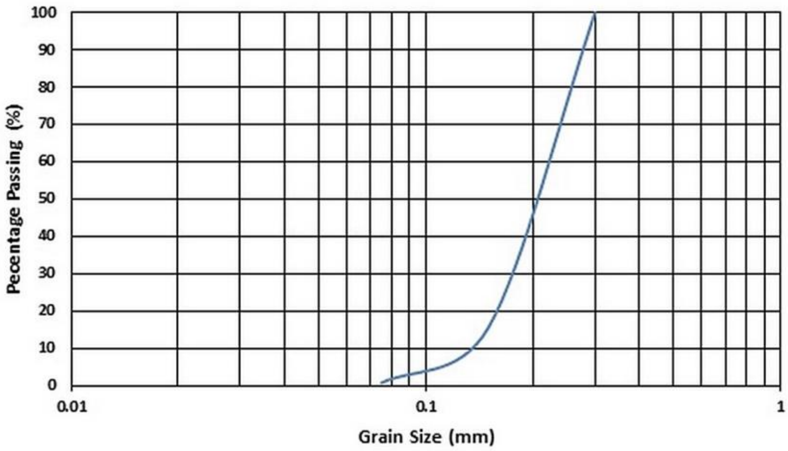

Fig. 1. Gradation curve of the prepared soil sample.

fibers [13].

According to the literature, some biopolymers such as xanthan, guar, and gellan gums have been useful to reduce hydraulic conductivity [9]. A significant decrease was reported in the hydraulic conductivity of sandy soil treated with 1.5% of xanthan gum [15]. Moreover, the effects of xanthan gum and modified starch (Starpol 136) on the hydraulic conductivity of two types of soils, namely sand, and silt, were evaluated. Based on this investigation, the reduction in the hydraulic conductivity was a function of type as well as the concentration of biopolymers [10]. Gellan gum had also a positive influence on the hydraulic conductivity reduction of two types of soils, i.e., poorly graded sand (SP) and poorly graded sand with silt (SP-SM) [16]. Furthermore, the effects of guar gum, xanthan gum, and sodium alginate on the hydraulic conductivity reduction of silty sand were evaluated [17]. In another investigation, it was found adding 0.5% of xanthan gum to silty - clay soil could decrease hydraulic conductivity to 18.6% of its initial value. This is while guar gum reduced the hydraulic conductivity just by 12 percent [7]. Similar results were also observed in studies conducted on xanthan gum-treated clayey soil [18]. Chitosan, as another type of biopolymer, was also effective to reduce the hydraulic conductivity of sandy soil [19]. This reduction in the hydraulic conductivity could be attributed to the filling process of the pores and the subsequent bio-clogging [20].

On the other hand, geotechnical problems are usually comprised of multiple variables [21]. These parameters are often determined based on laboratory or in-situ tests, inverse analysis, spatial estimation, and back analysis. Nonetheless, the major challenge of such approaches is the uncertainty of the obtained results. These uncertainties might occur due to the presence of a large number of variables in the analysis [22]. To deal with this problem, the use of statistical methods can be an effective solution. Genichi Taguchi, as the father of quality engineering, has been among pioneers in using statistical methods in engineering processes. Taguchi's parameter design or robust design involves maximizing performance and quality at minimum cost. This is achieved by determining the best set of designs influencing performance and adjusting those sets of designs and parameters affecting the average performance [23]. Therefore, regarding the high number of parameters in soil improvement problems, the Taguchi method might be an effective tool in identifying the optimum conditions via a limited number of tests.

The Taguchi method has been employed to optimize the amounts of additives used to improve the mechanical behavior of clayey soil [24], the amounts of additives needed to increase the compressive strength of sandy soil [25], the amounts of additives and polypropylene fibers used to modify the plasticity [26, 27] and the strength behavior of fine-grained soil [28, 29]. Moreover, it has been used to investigate the effect of crude oil on various geotechnical characteristics of soil [30] and the optimum conditions corresponding to the strength behavior of MICP- treated sandy soil [31].

As no investigation has been carried out to evaluate and optimize the hydraulic conductivity of soils reinforced with lignocellulosic fibers using the Taguchi method, this research was aimed at using a statistical approach (i.e., the Taguchi methodology) in this field. The optimum conditions corresponding to the hydraulic conductivity reduction of 1, 7, and 14 day-cured specimens were determined using Minitab software v.19. Moreover, the effects of different factors including type and length of the fibers as well as fiber content on the hydraulic conductivity of specimens at three curing times were evaluated.

2- Materials and Methods

2- 1- Soil

The soil used in this study was provided from an approximate depth of 0.5 meters below the ground surface in Galougah, Mazandaran province, Iran. Then, it was passed through the No. 50 sieve to obtain uniform sand. Fig. 1 shows the gradation curve of the prepared soil sample. The basic properties of the prepared sandy soil are given in Table 1.

Table 1. Basic properties of soil.

Soil properties	Quantity	Test method
Soil classification (USCS)	SP	ASTM D 2487 [32]
Uniformity coefficient, C_u	1.71	
Curvature coefficient, C_c	1.03	
Relative density, D_r (%)	40	
Specific gravity, G_s	2.60	ASTM D 854 [33]
Maximum dry unit weight, $\gamma_{d(max)}$, (gr/cm^3)	1.570	ASTM D 698 [34]
Optimum moisture content (%)	17	
Hydraulic conductivity coefficient, K_s(m/s)	6.660×10^{-5}	ASTM D 5084 [35]

Table 2. Results of chemical analysis of lignocellulosic fibers used in this investigation.

Type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	Extracts (%)
S.W.	98.82	-	-	1.00	0.18
O.C.	65.30	-	21.00	12.80	0.90
W.S.	63.50	24.89	8.40	2.67	0.54

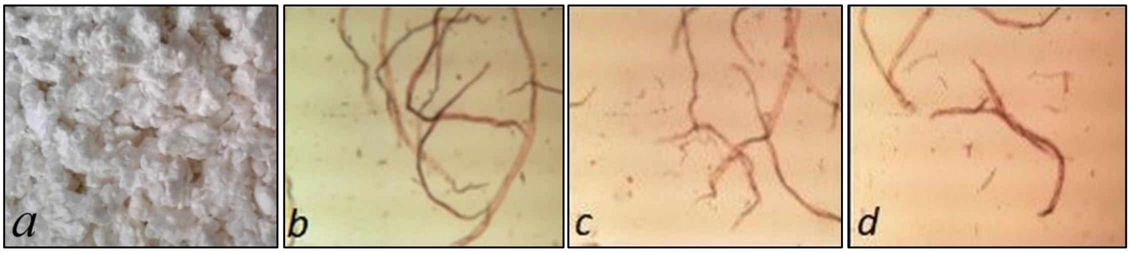

Fig. 2. (a) Macroscopic view of air - dried S.W. fibers; microscopic view of (b) 1.5 mm - long; (c) 1 mm-long; (d) 0.5 mm-long S.W. fibers.

2- 2- Fibers

Three types of lignocellulosic fibers, namely softwoods bleached pulp (S.W.), old containers pulp (O.C), and wheat straw soda high yield pulp (W.S.) were used as reinforcement. To prepare the fibers, they were soaked in water at room temperature for 2 hours. Then, the fibers were disintegrated using a 2500 rounds/min - power disintegrator. As two out of three lignocellulosic fibers (O.C. and W.S.) had the highest fiber length of 1.5 mm, the maximum fiber length was determined 1.5 mm. Moreover, the selected fiber lengths must have an acceptable difference to produce a probable meaningful effect on the hydraulic conductivity. Therefore, 0.5, 1, and 1.5 mm- long fibers must be prepared. To cut the fibers into the desired lengths (with an average length of 0.5, 1, and 1.5 mm), 50 gr dry weight of fibers was mixed with a sufficient amount of water to have 5 % suspension. Then, it was poured into a 10000 rounds/min - power mixer. In the next stage, samples were taken at different time intervals. Using an optical microscope, the average length of twenty-five fibers was calculated. Thereby, the required time to cut these fibers into a specific length will be different as well.. Since the fibers used in this investigation have different chemical and physical characteristics, the required time to cut these fibers into a specific length would be different as well. As a result, the abovementioned process must be conducted for each type, separately. It must be mentioned 0.5, 1, and 1.5 mm-long denote the average length of fibers. For the sake of simplicity, the term “average” will not be used hereafter.

Table 2 shows the cellulose, hemicellulose, lignin, ash, and extractable material contents of each type of lignocellulosic fibers pulp. The cellulose content was determined based on Kurschner and Hoffer method [36]. Lignin, ash, and extractable material contents were also specified according to TAPPI T 222 [37], TAPPI T 211 [38], and TAPPI T 204 [39], respectively. The results of chemical analysis are given in Table 2.

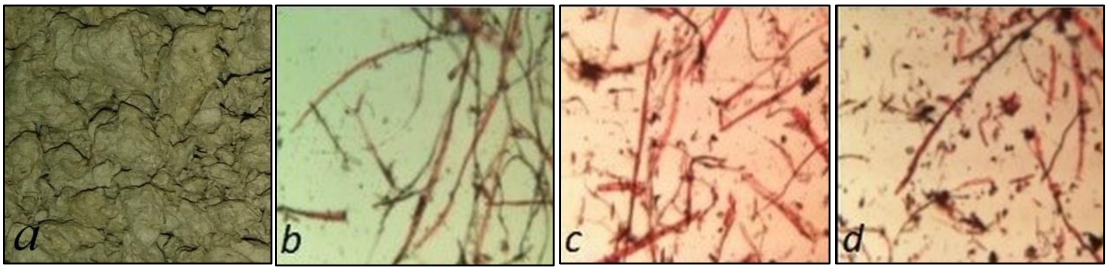

Fig. 3. (a) Macroscopic view of air - dried O.C. fibers; microscopic view of (b) 1.5 mm-long; (c) 1 mm-long; (d) 0.5 mm-long O.C. fibers.

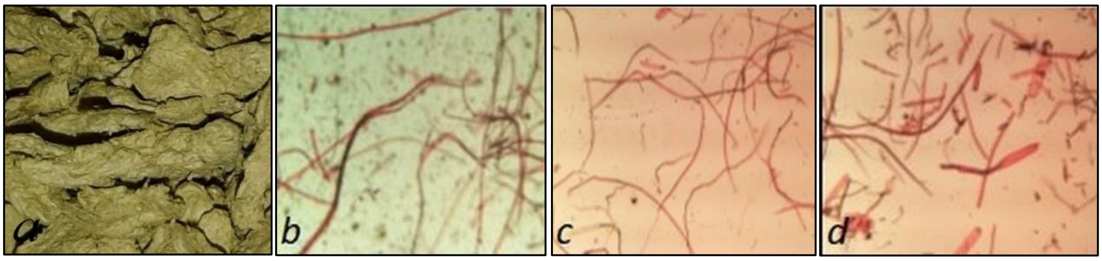

Fig. 4. (a) Macroscopic view of air - dried W.S fibers; microscopic view of (b) 1.5 mm-long; (c) 1 mm-long; (d) 0.5 mm-long W.S. fibers.

2- 3- Optimization

The Taguchi method involves the following steps: (i) determination of the specific quality to be optimized (ii) identification of the test conditions (iii) determination of the factors and their levels (iv) defining the set of experiments and data analysis procedure (v) conducting the experiments (vi) analyzing the data and (vii) predicting the performance at those levels [40]. In this optimization technique, orthogonal arrays are used to express factors and their relevant levels [41]. These arrays are expressed in the form of $L_n\left(a_L^{b_F}\right)$ in which the parameters n , b_F and a_L denote the number of experiments, factors, and levels, respectively. Orthogonality, uniformity in distribution, and comparability are among the main advantages of such arrays [42]. The results of the Taguchi analysis are displayed using signal-to-noise ratios (S/N) in which S and N are the mean and standard deviation, respectively. These S/N ratios are employed as objective functions as well as for determining the optimum values [43]. It is noteworthy that the test corresponding to the optimum conditions is not necessarily included in the set of experiments determined by the Taguchi method which could be considered one of the main advantages of this methodology [28]. The objectives of the optimization process using the Taguchi method can be categorized as: the larger the better (Eq. (1)), the smaller the better (Eq. (2)), and the nominal the better (Eq. (3)).

$$S/N = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} 1/Y_i^2\right] \tag{1}$$

$$S/N = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right] \tag{2}$$

$$S/N = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} (Y_i - Y_0)^2\right] \tag{3}$$

In which n denotes the number of repetitions for an experimental combination. Y_i and Y_0 are performance values corresponding to the i_{th} experiment and the nominal value, respectively [26]. Since the optimization is aimed at minimizing the hydraulic conductivity of the investigated soil, Eq. (2) would be valid.

In this study, an L9 Orthogonal Array (OA) was chosen, since it's the most suitable one for the conditions being investigated (i.e., 3 factors and 3 levels for each one). Table 3 shows the factors and relevant levels studied in this paper.

Table 3. Factors and levels used in the Taguchi's DOE.

Factors	Level 1	Level 2	Level 3
Fiber Type	S.W.	O.C.	W.S.
Fiber Content (%)	0.5	1	2
Fiber Length (mm)	0.5	1	1.5

Table 4. Taguchi L9 orthogonal array for each curing time.

Test No.	Factors and Levels		
	Fiber Type	Fiber Content (%)	Fiber Length (mm)
1	S.W.	0.5	0.5
2	S.W.	1	1
3	S.W.	2	1.5
4	O.C.	0.5	1
5	O.C.	1	1.5
6	O.C.	2	0.5
7	W.S.	0.5	1.5
8	W.S.	1	0.5
9	W.S.	2	1

Taguchi's DOE is also given in Table 4.

2- 4- Sample Preparation

To investigate the above-mentioned factors on the hydraulic conductivity of lignocellulosic fibers-reinforced soil, all specimens were prepared at the identical dry unit weight (1.490 gr/cm^3) corresponding to relative density (Dr) and optimum moisture (ω). The soil was oven-dried at a temperature of 105 $^{\circ}C$ for 24 hours. In the next stage, specified amounts of air-dried fibers and distilled water were mixed and then added to the soil (for untreated specimens, only distilled water was added to the soil). As the fibers have a much lower density than the sandy soil, compacting reinforced specimens containing more than 2% of such fibers is practically impossible. Moreover, the fiber contents must be determined somehow to produce a probable meaningful effect on the hydraulic conductivity of the reinforced soil. By considering such issues, fiber contents were determined 0.5, 1, and 2 percent by dry weight of soil. Then, the homogeneity of the mixture was secured by hand mixing. Next, the mixtures were compacted in cylindrical steel moulds of D 67.5 mm × H 50 mm. Having been saturated, the moulds were attached to the holders and cured in a 25 $^{\circ}C$ water bath for 1, 7, and 14 days.

2- 5- Test Procedure

To perform the falling head hydraulic conductivity test (as per ASTM D 5084), the initial water head was set at 5 cm. If three successive tests conducted on a single specimen had a similar result with a difference of lower than 3 percent, the test would automatically be terminated and the last value would be reported as the hydraulic conductivity coefficient of that particular specimen. Otherwise, the average of all values would be considered as the hydraulic conductivity coefficient of that sample.

3- Results and Discussion

To determine the optimum conditions corresponding to each curing time as well as the significance of different factors on the hydraulic conductivity coefficient of lignocellulosic fibers -reinforced soil, Taguchi analysis has been performed using Minitab software v.19. The optimum conditions corresponding to the lowest hydraulic conductivity coefficient are indicated by higher S/N ratios. Furthermore, analysis of variance (ANOVA) is an effective technique to quantitatively determine the influence of different factors on a specific characteristic. To this end, the pure sum is divided by the total sum of squares [31].

Fig. 5 demonstrates the response graph of main effects for the hydraulic conductivity coefficients of 1 day-cured

Table 5. Laboratory test results of the Taguchi's DOE.

Test No.	Curing time (days)	Hydraulic conductivity $\times 10^{-5}$ (m/s)
	1	3.875
1	7	3.691
	14	2.880
	1	5.560
2	7	2.804
	14	0.140
	1	2.992
3	7	2.197
	14	1.572
	1	4.844
4	7	1.785
	14	0.838
	1	4.736
5	7	0.056
	14	0.562
	1	6.089
6	7	3.806
	14	0.156
	1	6.525
7	7	3.089
	14	0.546
	1	5.820
8	7	3.893
	14	0.035
	1	2.110
9	7	1.380
	14	0.950

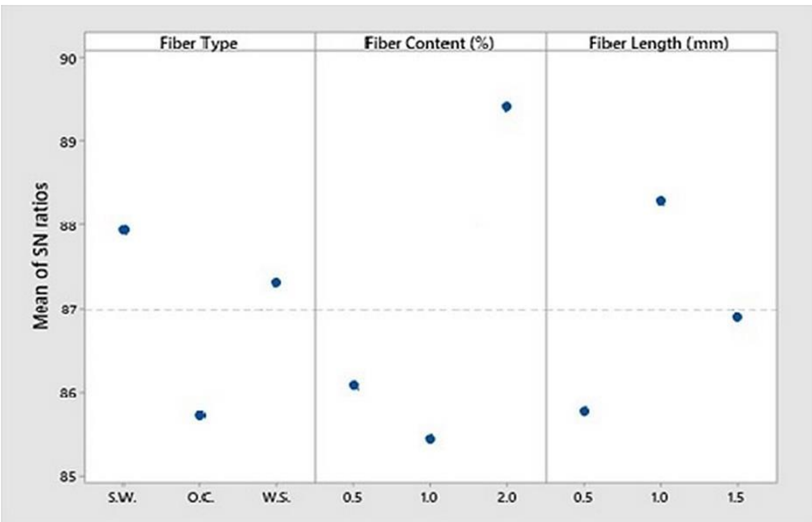

Fig. 5. Response graph of main effects for the hydraulic conductivity coefficients of 1 day-cured specimens.

Table 6. Signal to noise ratios for 1 day-cured specimens.

Level	Fiber Type	Fiber Content (%)	Fiber Length (mm)
1	87.94	86.08	85.75
2	85.70	85.43	88.30
3	87.31	89.43	86.89
Delta	2.24	4.00	2.55
Rank	3	1	2

Table 7. ANOVA results of S/N ratios for 1 day-cured specimens.

Factor	Degree of Freedom	Sum of Squares	Pure Sum	*P* (%)
Fiber Type	2	7.999	7.999	17.57
Fiber Content	2	27.711	27.711	60.86
Fiber Length	2	9.823	9.823	21.57
Total	6	45.533	-	100

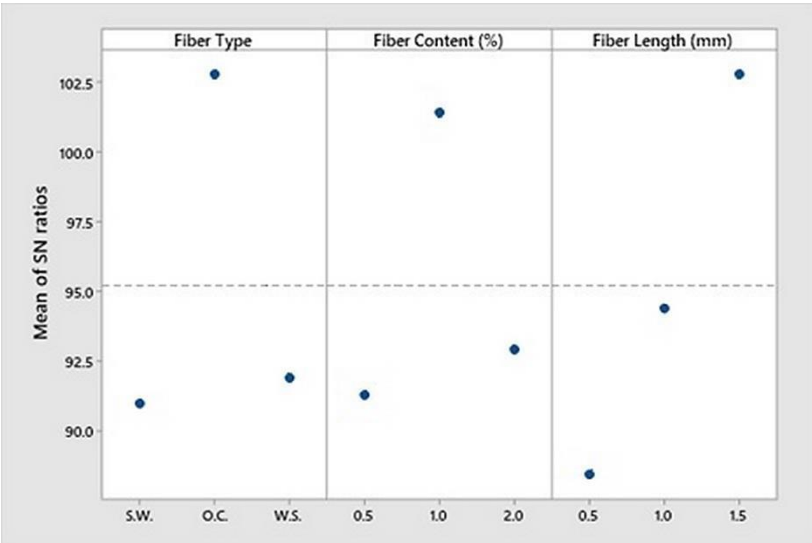

Fig. 6. Response graph of main effects for the hydraulic conductivity coefficients of 7 day-cured specimens.

specimens. It is expected that 2% of 1 mm-long S.W. fibers would leads to the lowest hydraulic conductivity coefficient among 1 day-cured specimen.

Table 6 shows the signal-to-noise ratio for 1 day-cured specimen. As seen, fiber content has the highest influence on the hydraulic conductivity, followed by fiber length and type of the fibers used. Moreover, based on the ANOVA results of S/N ratios for 1 day-cured specimen, fiber content accounts for 60.86% of the overall variance while fiber length and fiber type have relatively smaller effects (21.57% and 17.57 %, respectively) (Table 7).

According to the Taguchi analysis, among 7 day-cured specimens, the lowest hydraulic conductivity is expected for that specimen reinforced with 1% of 1.5 mm-long O.C. fibers (Fig. 6).

Based on the values of S/N ratios for 7 day-cured specimens, length of the fibers has the highest contribution to lowering the hydraulic conductivity whereas fiber type

Table 8. Signal to noise ratios for 7 day-cured specimens

Level	Fiber Type	Fiber Content (%)	Fiber Length (mm)
1	90.95	91.28	88.41
2	102.80	101.42	94.40
3	91.87	92.92	102.80
Delta	11.84	10.15	14.39
Rank	2	3	1

Table 9. ANOVA results of S/N ratios 7 day-cured specimens.

Factor	Degree of Freedom	Sum of Squares	Pure Sum	*P* (%)
Fiber Type	2	260.6	260.6	34.65
Fiber Content	2	178.1	178.1	23.68
Fiber Length	2	313.4	313.4	41.67
Total	6	752.1	-	100

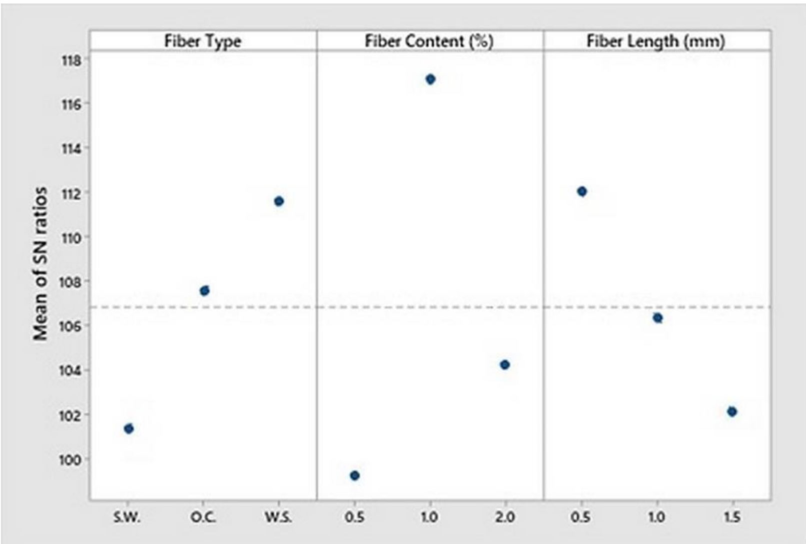

Fig. 7. Response graph of main effects for the hydraulic conductivity coefficients of 14 day-cured specimens.

and fiber content have smaller effects (Table 8). Based on the ANOVA results of S/N ratios calculated for 7 day-cured specimens, fiber length accounts for 41.67 % of the variance, followed by fiber type (34.65%) and fiber content (23.68%) (Table 9).

Fig. 7 shows the optimum conditions corresponding to the hydraulic conductivity of reinforced specimens following 14 days of treatment. As seen, 1% of 0.5 mm-long W.S. fibers will lead to the lowest hydraulic conductivity.

Among 14 days-cured specimens, fiber content is the most effective parameter on the hydraulic conductivity coefficient of the treated samples. Moreover, fiber type and length of the fibers are the second and third most influential parameters, respectively (Table 10). The ANOVA results of S/N ratios indicate the higher contribution of fiber content (62.21%) compared to the fiber type (19.67%) and fiber length (18.12%) (Table 11).

Table 5 shows the hydraulic conductivity coefficients of a

Table 10. Signal to noise ratios for 14 day-cured specimens.

Level	Fiber Type	Fiber Content (%)	Fiber Length (mm)
1	101.32	99.20	112.02
2	107.56	117.07	106.35
3	111.61	104.22	102.11
Delta	10.29	17.87	9.91
Rank	2	1	3

Table 11. ANOVA results of S/N ratios for 14 day-cured specimens.

Factor	Degree of Freedom	Sum of Squares	Pure Sum	*P* (%)
Fiber Type	2	161.1	161.1	19.67
Fiber Content	2	509.5	509.5	62.21
Fiber Length	2	148.4	148.4	18.12
Total	6	819	-	100

set of experiments determined by the Taguchi method at three curing times. Regarding specimens reinforced with S.W. fibers, the hydraulic conductivity of 1 day-cured specimen reinforced with 0.5% of 0.5mm-long fibers was determined 3.875×10^{-5} m/s (0.580 of the initial value) while the hydraulic conductivity of 7 and 14 day-cured specimens decreased to 3.691×10^{-5} and 2.880×10^{-5} m/s, respectively (0.550 and 0.430 of the initial value). The hydraulic conductivity of 1 day-cured specimen reinforced with 1% of 1 mm-long fiber was determined 5.560×10^{-5} m/s (0.830 of initial value). However, the hydraulic conductivity of 7 and 14 day-cured specimens decreased to 2.804×10^{-5} and 1.400×10^{-6} m/s (0.420 and 0.021 of initial value), respectively. Furthermore, 2 % of 1.5 mm-long fibers reduced the hydraulic conductivity of 1 day-cured specimen to 2.992×10^{-5} (0.450 of initial value) while the hydraulic conductivity of 7 and 14 day-cured specimens decreased to 2.197×10^{-5} and 1.572×10^{-5} m/s, respectively (0.330 and 0.240 of initial value).

For specimens reinforced with O.C. fibers, the hydraulic conductivity of 1 day-cured specimen reinforced with 0.5% of 1 mm-long fiber was reduced to 4.844×10^{-5} (0.730 of initial value). However, the hydraulic conductivity of 7 and 14 day-cured specimens decreased to 1.785×10^{-5} and 8.380×10^{-6} m/s (0.270 and 0.126 of initial value), respectively. Moreover, the hydraulic conductivity of 1 day-cured specimen reinforced with 1% of 1.5 mm- long fibers was determined 4.736×10^{-5} m/s (0.71 of initial value) while the hydraulic conductivity of 7 and 14 day-cured specimens decreased to 5.600×10^{-7} and 5.620×10^{-6} m/s (0.008 and 0.084 of initial value). The hydraulic conductivity of 1 day-cured specimen reinforced with 2% of 0.5 mm-long fibers was reduced to 6.089×10^{-5} m/s (0.910 of initial value) while the hydraulic conductivity of 7 and 14 day-cured specimens decreased to 3.806×10^{-5} and 1.560×10^{-6} m/s, respectively (0.570 and 0.023 of initial value).

Regarding specimens reinforced with W.S. fibers, 0.5% of 1.5 mm-long fibers reduced the hydraulic conductivity just to 6.525×10^{-5} (0.98 of the initial value) while the hydraulic conductivity of 7 and 14 day-cured specimens decreased to 3.089×10^{-5} and 5.460×10^{-6} m/s (0.460 and 0.080 of initial value). Furthermore, 1% of 0.5 mm-long fibers reduced the hydraulic conductivity to 5.820×10^{-5} m/s (0.88 of initial value). However, the hydraulic conductivity of 7 and 14 day-cured specimens was determined 3.893×10^{-5} and 3.500×10^{-7} m/s, respectively (0.580 and 0.005 of initial value). The hydraulic conductivity of the specimen reinforced with 2% of 1 mm-long fiber was determined 2.110×10^{-5} m/s (0.320 of initial value). This is while the hydraulic conductivity of 7 and 14 day-cured specimens decreased to 1.380×10^{-5} and 9.500×10^{-6} m/s, respectively (0.210 and 0.140 of initial value).

By comparing the hydraulic conductivity values of the Taguchi's DOE and those predicted conditions, the lowest hydraulic conductivity coefficient values were observed in specimens reinforced with 2% of 1 mm-long S.W. (1.120×10^{-5} m/s i.e., 0.170 of the initial value), 1% of 1.5 mm-long O.C. (5.600×10^{-7} m/s i.e., 0.008 of the initial value) and 1% of 0.5 mm-long W.S. fibers (3.500×10^{-7} m/s i.e., 0.005 of the initial value) for 1, 7, and 14 day-cured specimens, respectively. It is worth mentioning that the optimum conditions corresponding to 1 day curing were not included in the initial experimental program (Taguchi's DOE). However, the Taguchi method could appropriately predict it, demonstrating the high capability of this method in geotechnical engineering problems.

This drastic reduction in the hydraulic conductivity of the sandy soil can be attributed to boding the soil particles by lignocellulosic fibers. Moreover, as fibers absorb water, their viscosity increases. These two factors contribute to filling the pores and the subsequent bio-clogging which are highly influential to reduce the hydraulic conductivity [20]. Besides, curing time has a predominantly decreasing effect on the hydraulic conductivity of the reinforced species (Table 5). This may be attributed to the increased viscosity of the fibers and growing bio-clogging. However, the early degradation of O.C. fibers may lead to the increased hydraulic conductivity of 14 day-cured specimen reinforced with 1% of 1.5 mm-long O.C. compared to the 7 day-cured sample.

Despite various benefits of lignocellulosic fibers including economic and environmental ones, their low durability is considered the main challenge facing the application of such fibers in soil reinforcement projects [44]. To overcome this problem, a wide range of techniques such as chemical pretreatment and coating have been proposed [45]. Depending on which characteristics of lignocellulosic fibers (i.e., water absorption capacity, tensile strength, etc.) are more favorable for a specific project, the appropriate method can be applied. Besides the low durability of lignocellulosic fibers, the other problem hindering the extensive use of such fibers in geotechnical engineering projects is the lack of large-scale investigations. So far, most studies have been conducted in small-scale laboratory investigations. Therefore, more large-scale tests must be conducted to understand the real effect of fibers reinforcement irrespective of boundary conditions [1].

4- Conclusions

In this study, Taguchi's DOE was used to determine the optimum conditions corresponding to the hydraulic conductivity reduction of 1, 7, and 14 days-cured specimens. By considering the hydraulic conductivity values of the Taguchi's DOE and the predicted conditions, it is observed that 2% of 1 mm-long S.W. fibers leads to the lowest hydraulic conductivity among 1 day-cured specimen. Moreover, the use of 1% of 1.5 mm-long O.C. fibers and 1% of 0.5 mm-long W.S. fibers causes the highest decrease in the hydraulic conductivity of 7 and 14 day-cured specimens, respectively. It should be noted that the optimum conditions corresponding to the 1 day-curing were not included in the Taguchi's DOE. However, the Taguchi method could appropriately predict it. Therefore, the Taguchi methodology is useful in determining the optimum conditions via a limited number of tests, leading to a considerable reduction in time as well as laboratory costs. Moreover, according to the ANOVA results of S/N ratios, fiber content is the most influential factor in lowering the hydraulic conductivity of 1 and 14 day-cured specimens whereas fiber length has shown to be the most effective factor in reducing the hydraulic conductivity of 7 day-cured specimens. In contrast, type of the fibers, fiber content, and length of the fibers are the least influential parameters in lowering the hydraulic conductivity coefficients of 1, 7, and 14 day-cured samples, respectively. Furthermore, curing time has a predominantly decreasing effect on the hydraulic conductivity which can be attributed to the growing bio-clogging effect of such fibers. Although the positive effect of lignocellulosic fibers on the hydraulic conductivity of the reinforced specimens is demonstrated in laboratory-scale studies, more large-scale investigations should be conducted to evaluate the suitability of these materials in geotechnical engineering.

Nomenclature

a_L	Number of levels
ANOVA	Analysis of variance
b_F	Number of factors
D	Diameter, mm
D_r	Relative density
G_s	Specific gravity
H	Height, mm
K_s	Hydraulic conductivity coefficient, m/s
N	Standard deviation
n	Number of repetitions for an experimental combination
OA	Orthogonal array
$O.C.$	Old containers pulp
P	Percent
S	Mean
$S.W.$	Softwoods bleached pulp
$W.S.$	Wheat straw soda high yield pulp
Y_0	Nominal value
Y_i	Performance value of the i_{th} experiment

Greek symbols

$\gamma_{d(max)}$	Maximum dry unit weight
ω	Optimum moisture

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