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Indirect measure of shear strength parameters of fiber-reinforced sandy soil using laboratory tests and intelligent systems

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Abstract. In this paper, practical predictive models for soil shear strength parameters are proposed. As cohesion and internal friction angle are of essential shear strength parameters in any geotechnical studies, we try to predict them via artificial neural network (ANN) and neuro-imperialism approaches. The proposed models was based on the result of a series of consolidated undrained triaxial tests were conducted on reinforced sandy soil. The experimental program surveys the increase in internal friction angle of sandy soil due to addition of polypropylene fibers with different lengths and percentages. According to the result of the experimental study, the most important parameters impact on internal friction angle i.e., fiber percentage, fiber length, deviator stress, and pore water pressure were selected as predictive model inputs. The inputs were used to construct several ANN and neuro-imperialism models and a series of statistical indices were calculated to evaluate the prediction accuracy of the developed models. Both simulation results and the values of computed indices confirm that the newly-proposed neuro-imperialism model performs noticeably better comparing to the proposed ANN model. While neuro-imperialism model has training and test error values of 0.068 and 0.094, respectively, ANN model give error values of 0.083 for training sets and 0.26 for testing sets. Therefore, the neuro-imperialism can provide a new applicable model to effectively predict the internal friction angle of fiber-reinforced sandy soil.

Keywords: shear strength; reinforced-soil; artificial neural network; neuro-imperialism

1. Introduction

Providing an accurate estimate of shear strength of soils is of foremost importance in geotechnical investigation of any soil structures like embankments, highways and earthfill dams. Physical and mechanical properties play pivotal role in shear strength behavior of soils, and most importantly, angle of internal friction, commonly known as internal friction angle (ϕ) and interlocking of particles which known as cohesion (c) are determinant (Gan *et al.* 1988, De Blasio 2011). By developing geotechnical science during last century, vast research and studies result in establishment of several experimental techniques for assessment and determining the parameters relating to soil's shear strength which researchers advantaged them to investigate different soil type in various conditions. Main categories include the triaxial compression test, directional shear cell test, true triaxial test, plane strain compression test, and hollow cylinder apparatus (Donaghe *et al.* 1988, Guo 2008).

The application of reinforcing elements in soil has been commonplace in the far past like fixing steep slopes using vegetation or mixing straw in mortals. Soil reinforcement is one of the significant branches of geotechnical science, which utilizing scientific principles and new technologies, improves the type of materials used in soil reinforcement, and modifies engineering specifications and mechanical properties of soils. Segregated small Pieces and shreds derivative from metals, polymers, or natural materials such as plant components that show suitable physical properties can be benefited as reinforcement element (Michalowski 2004, Li 2005). Despite the long history of soil reinforcement, over the past half century extensive researches have been carried out on the recognition and evaluation of mechanical behavior of fiber-reinforced soil. The idea of reinforcing soil was firstly presented by Vidal in the early 1960s, who drew theoretical principles and practical methods of topic (Vidal 1969). However, mixing fiber in soil known as RDFR (randomly distributed fiber reinforcement) emerged in the early 1970s. In this method, a composite environment is created in which the involvement of tensile components (the reinforcement element) with soil grains improves the strength and soil shape ability. The behavior mechanism of reinforced soil is based on the interaction of soil and reinforcement element so that friction between soil particles and fiber plays fundamental role in enhancing soil properties. Reinforced

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sand with synthetic fiber under direct shear tests (Gray and Ohashi 1983), numerous triaxial compression tests on sand (Gray and Al-Refeai 1986, Maher and Gray 1990), determining soil strength by experimental and analytical methods regarding measure the effect of fiber inclusion (Penumadu *et al.* 1999), stiffness studies to investigate the fiber inclusions in granular soil (Consoli *et al.* 2005), Modified Proctor Compaction test (Tiwari *et al.* 2012), evaluation of compressive strength and ductility of fiber-reinforced cemented sand (Park and materials 2011) are some examples of these researches. Overall, results showed that reinforcement cause an obvious increase in soil shear strength beside a reduction effect in post-peak strength, and the measure of this amendment is proportional to the amount of fibers (Ayoub *et al.* 2011, Hejazi *et al.* 2012). These promising outcomes encourage researchers to suggest reinforced soils for various geotechnical applications.

Given that, aforesaid tests necessitate time, costs and expertized instruments to determine shear parameters of soil in field or laboratories, researchers tried to find new approaches to estimate shear strength parameters of soil. Although empirical techniques have highlighted a successful report in estimating soil parameters, only limited number of these efforts dedicated to proposing models for prediction of shear resistance in soil because of the reinforcement. Most of earlier modelling sought for estimate to what extend fibers participates in improvement of shear strength. Some authors utilized force equilibrium (Gray and Ohashi 1983, Maher and Gray 1990, Ayoub *et al.* 2011), while more recent studies concentrated on energy dissipation in soil mixed by fibers (Michalowski *et al.* 2002, Michalowski 2008). Part of these studies tried to analyze the deformation pattern of structures and provided a fundamental regulation formula for reinforced sand (di Prisco *et al.* 1993). Another kind of work used independent properties of soil and fiber to equivalently predict the shear strength of soil reinforced with fiber, and accordingly proposed a discrete framework to predict the failure mood in reinforced soils (Zornberg 2002). Other fields of providing empirical formulas are relationships that developed with single variable, like study the role of clay content in prediction of residual friction angle (ϕr) (Kaya and Kwong 2007), or investigation the effect of Atterberg limits and presence of clay on ϕr and proposing an empirical formula to predict it (Meyers 1977) or which study the relation between ϕr and ΔPI which is a function of Atterberg limits ($\Delta PI = PI - 0.73(LL-20)$) (Wesley 2004). In all mentioned literatures, good accordance was successfully-showed between predicted results and experimental or actual results.

Another major part of modeling investigation belongs to studies try to benefit mathematical relationships in forms of statistical models based on a simple force-equilibrium to estimate shear strength and more particularly related soil parameters regarding fibers, soil and tests specifications (Waldron 1977, Michalowski, Cermak *et al.* 2002, Babu *et al.* 2008). Based on experimental studies and statistical analysis, these researches concluded that regarding shear strength of fiber-reinforced soil, most important index properties include confining stress, fiber content, aspect ratio, and internal friction angle of soil-fiber mixture. Along with these works, some authors tried to estimate deviator stress in reinforced clays by paraphrasing Cam Clay model (Xia *et al.* 2002, Diambra and Ibraim 2014). More recently, modeling approaches were used to understand behaviors of fiber-reinforced soils subjected to various tests. For instance effects of soil parameters (c and φ) on bearing capacity evaluated using a modeled constructed on elastoplastic finite element analysis (Fenton and Griffiths 2003). Another model was built based on combination of the superposition method with the energy-based homogenization technique in order to fully capture before-failure and failure behaviors of fiber-reinforced clay subjected to triaxial compression (Teng and Lam 2004).

More recently, soft computing techniques, such as gene expression programming, fuzzy system, particle swarm optimization (PSO) and artificial neural network (ANN) have been used alternatively for managing/evaluating various geotechnical problems (Zhou *et al.* 2016, Koopialipoor *et al.* 2017, Wang *et al.* 2018). Wide range of soil's properties have been studied by utilizing this promising approach and large part of these investigations aim to estimating soil shear strength (Khalilmoghadam *et al.* 2009) or predict the friction angle of soils (Zorlu *et al.* 2008, Kayadelen *et al.* 2009, Göktepe and Sezer 2010). In this regard, ANN particularly showed high potential as an alternative method for predicting internal friction angle. For instance an ANN model using four various soil properties including CF(clay fraction), LL (liquid limit), PI (plasticity index), ΔPI (i.e., the deviation from the A-line in classification chart;$\Delta PI=PI-0.73$ (LL - 20)) allow prediction of residual friction angle regarding fraction of clay soil and its Atterberg's limits (Das and Basudhar 2008). In other study, (Khalilmoghadam *et al.* 2009) tried to predict shear strength of surface soil by applying some soil index such as distribution of particle size, vegetation attributes (NDVI), topographic properties, and specific organic elements in soil, as inputs in three different ANNs to investigate erosion. In a very recent work, (Aghajani *et al.* 2015) based on performed stress rotation tests, tried to predict effect of loading orientation in sand friction angle using seven parameters (stress ratio, confining consolidation pressure, void ratio, sample preparation, mean diameter (D505) of sand particles, angularity of grain and stress direction) as inputs. They processed an ANN modelling regarding sensitivity analyses and showed that soils with lower grain size experience more anisotropic effects on shear strength, and angularity of grains amplify this effects. In another remarkable study conducted by (Pham *et al.* 2018), four machine learning methods i.e., PANFIS (particle swarm optimization-adaptive network based fuzzy inference system) and GANFIS (genetic algorithm-adaptive network based fuzzy inference system) which both are soft computing/intelligence methods developed by integrating neural fuzzy models and metaheuristic optimization algorithms, SVR (support vector regression), and (ANN), applied to predict strength of the fine-grained soils. For this purpose, they constructed training and testing datasets of the mentioned techniques based on results of 188 clay soil samples. Using shear strength parameters of 230 shale samples obtained from triaxial compression test as inputs, (Armaghani *et al.* 2014) proposed an integrated PSO-ANN model to predict shear strength parameters as outputs. Generally, high correlation of the proposed hybrid ANN models inferred their satisfying accuracy and applicability.

As mentioned previously, precursor numerical approaches are integrated with intelligent techniques that have led to new artificial intelligence methods. These techniques have been proposed to solve the numerical problems, and their accuracy has been proved to predict and optimize the experimental data. There are some existing systems like machine learning, natural algorithms (particle swarm optimization, bee colony), and genetic algorithm, which are the most useful methods to provide reliable results in addition to saving time and cost (Shariati *et al.* 2011, Arabnejad Khanouki *et al.* 2011, Daie *et al.* 2011, Sinaei *et al.* 2011, Mohammadhassani *et al.* 2013, Mohammadhassani *et al.* 2014, Toghroli *et al.* 2014, Safa *et al.* 2016, Toghroli *et al.* 2016, Sadeghipour Chahnasir *et al.* 2018, Sedghi *et al.* 2018, Shariat *et al.* 2018, Zandi *et al.* 2018, Katebi *et al.* 2019, Luo *et al.* 2019, Mansouri *et al.* 2019, Milovancevic *et al.* 2019, Shariati *et al.* 2019, Shariati *et al.* 2019, Shariati *et al.* 2019, Shariati *et al.* 2019, Trung *et al.* 2019, Safa *et al.* 2020, Shariati *et al.* 2020, Shariati *et al.* 2020, Shariati *et al.* 2020).

Composite systems have always been of interest to researchers, which benefit from the combined properties of different materials simultaneously. Shear connectors are generally used in steel-concrete composite systems to establish a connection through which the developed shear forces at the interface of the materials can be collected and transferred. Hence, the proper performance of the composite systems largely depends on the behaviour of the used shear connectors at the interface of the materials (Shariati *et al.* 2010, Shariati *et al.* 2011, Shariati *et al.* 2011a, b, Shariati *et al.* 2012, Shariati *et al.* 2012, Shariati 2013, Shariati *et al.* 2014, Shariati *et al.* 2015, Khorramian *et al.* 2016, Shah *et al.* 2016, Shahabi *et al.* 2016, Shahabi *et al.* 2016, Tahmasbi *et al.* 2016, Khorramian *et al.* 2017, Shariati *et al.* 2017, Hosseinpour *et al.* 2018, Ismail *et al.* 2018, Nasrollahi *et al.* 2018, Paknahad *et al.* 2018, Wei *et al.* 2018, Davoodnabi *et al.* 2019, Shariati *et al.* 2020).

Seismic events are always an issue for the researchers, which have investigated the dynamic response of the structural elements through several studies. Different types of structural components have been introduced to mitigate the seismic effects on the building, such as damper and composite columns (Shariati 2008, Arabnejad Khanouki *et al.* 2010, Jalali *et al.* 2012, Khorami *et al.* 2017, Khorami *et al.* 2017, Shariati 2020).

Cold-formed steel storage rack structures are widely used in different industries to store the products in safe and secure warehouses before distribution to the market. Racking systems lose their stability under lateral loads, such as seismic actions due to the slenderness of elements and low ductility. This justifies a need for more investigation on these systems to improve their behaviour and increase their capacity to survive medium to severe loads. By investigating the original rotational stiffness value, moment resistance, ductility, and failure mode of the connection, a standardized connection can be established to improve the performance of the rack structures (Mohammadhassani *et al.* 2014, Shah *et al.* 2015, Shah *et al.* 2016, Shah *et al.* 2016, Shariati *et al.* 2018, Chen *et al.* 2019).

Pervious concrete is a type of porous concrete, which can be effectively used in pavement applications as an alternative to conventional concrete. Pervious concrete pavements allow the excessive surface runoff to soak into the soil, thereby mitigating the risk of urban flooding. The use of recycled concrete aggregate (RCA) can make pervious concrete as a more environmental-friendly material (Toghroli *et al.* 2017, Toghroli *et al.* 2018, Li *et al.* 2019, Shariati *et al.* 2019, Toghroli *et al.* 2020).

Concrete has outstanding compressive strength due to its dense and robust texture that does not experience the local or distortional buckling or other accidental deformations along with low flexural and tensional strength. This made the concrete as a useful material for columns axial structural elements. Self-consolidating concrete is a kind of concrete in which fluidity and workability parameters should be enhanced (Nosrati *et al.* 2018, Ziaei-Nia *et al.* 2018, Sajedi and Shariati 2019, Shariati *et al.* 2019, Xie *et al.* 2019). Moreover, various studies have been conducted to investigate the effect of vegetation on the slope angles and soil parameters. In another study, the effect of geogrid layers and length of piles on the foundation settlement has been evaluated. In addition, the strain rate effect on soil-geosynthetic interaction has been investigated, and it was found that increasing strain rate leads to increment in shear strength (Safa *et al.* 2019, Shariati *et al.* 2019, Suhatril *et al.* 2019).

Despite using ANN techniques in literatures in order to resolving various civil and geotechnical problems (Armaghani *et al.* 2015, Tonnizam Mohamad *et al.* 2017, Bejarbaneh *et al.* 2018), some studies (e.g., Wang *et al.* 2004) confirmed that ANN has several inherent limitations such as lagging in learning rate and getting trapped in local minima. So, using optimization algorithms (OAs) such as imperialism competitive algorithm (ICA), genetic algorithm (GA) and particle swarm optimization (PSO) show significant gain in order to dominate these restrictions and allow promotion of models predicted by adjusting bias and weight of ANNs. Recently, considerable capacity of these algorithms drew more attentions and researchers tried to combine them in order to optimize ANN models. In this study, based on a series of laboratory tests, the effects of adding fibers to sandy soils on its shear strength are investigated. Then, shear strength parameters of the fiber-reinforced sandy soil are predicted through the most effective input parameters developing ANN and neuro-imperialism models. Eventually, the obtained models are evaluated and compared in order to find the best predictive model for prediction of internal friction angle.

2. Methods

2.1 Artificial neural network

Artificial Neural Network (ANN) refers to a computational system simulating the principles of the human beings' neural system in a way to configure. an artificial system. The ANN-based models typically make use of input training patterns for the purpose of developing accurate predictions regarding the automatic relationships between input and output data, which makes a big difference between this system and any other system working in this field (Zurada 1992). In an attempt to imitate a biological brain, an ANN utilizes the artificial neurons as fundamental units in a way to process data in a parallel behavior. As a pioneering study making attempt to model the neural network, (McCulloch and Pitts 1943) constructed a binary decision unit and succeeded to model effectively the artificial neurons' behaviors. In their system, any artificial node was assigned with the total weight of input signals; then, activation function was applied to these signals. This way, they could obtain an output of a higher accuracy level.

The instruction of the network for certain training samples remarkably modifies and upgrades the performance of the network. In fact, in the course of the training stage, it is possible to minimize error in case of the output of any node within every layer. This can be done through the repetitive modification of the connection weights. The error generated for the output is function of the error square as expressed in the following equation:

$$E = \frac{1}{2}\sum_{i=1}^{p}(t^{(i)} - y^{(i)})^2 \tag{1}$$

where t stands for target value, y denotes the actual value generated, and P signifies the number of training patterns.

From a structural perspective, the ANN functions fall into two main groups: feed-forward and feedback. Among the feed-forward multilayer networks with highest popularity, multilayer perceptron (MLP) is the one that processes the available data through the use of activation functions within consecutive layers (Simpson 1990). The back-propagation (BP) makes use of a learning procedure-based gradient in order to help the network to learn. BP that is consisted of a twofold training cycle (a forward and a backward stage) is capable of delivering acceptable results, especially for those nets that contain feed-forward multilayer. Other scholars in more complementary investigations have given more explanations in regard to the operation of each stage (Koopialipoor *et al.* 2018, Zhou *et al.* 2019). As demonstrated by these researchers, during one stage, input signals move forwards and transmit error signal for each node that exists in the output layer; after that, the resultant error rates are moved backwards. This way, the weights and biases of network are modified. In general, each neuron's output is generated through applying a number of activation functions to inputs. Then, the outputs will be transmitted to the neurons existing within subsequent layer as inputs. Principally, the activation function type is determined depending on complexity of the problem in hand. For that reason, in case of nonlinear problems, sigmoid transfer functions such as log or tangent sigmoid can be effectively used (Haykin 1999, Priddy and Keller 2005).

In each layer of the system, the incoming signal (x_i) that is multiplied by the corresponding weight coefficient (w_{ij}) shows the total weighted net input. Then, the summation function is applied to the obtained result; next, a little bias is added to it and the hidden neurons are fed with final results. The overall output of the system is formed through the iterative performance of this process. The following is the mathematical equation for every output neuron-based total net input:

$$net_{h_j} = \sum_{i=1}^{n} w_{ij} \cdot x_i + b_j \tag{2}$$

As a result, the total net input passes through the activation function, e.g., the sigmoid function, in such a way that each hidden or output neuron can be computed using Eq. (3) as follows:

$$y_j = 1\Big/\left(1 + \exp\left\{-net_{h_j}\right\}\right) \tag{3}$$

2.2 Imperialism competitive algorithm

The Imperialism Competitive algorithm (ICA) was originally proposed by 54545 (Atashpaz-Gargari and Lucas 2007). This algorithm is based on population and can be used in global searching purposes. It can be effectively applied to optimization problems that appear in science and engineering fields. Similar to other optimization algorithms like PSO, the ICA operation is also started with a random initial population denoted by countries. After the production of N countries ($N_{country}$), the countries with minimum costs or objective functions, e.g., root mean square error (RMSE), will be selected and assigned as imperialists (N_{imp}), while the others will be allocated to the imperialists as their colonies (N_{col}). Remember that the colonies are distributed among the existing imperialists depending on the initial power of the empires. As a result, more intense imperialists (with minimum RMSE) will obtain more colonies. ICA consists of three operators, namely the assimilation, revolution, and competition. Through assimilation and revolution, each colony will be capable of achieving a state better than that of its corresponding imperialist. If it occurs, the colony can take the control of the empire and transformed to an imperialist.

Through the competition operator, imperialists make effort to take control of the other empires' colonies as more as possible. Any empire can take the possession of at least one colony belonging to the weakest empire in the system. Therefore, the empires' power is the key factor in this phase. The ICA operation stops in two conditions: when the most powerful empire is remained in power and all others have been collapsed, or when a predefined stopping criterion is satisfied (i.e., the achievement of a desired RMSE value or the maximum number of decades). This is worth mentioning that, in ICA, the number of decades (N_{decade}) is theoretically similar to the number of iterations in PSO. Though, in the present study, the ICA mathematical formulation is not provided. The flowchart of ICA is presented in Fig. 1. For more detailed information regarding ICA, you can refer to literature (Hajihassani *et al.* 2014, Armaghani *et al.* 2017).

2.3 Hybrid algorithms

The ANN performance quality has been enhanced by lots of scholars using some optimization algorithms, e.g., PSO, and ICA. On the other hand, the ANN optimum search process has offered no satisfactory solution; the reason is that BP is a local search learning algorithm (Liou *et al.* 2009). For that reason, the adjustment of the weight and bias of ANN with the use of optimization algorithms can result in improving the ANNs prediction capabilities. This is true that the ANNs local minimum commonly offers a higher contingency of convergence, but the optimization algorithms are able to explore global minimum. Thus, hybrid systems such as ICA-ANN have the search advantages of ANN and ICA. In such systems, ICA explores the global minimum within the search space, whereas ANN searches for obtaining the perfect system results. For more details regarding these hybrid models, you can refer to the previous studies.

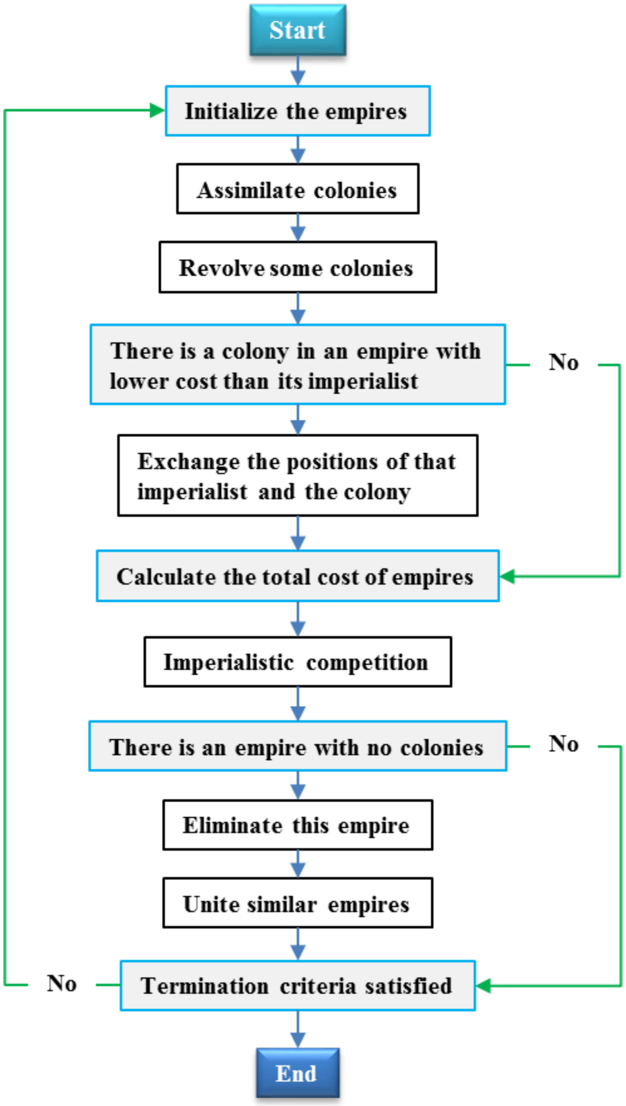


Fig. 1 ICA flowchart (Liou *et al.* 2009)

3. Experimental framework and established database

3.1 Conducted test procedure

In this study, the effects of adding fibers to a type of sandy soils on its shear strength and deformation characteristics were investigated. In this regard, a series of consolidated undrained triaxial tests (ASTM D 4767-88) have performed to survey inherent strength increase due to addition of polypropylene fibers to this kind of soil. A relatively uniformly graded sand with low content of silt, that according to Unified Soil Classification System (USCS) (Soil and Rock 2017) classified as SP was used in this study. According to standard Proctor compaction tests, maximum dry density of the soil was approximately obtained as 18.4 N/m^3 with an optimum moisture content of 15.4%. Fig. 2 shows the particle size distribution of studied sand. Reinforcement elements are Polypropylene DTY (Dipped Tire Yarn) fibers which are waste material, produced by Zanjan Tire Cord Co. Based on information provided by the tire factory, the fibers have density of 9.1 kN/m^3, increase in length up to 23% at break point, and tensile strength as 309 N.

The height and diameter of cylinder specimens tested in this investigation were reported as 150-mm and 70-mm, respectively. They all prepared by under compaction method in six layers, so that final density of soil specimens is 15.4 kN/m^3 and moisture content in all the specimens was kept at a constant value of 12%. In order to prepare homogeneous specimens, required weights of soil and fibers were divided to four equal portions and each part of soil was mixed well with fibers. Soil samples reinforced with fibers that vary by 0, 0.5%, 1.0% and 1.5% of weight of dry soil, with three different lengths including 1, 2 and 3 cm. Moreover, repeatability of experiments studied by performing verification tests as well. When mixing and preparing samples, it was intended that fibers distribute randomly so that isotropy of specimens can be assumed.

In order to evaluate the stress-strain and shear strength behavior of fiber-reinforced specimens, a total of thirty consolidated undrained triaxial compression tests were conducted. For all specimens, back pressure method was used for saturate samples initially. During this stage, B coefficient of Skempton's pore pressure was gauged constantly. After B-parameters exceeded 0.98%, the consolidation process conducted at three different confining pressures of 50, 100 and 150 KPa. By completing the phase of saturation and consolidation, with a controlled strain rate of 0.15% per minute, compression load was applied. Applying deviator stress continued until strain of 20%, except for samples that experience failure before this specific strain. Fig. 3 demonstrates different stage of running a triaxial test.

3.2 Test results

The effects of length and percentage of fibers studied by triaxial tests under three different confining pressures. In Fig. 4, stress-strain diagram is presented for different fiber contents at different confining pressures.

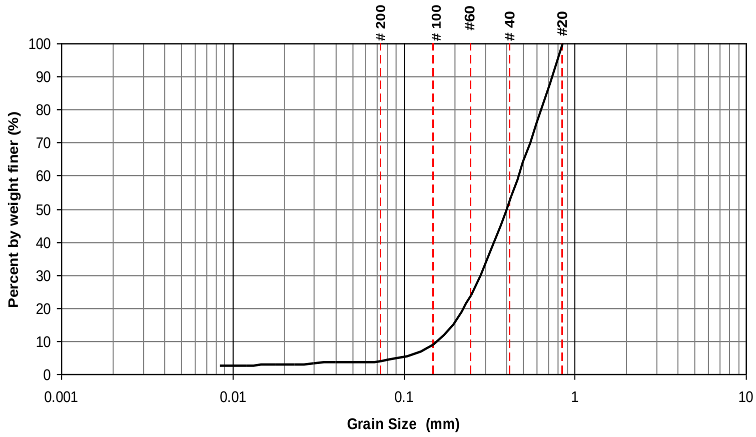
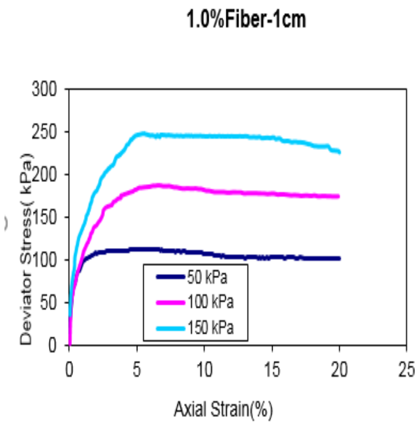
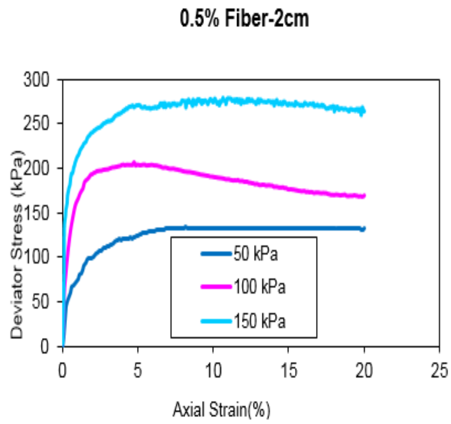


Fig. 2 Grain size distribution curve for the used material

Fig. 3 Different steps of running triaxial test on reinforced sand specimen

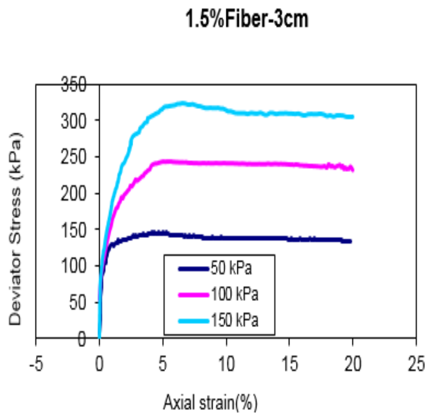


(a) (1.0%-1 cm)



(b) (0.5%-2 cm)

Fig. 4 Examples of Stress-strain response for different fiber contents at different confining pressures



(c) (1.5%-3 cm)

Fig. 4 Continued

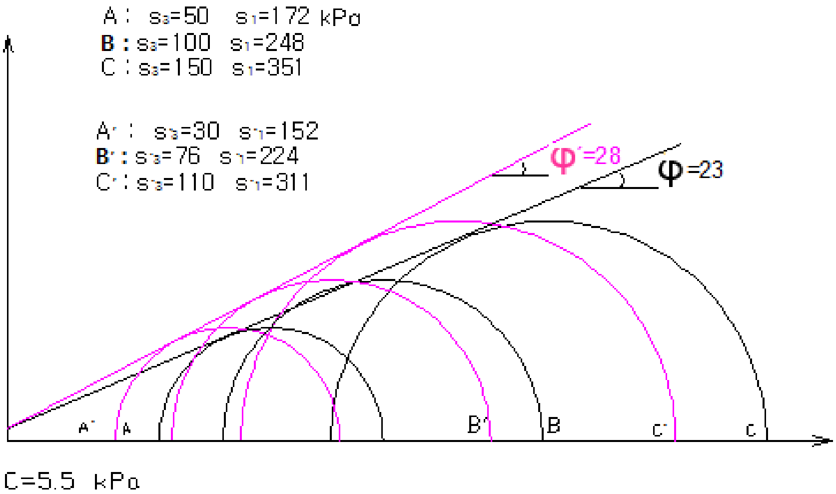
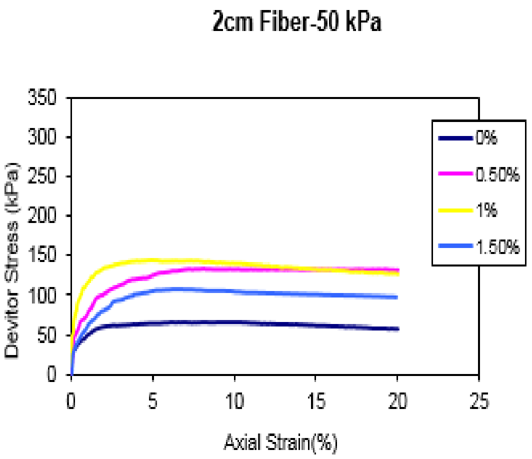
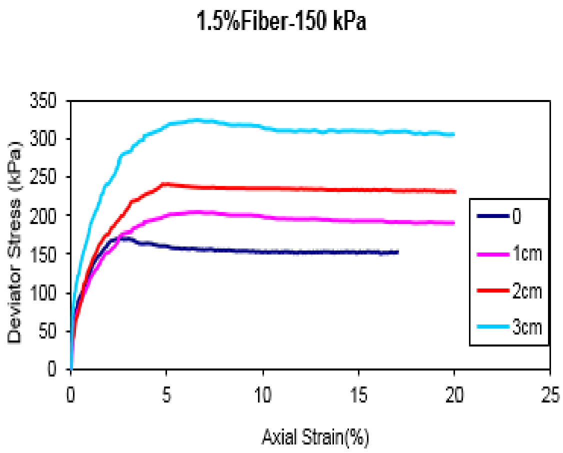


Fig. 5 Mohr-Coulomb failure envelopes for a reinforced specimen with 0.5% fiber and 1cm length (unreinforced specimen ϕ=21° and C=0)



(a) Effect of different fiber percentage



(b) Effect of different fiber length

Fig. 6 Effect of different length and percentage of fiber

Based on these diagrams and other measurements obtained from CU tests, Deviator stresses ($\Delta\sigma$) are determined and Mohr-Coulomb failure envelopes were depicted to calculate the internal frictional angle (φ) and cohesion (C) of reinforced soil. Mohr-Coulomb failure envelopes for specimen reinforced with 0.5% fiber 1 cm are presented in Fig. 5.

According to the obtained laboratory results, the considerably increase in strength of soil because of adding fibers is obvious, especially in term of internal friction angle results. In the following, effects of different parameters on shear strength results will be discussed in

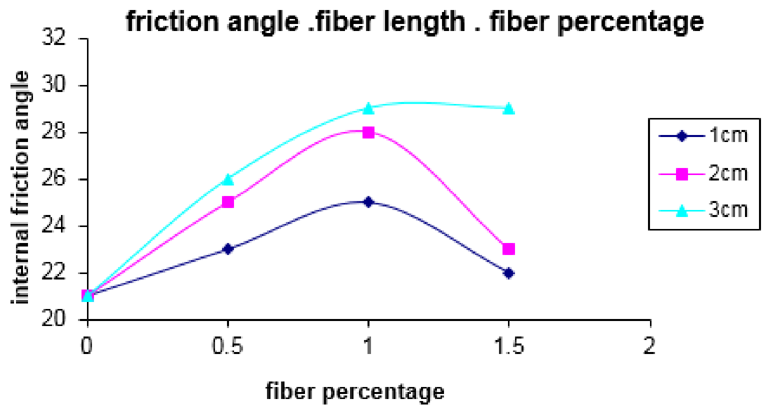


Fig. 7 Changes in internal friction angle in terms of length and percentage of fiber

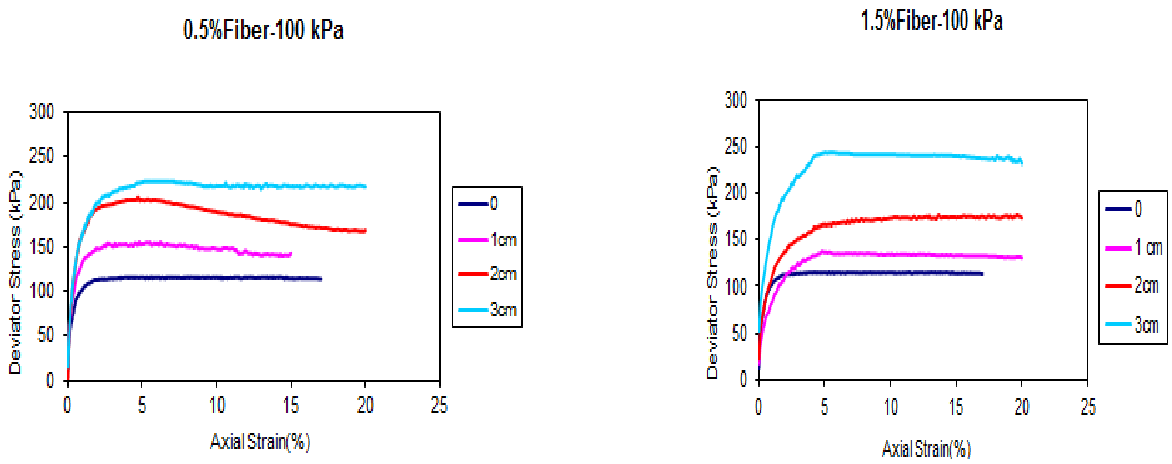


Fig. 8 Effects of fiber content in increasing Deviator Stress

more detail.

3.2.1 Effects of length and weight percent of fiber

Based on results, in constant fiber percentage, more fiber length, more increases in the strength of the samples was observed in all cases. On the other hand, in constant confining pressures and fiber length, increasing in fiber percentage result in improved ultimate strength of samples and this improvement has a direct relationship with fiber percentage (Fig. 6). However, all results showed that there is an optimum value for fiber percentages and fiber length regarding any discussed parameter including shear strength or test parameters. Generally, it can be said that strength obtained by reinforced specimens with 1.5% fiber always are less than specimens with 1.0% fiber reinforcement. It seems that, despite the positive effect of tensile strength of fiber in shear strength of soil, in higher fiber percentage, replacing more soil with fiber, which play a separator role between soil particles, determine the behavior of reinforced soil. With respect to the interactions of fiber percentages and fiber lengths, it is not possible to attribute improvement in resistance properties of the reinforced soil to only one of these two parameters.

3.2.2 Shear strength parameters (C, φ)

Of the most important goals of reinforcing soil is to enhance the shear strength of soils. As mentioned before, failure envelopes depicted based CU tests results. Accordingly, internal friction angle increase from 21° for unreinforced sample, to 29° in its maximum value for sample reinforced with 1.5% fiber 3 cm. The values for cohesion are zero for unreinforced sandy soil to 22.8 kPa in its highest level for soil reinforced with 0.5% fiber 3 cm. This significant increase can be a promising indicative of the potential of soil reinforcement on improving soil shear strength. Fig. 7 shows the variations in the internal friction angle based on the percentage and length of the fibers.

It could be seen that increasing in fiber percentage up to 1% has improvement effect on friction angle, but after this specific percentage, values decreased for higher fiber percentage. However, for 3cm fiber, this trend becomes different and sample achieves the highest value for φ. It seems that length of fiber plays more important role in enhancing strength properties of soil. In other word, this means fiber’s mobilized tensile force is controlling parameter in increasing strength of specimens. Moreover, as fiber has higher tensile strength (309N) comparing to tensile forces arising during the test, tension failure of fibers here is not the case. The failure mood of the samples in a triaxial tests confirms that the performance of reinforcement elements on the failure plane was slipping not rupturing. Once again, this is predictable due to the high resistance of DTY fibers to tensile strength. This mechanism reported in other similar studies (Babu, Vasudevan *et al.* 2008).

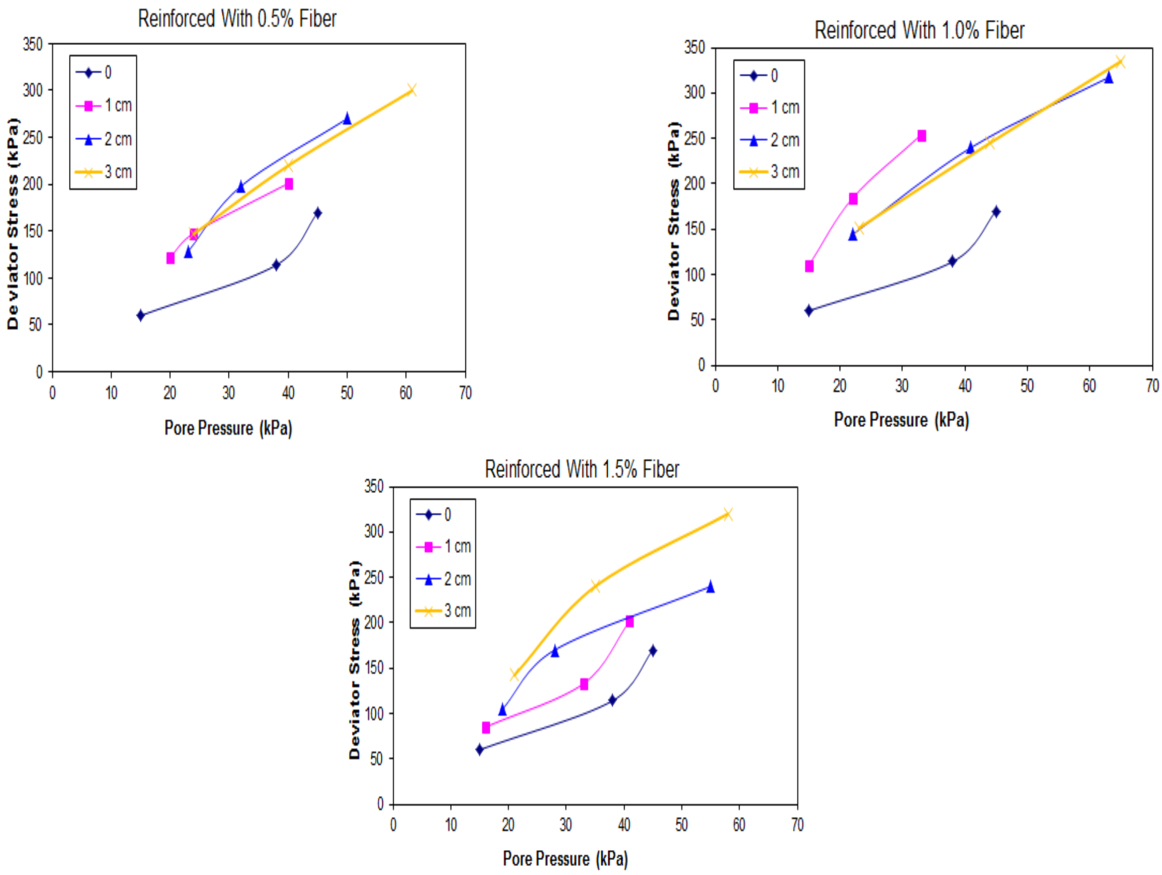


Fig. 9 Effects of fiber presence on deviator stress and pore pressure

3.2.3 Deviator stress (Δσ)

Based on the obtained results, with increase in fiber content, a tendency for increase in deviator stress was observed at each normal stress. This behavior can be attributed to fiber. Hypothetically, fibers undertake part of induced stresses so that frictional interaction between fiber and soil result in additional confinement effect. However, in some cases with lower fiber contents, after reaching higher strain levels, deviator stress remains constant. The results show that in higher confining stress, deviator stress in failure point increases. Furthermore, by adding fibers to soil, failure deviator stress has enhanced (see Fig. 8).

3.2.4 Confining pressure and pore pressure (u)

As all performed tests are consolidated undrained test, and drainage is not permitted during increase of deviator stress, the pore water pressure due to deviator stress (u) increases in the specimen. Pore pressures measured simultaneously during the test and take a direct effect of confining pressure. This means pore pressure could also be a representative for confining stress which stay constant and take three different values (50, 100 and 150 kPa) in each set of CU test, and does not play a direct role in soil reinforcement investigation. However, effects of confining stress should not be underestimated. It seems that in fiber presence, various confining pressures create different pull-out resistance in fibers that lead to a determinant impact on performance of fiber in soil specimen. In Fig. 9, effects of fiber content and length in deviator stress and pore pressure are presented. As it can be seen, by increasing in fiber length and weight content, the Deviator Stress and consequently pore pressure increase too.

3.2.5 Deformation of reinforced soil

Based on the results obtained in this study, reinforced soil shows more elastic behavior has in comparison with unreinforced soil. In other words, while soil sample without fiber behaves similar to a brittle material, by adding fiber, it becomes softer and more shap able. These changes in behavior can be deduced from the reduction of the initial slope of the curves and the increase of the strain at the maximum stress point (strain of fracture). It is evident that changing the behavior of the soil from fragile to more elastic along with increasing soil strength is a significant advantage in changing the behavior of reinforced soil.

3.3 Selection of input parameters

This study investigates the effects of reinforcement on improvement of shear strength of sandy soil. Regarding that, determining friction angle value is a major requirement for design process of any geotechnical structures, the use of modeling techniques for prediction of ϕ value of soils could save many costs and labor. Following some earlier studies (Das and Basudhar 2008, Kayadelen, Günaydın *et al.* 2009), in the content of this paper, new approach based on ICA-ANN is presented for the prediction of internal friction angle of the soils.

Table 1 Descriptive statistics of the experimental database in this research

Parameter/Category	Unit	Range
Percentage of fiber/Input	%	0-2
Length of fiber/Input	cm	0-3
Deviator stress/Input	kPa	60-335
Pore water pressure/Input	kPa	15-65
Internal friction angle/Output	Degree	21-29

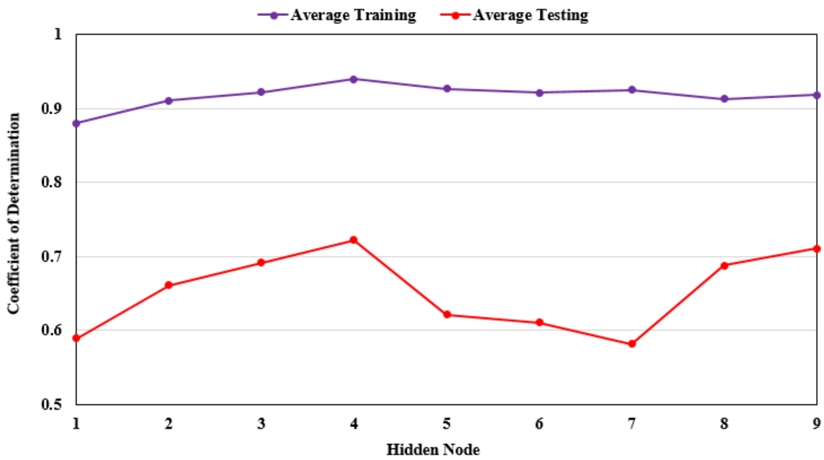


Fig. 10 ANN results to predict internal friction angle of the fiber-reinforced sandy soil

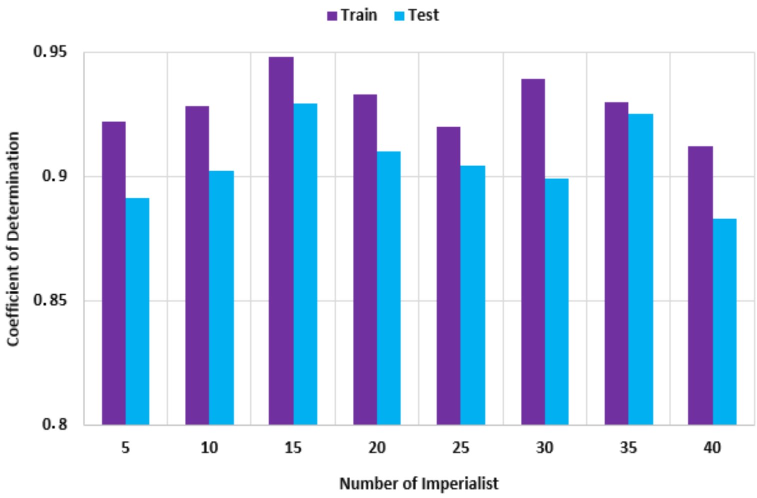


Fig. 11 Different values of N_{imp} with their results of R^2

Any attempt to construct a model to predict effects of reinforcement on shear strength of soil and more specifically soil's friction angle, require distinguishing the variables that are significant enough to be considered as inputs of the model. The overall review of achieved result presented in above sections show that percentage and length of fiber are two significant parameters that effect directly on improvement of shear strength. Deviator stress ($\Delta\sigma$) and pore water pressure (u), considered as two other determinant variables that influenced by presence of fiber in soil specimens and affect the outcomes. The review of the obtained results proved that shear strength parameters increase significantly due to addition of fibers. All result can be summarized as:

1- The increase in the strength of the samples, which is directly related to the tensile strength of the fibers, is a function of the confining pressure and the coefficient of friction between the soil and the fibers.

2- Increase the internal friction angle and soil adhesion; an increase in the angle of internal friction in the soil indicates increased resistance mainly due to the slippage of the fibers in the reinforced soil environment.

3- Soil reinforcement reduces fragile behavior of soil and increases its shape ability.

According to review of the previous investigations and available results of laboratory tests, the authors have decided to use fiber percentage, fiber length, and deviator stress and pore water pressure as model inputs for prediction of angle of internal friction of the sand soil combined with fiber. Therefore, in the modeling of this study, these parameters were utilized for applying intelligent systems. Table 1 shows ranges of the input and output parameters used in this study.

4. Developing of intelligent techniques

4.1 ANN model

According to (Liou *et al.* 2009), ANN modelling starts with normalizing developed datasets and design procedure facilitate by this equation:

$$Xnorm = (X - Xmin) / (Xmax-Xmin) \tag{4}$$

where *X* is measured values whereas *Xnorm* is normalized values and *Xmax* and *Xmin* stand for maximum and minimum values of the *X* respectively.

After that, it is the time to distinguish the datasets on the basis of their testing or training nature, previous to starting the model assessment process. According to Nelson and Illingworth (Nelson and Illingworth 1991), it is better to assign approximately 20-30 percent of available datasets to testing datasets. As a result, we allocated 20% of whole datasets to testing datasets. Since prosperous applying of Levenberg–Marquardt (LM) training algorithm has noticed in many researches (Monjezi *et al.* 2012), it was also used in this study to implement ANN. Moreover, an ANN with one hidden layer is capable to approximate any continuous function, reportedly. Characterize the number of hidden nodes fulfilled by (Hornik *et al.* 1989) suggested formula that is based on Ni as number of input layers in form of $\leq 2\times Ni + 1$. Replacing Ni = 4 in this equation indicate that the problem of internal friction angle can be solved by a range of 1 to 9. Therefore, for each node, 10 ANN models were constructed to predict internal friction angle and the results were considered as coefficient of determination (R^2). The average values of R^2 for training and testing datasets are shown in Fig. 10. According to this figure and considering results of training and testing, testing results of all nodes are remarkably lower than training results. As a result, ANN model with 4 hidden nodes is able to deliver the best results in predicting internal friction angle of the fiber-reinforced sandy soil. Therefore, the best ANN model among all 10 models constructed with 4 hidden nodes (with R^2 values of 0.941 and 0.728) was selected in this study. It is confirmed that the optimum ANN to predict friction angle of reinforced sandy soil would have the architecture of $4\times 4\times 1$. More details of the selected ANN model will be given later.

4.2 Neuro-imperialism model

ICA-ANN or neuro-imperialism modelling consists of investigating and then designing the most important factors of ICA which are N_{imp}, $N_{country}$, and N_{decade}. To design N_{imp}, different values for this parameter were considered and based on them, several neuro-imperialism models were conducted to predict internal friction angle. The results of analyses based on R^2 values are presented in Fig. 11. Based on this figure, among N_{imp} of 5, 10, 15, 20, 25, 30, 35 and 40, R^2 results of N_{imp} = 15 are better than the other N_{imp} values. Therefore, N_{imp} = 15 was selected as the best one and it will be used in the following parts of modelling.

Till now, approximating various geotechnical engineering problems have fulfilled by different values of $N_{country}$. Herein, (Ahmadi *et al.* 2013, Hajihassani, Jahed Armaghani *et al.* 2014) suggested 40, 56, and 135 for appropriate number of $N_{country}$, respectively. According to the mentioned studies, a number of neuro-imperialism models using different $N_{country}$ values between 25 to 500, were performed according to RMSE results as shown in Fig. 12. Based on the results, the minimum error has received by an ICA-ANN model hat used 400 number of country. Hence, $N_{country}$ = 400 is considered as the optimum one in designing neuro-imperialism hybrid model. In next stage, N_{decade} as another important parameter of ICA, must be also determined. The effects of N_{decade} on efficiency of the network were investigated by conducting the same parametric study presented in Fig. 12. A maximum number of 500 was set for number of decade in this study and 12 neuro-imperialism models were built using various number of countries. In Fig. 12, after N_{decade} = 350, changes in network performance (RMSE) are ignorable. Having in mind RMSE, as preferable index to assess predictive models considered for characterize N_{decade}, 350 was set/selected as the optimum value. In other word, any value more than 350 cannot lead to excess amendment in network results and only result in waste more time for modelling. Therefore, a neuro-imperialism model with N_{imp}, $N_{country}$, and N_{decade} of 15, 400 and 350, respectively was introduced in this study for prediction of internal friction angle of fiber-reinforced sandy soil. More information regarding the best neuro-imperialism developed in this study will be discussed later. It is worthwhile to mention that MatLab version 7.14.0.739 was utilized to create all intelligent models.

4.3 Model evaluation

In this section, more discussion regarding investigation of results which used for predicting internal friction angle of reinforced soil is rendered. Three performance indices including R^2, RMSE and variance account for (VAF) are considered in evaluating all developed models as:

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (y - y')^2}{\sum_{i=1}^{N} (y - \tilde{y})^2} \tag{5}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (y - y')^2} \tag{6}$$

$$VAF = [1- \frac{var\ (y-y')}{var\ (y)}] \times 100 \tag{7}$$

where, *y* is predicted value of internal friction angle; *y′* is measured value of internal friction angle; $\tilde{y}$ equals to average of *y* values; and the total number of data shows by *N*. The optimum state of model happens when R^2 = 1, VAF = 100 and RMSE = 0.

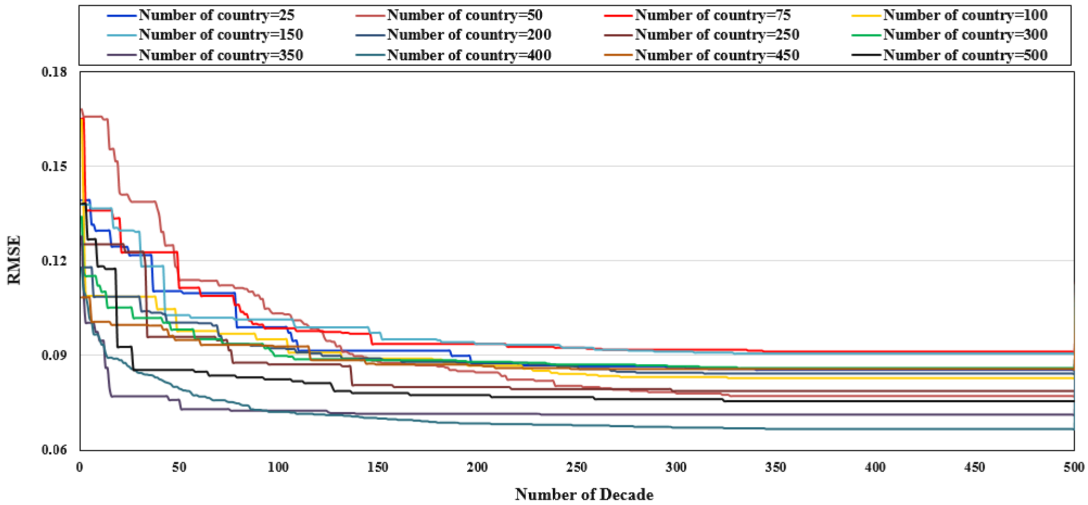


Fig. 12 Effects of number of country and number of decade on network results

Table 2 Performance comparison for the proposed models

Model	Performance Index					
	R^2		RMSE		VAF (%)	
	Train	Test	Train	Test	Train	Test
ANN	0.941	0.728	0.083	0.26	94.109	65.066
Neuro-Imperialism	0.961	0.948	0.068	0.094	95.964	94.585

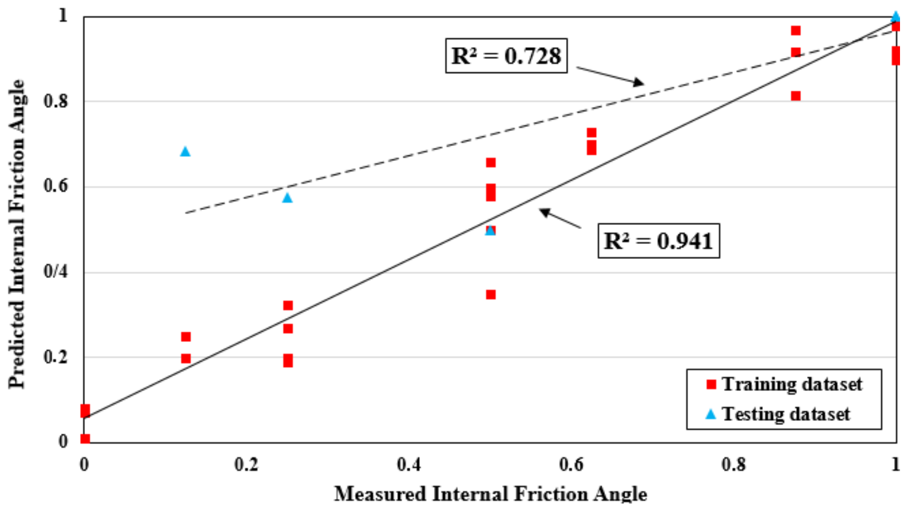


Fig. 13 ANN results in estimating internal friction angle

For comparison purpose, the computed values of performance indices relating to the proposed ANN and neuro-imperialism models are listed in Table 2. According to this table, it is found that both of the proposed models have acceptable prediction results, but the accuracy level of the new neuro-imperialism is more than ANN model especially in section of testing datasets. It can be seen that by developing a new hybrid model (neuro-imperialism), results of testing datasets are significantly increased. As a result, an improvement of 0.22 in R^2, a reduction of about 0.16 in RMSE and an improvement of about 30% were obtained when a neuro-imperialism is developed. Hence, the neuro-imperialism model is selected as the best predictive model of internal friction angle of fiber-reinforced sandy soil.

In Figs 13 and 14, relations between the reinforced soil's friction angle and the obtained values obtained from the best models of ANN and neuro-imperialism are displayed. It can be seen that in ANN model, training and testing datasets deliver values of 0.941 and 0.728 for R^2, respectively. Comparatively, these values for R^2 of the developed neuro-imperialism model are 0.961 and 0.948, respectively. Therefore, based on these results, the introduced hybrid neuro-imperialism model shows more precise outcome for friction angle of reinforced soil. Thus, the developed neuro-imperialism model can be considered as a new model with more precise results in assessment of shear strength parameters of the reinforced sandy soils.

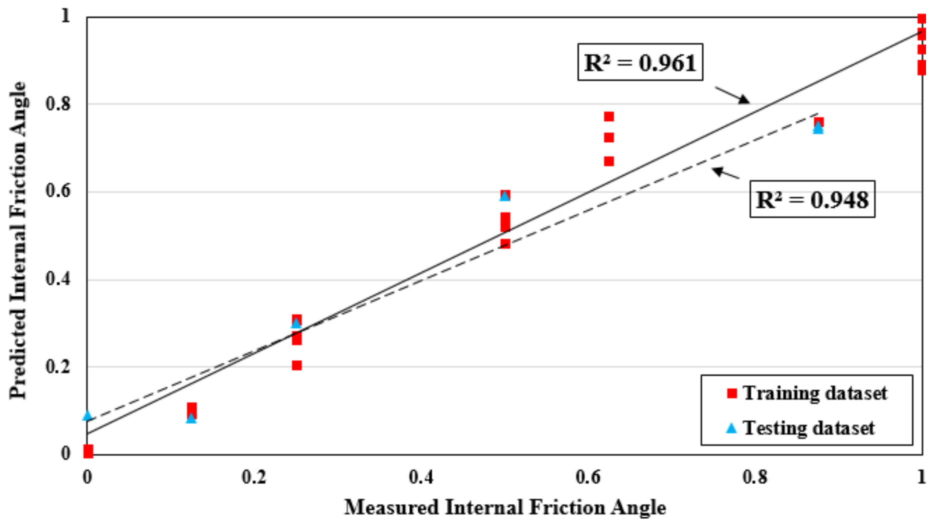


Fig. 14 Neuro-imperialism results in estimating internal friction angle

5. Conclusions

The prediction of shear strength parameters can be very useful in all types of geotechnical applications. In this study we introduce two intelligence predictive models for internal friction angle of fiber-reinforced sandy soil. The models are based on result of a series of triaxial tests that survey inherent strength increase due to addition of fiber reinforcements to sandy soil. According to result of experiments four main parameters of fiber percentage, fiber length, deviator stress, and pore water pressure influence the values of internal friction angle. Using these parameters as model inputs, two intelligent systems including ANN and neuro-imperialism was developed. Aiming to predict internal friction angle, several ANN and neuro-imperialism models were studied and their prediction capacity for each developed model was determined by calculating R^2, RMSE and VAF as the most common statistical indices. According to statistical results, the proposed neuro-imperialism model (with R^2=0.948, RMSE=0.094, VAF=94.585% on testing data set) has a higher level of performance comparing to the ANN model (R^2=0.728, RMSE= 0.26, VAF=65.066) for predicting internal friction angle. These results confirm that the proposed neuro-imperialism model deliver reliable performance for estimating internal friction angle of the fiber reinforced soils. Hence, the developed neuro-imperialism model is useful as an initial predictive approach in site investigation phase using inputs in the mentioned ranges of this study.

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