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Compressive and tensile strength enhancement of soft soils using nanocarbons

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Abstract. Technological innovations in sustainable materials for soil improvement have attracted considerable interest due to energy crisis and environmental concerns in recent years. This study presents results of a comprehensive investigation on utilization of nanocarbons in reinforcement of a residual soil mixed with 0, 10 and 20% bentonite. Effects of adding proportionate quantities (0, 0.05, 0.075, 0.1 and 0.2%) of carbon nanotubes and carbon nanofibers to soil samples of different plasticities were evaluated. The investigation revealed that the inclusion of nanocarbons into the soil samples significantly improved unconfined compressive strength, Young's modulus and indirect tensile strength. It was observed that carbon nanofibers showed better performance as compared to carbon nanotubes. The nanosized diameter and high aspect ratio of nanocarbons make it possible to distribute the reinforcing materials on a much smaller scale and bridge the inter-particles voids. As a result, a better 'soil-reinforcing material' interaction is achieved and desired properties of the soil are improved at nanolevel.

Keywords: soft soils; nanocarbons; soil improvement; unconfined compression; elastic modulus; indirect tensile strength

1. Introduction

Soil improvement is becoming essential part of civil engineering projects in design of geosystems, slopes, dams, highway embankments, hydraulic barriers for landfills and other earthen structures (Abbey *et al.* 2017). The primary objective of reinforcing soil matrix is to increase shearing resistance and reduce settlements. Since a number of soil improvement techniques use additives which involve chemicals of various types, care must also be taken towards environmental considerations (Lee *et al.* 2017, Rashid *et al.* 2017, Latifi *et al.* 2016, Akinwumi and Booth 2015). In recent years, technological innovations in sustainable materials development have attracted considerable interest due to the energy crisis and the environmental concerns. In this context, several natural and artificial fibers are being widely used to improve mechanical behavior of marginal soils (Güllü and Fedakar 2017, Abi-Rekha *et al.* 2016, Li *et al.* 2014). Characteristically, high tensile strength and extendibility of added fibers effectively help in increasing strength as well as reducing compressibility and brittleness of host soil, which is generally superior to traditional soil improvement techniques (Tang *et al.* 2016, Estabragh *et al.* 2012, Fatahi *et al.* 2012).

Several studies have been conducted on chemical stabilization of soft soils (Aziz *et al.* 2015, Kamei *et al.* 2013). However, over the last decade, nanomaterials have evolved as sustainable stabilizers for soft soils and have attracted great interest of various researchers across the globe. Additives consisting of nanoparticles, more precisely nanocarbons (NCs) exhibit unique physical properties, including ultra-high specific surface area, extremely high tensile strength and elastic modulus, all indicating to the potential of NCs in reinforcing applications (Correia *et al.* 2015). Use of nanotechnology in geotechnical engineering is to improve soil behavior using various types of commercially available nanomaterials, such as carbon nanotubes (CNTs) and carbon nanofibers (CNFs). These nanocarbons are not cementitious materials but once introduced to soft soils in a small amount and due to their very high specific surface area and morphologic properties, they can significantly influence physical and chemical behavior of soils (Ghasabkolaeia *et al.* 2017). However, natural tendency of nanocarbons to aggregate which results in loss of their beneficial properties is a challenge to their potential application as an additive in soil stabilization. Therefore, it is common to use surfactants and/or ultrasonic energy to disperse the nanoparticles in suspension (Correia *et al.* 2015).

The nano size and high aspect ratio of nanocarbons enable the distribution of reinforcing materials on a much smaller scale as compared to commonly used macro- and

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micro-reinforcing fibers. In addition, inclusion of nanocarbons with soil makes it possible to determine the moisture content of soil-nanocarbons mixture without changing physical properties as nanocarbons have relatively high melting point (Jorio *et al.* 2008). Nanocarbons as nanofibers are chemically inert and exhibit a super-hydrophobic property as well as they do not absorb or react with the soil moisture or leachate (Wang *et al.* 2007). However, traditional micro-fibers are prone to extend and break due to absence of high tensile resistance. Depending on wall thickness, nanocarbons with unique tensile strength of 25-200 GPa can solve this problem (Lawrence *et al.* 2008).

Extensive work has been published on nanocarbons based reinforcement of cement matrix (Manzur and Yazdani 2016, Konsta-Gdoutos and Aza 2014, Yazdani and Mohanam 2014, Cui 2013, Peyvandi *et al.* 2013). Limited literature is available on the effects of carbon nanotubes and carbon nanofibers on strength and deformation behavior of soil-nanocarbons matrix (Ghasabkolaeia *et al.* 2017, Bahmani *et al.* 2014, Ghazi *et al.* 2011). Alsharef *et al.* (2016) have shown the effects of nanocarbons on index properties of soils such as Atterberg limits, optimum moisture content, maximum dry density, specific gravity, *pH* and hydraulic conductivity. This study presents the influence of CNTs and CNFs on unconfined compressive strength, elastic modulus, and indirect tensile strength of a residual soil mixed with bentonite.

2. Materials and methods

2.1 Soil samples

Residual soil was sampled from the Universiti Kebangsaan Malaysia (UKM) campus from 0.5-1.0 m below ground surface and was classified according to Unified Soil Classification System (ASTM D2487-11) as clayey sand, SC. The UKM soil (referred as S1 sample) was mixed with 10% and 20% bentonite (referred as S1 and S2 samples, respectively) to investigate effects of plasticity on mechanical properties of soil samples reinforced with nanomaterials. The bentonite used in this study was a high swell sodium bentonite containing sodium montmorillonite with a cation-exchange capacity (CEC) of 90 meq/100 g. A field emission scanning electron microscopy (FESEM) of the bentonite sample revealed that it consists mostly of layered particles with thickness of around 12 nm and different length sizes up to 15 µm. The particle size distributions of soil samples (S1, S2 and S3) and bentonite are presented in Fig. 1. The physical and chemical properties of UKM soil and bentonite are listed in Table 1. The chemical composition of UKM soil reveals a high content of silica (SiO_2 = 62.1%) and alumina (Al_2O_3 = 29.5%), which confers pozzolanic properties to the soil. Therefore, in the long term it can react with calcium hydroxide producing strength-enhancing reaction products. Low pH value of the soil shows that it can restrain and/or delay some reactions during the chemical stabilization (Kitazume and Terashi 2017).

2.2 Nanocarbons

Two types of nanocarbons (NCs), multi-wall carbon nanotubes (CNTs) and carbon nanofibers (CNFs) were selected for this study. The CNTs are produced by *Arkema Inc.* under the trade name of "Graphistrength". CNFs used in this study were PR-19-XT-LHT, a product of *Pyrograf Inc.* According to Lehman *et al.* (2011), density and area of nanocarbons are quantitative measures that support the fundamental questions for making engineering and economic decisions for a given application. Table 2 gives detailed description of CNTs and CNFs provided by their respective manufacturers. It can be noted that CNTs and CNFs are composed essentially of pure carbon (95% and 98%, respectively). FESEM imaging is an important tool to characterize overall morphology of soil and nanocarbons as well as to quantify the degree of purity within samples (Lehman *et al.* 2011).

It can be observed in Fig. 2 that CNTs and CNFs samples contain bundles of randomly arranged nanotubes and nanofibers, respectively and the amount of unwanted particles is relatively small. Fig. 3 presents a quick comparison in terms of density of the materials used in this study. Obviously, NCs have low density because of the porous nature and void spaces in between the bundles of nanotubes / nanofibers.

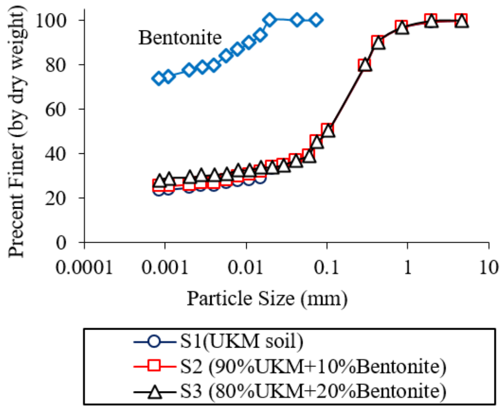


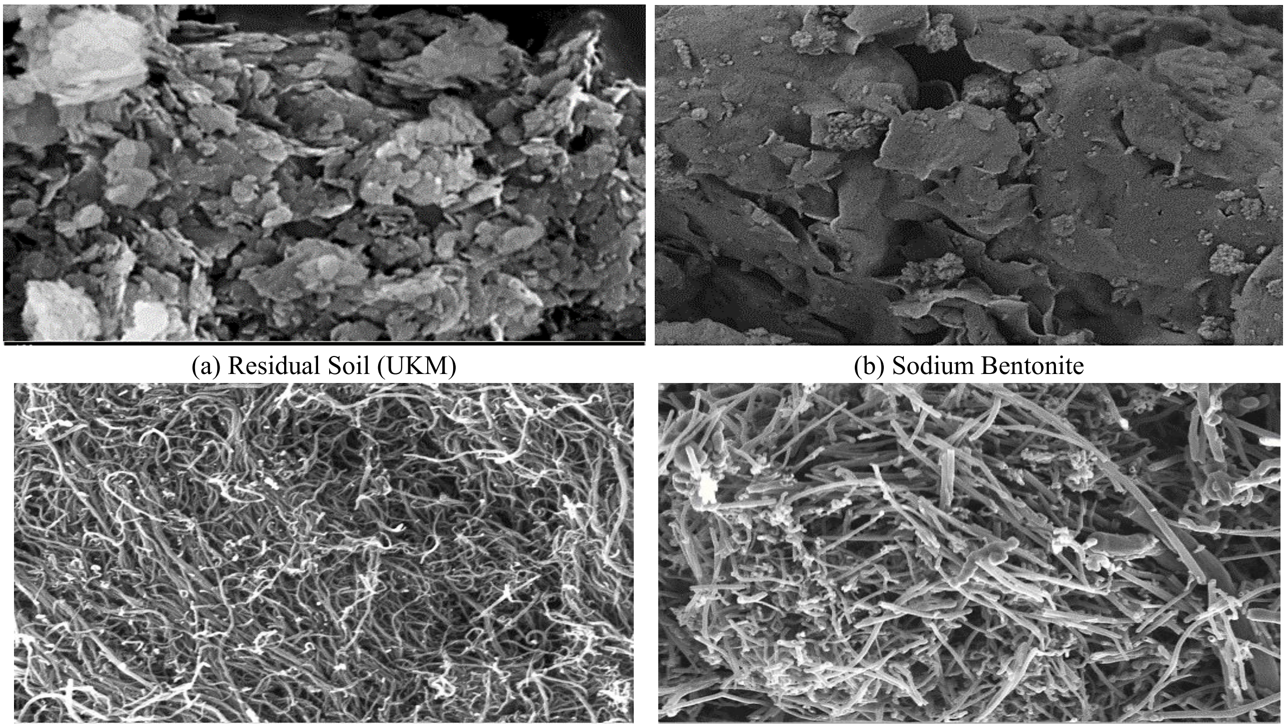
Fig. 1 Particle size distribution of soil samples

Table 1 Physical properties and chemical composition of UKM soil and bentonite

Physical Properties	UKM Soil	Sodium Bentonite	Chemical Composition	UKM Soil	Sodium Bentonite
Specific gravity	2.60	2.66	SiO_2 (%)	62.1	60.9
Plasticity index (%)	13.6	464.6	Al_2O_3 (%)	29.5	14.8
Linear shrinkage (%)	8.9	70.0	Fe_2O_3 (%)	5.7	4.4
Fines (%)	45.4	100	MgO (%)	0.6	3.1
Clay content (< 1 µm) (%)	23.8	75.2	Others (%)	0.8	1.8
USCS classification	SC	CH	Heat loss (%)	0.2	8.2
pH	4.1	9.9			

2.3 Preparation of soil-nanocarbons mixtures

Dispersion solution was prepared by mixing 50 g of soil



(a) Residual Soil (UKM) (b) Sodium Bentonite

(c) Carbon Nanotubes (CNTs) (d) Carbon Nanofibers (CNFs)

Fig. 2 Scanning electron microscopic images of the tested materials

Table 2 Composition of nanocarbons used in this study

Properties	CNTs (Graphistrength® C100)	CNFs (PR-19-XT-LHT)
Average diameter (nm)	10-15	150
Average length (μm)	1-10	50-200
Apparent density (kg/m^3)	50-150	30-300
Relative density (g/ml) at 25°C	2.1	2.0-2.1
Aspect ratio	600-700	1300-1500
Carbon purity (%)	95	98

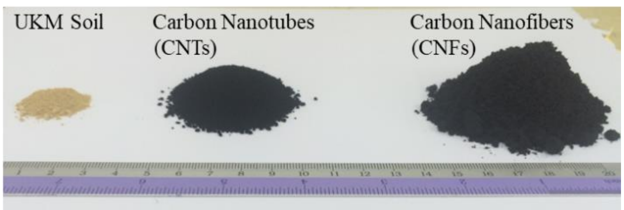
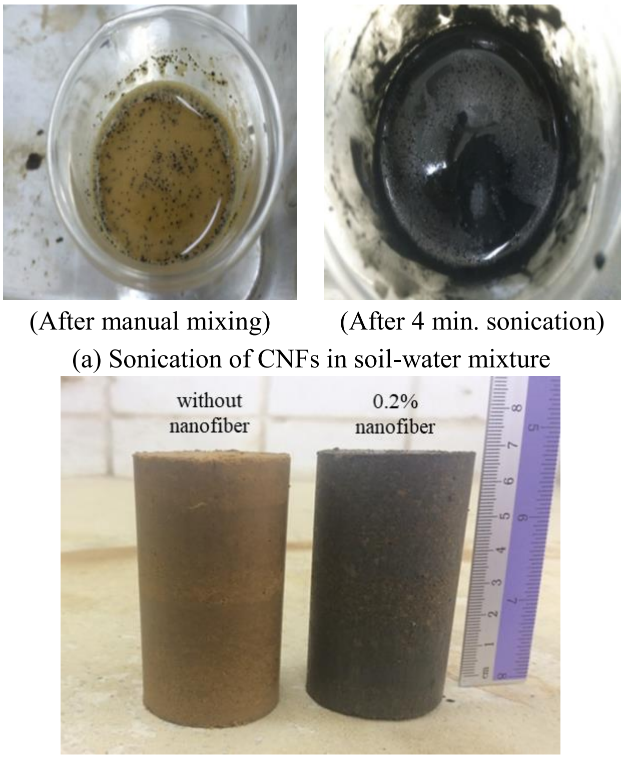


Fig. 3 One gram of UKM soil, CNTs and CNFs

in 100 ml distilled water. The amount of NCs added to the water-soil solution was 0, 0.05, 0.075, 0.1, and 0.2% of dry weight of soil. After manual mixing for 5 minutes, the solution was sonicated for 4 min. in an ultrasonic tip to disagglomerate the NCs and avoiding possible tube fragmentation (Vaisman *et al.* 2006). This time is also sufficient to accomplish dispersal of soil in an aqueous solution (Firoozi *et al.* 2015). Fig. 4a shows the NCs in soil-water suspension after sonication. After ultra-sonication, the suspension was mixed thoroughly with dry soil to achieve uniform and homogeneous mixture. Mixture was



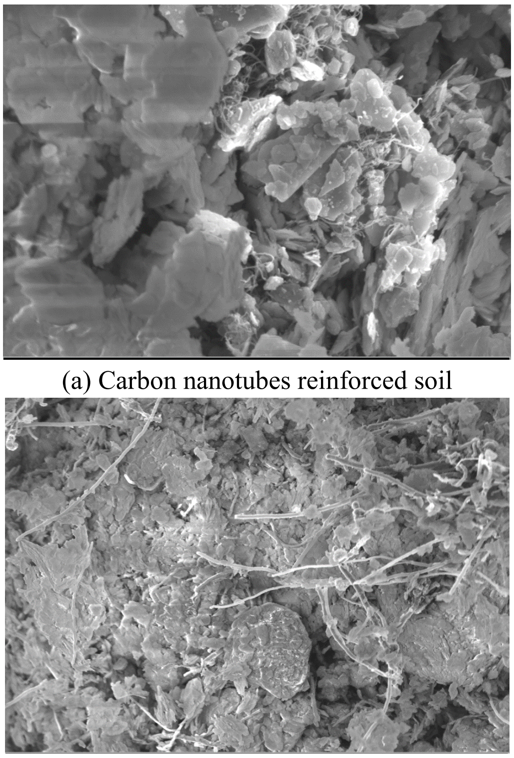
(After manual mixing) (After 4 min. sonication)

(a) Sonication of CNFs in soil-water mixture

(b) Sample colors with and without CNFs

Fig. 4 Preparation of soil samples for strength tests

allowed to mellow for 24 hrs (a recommended standing time by ASTM D698-12 to allow the water to be absorbed thoroughly by the soil particles) followed by adding water to achieve optimum moisture content. This method produced homogeneous samples with uniform colour after



(a) Carbon nanotubes reinforced soil

(b) Carbon nanofibers reinforced soil

Fig. 5 FESEM images of soil-NC composite

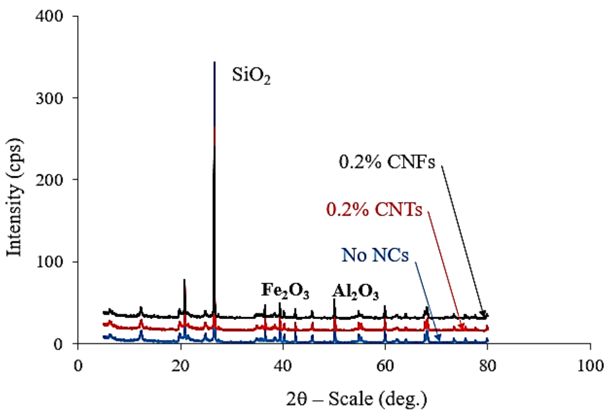


Fig. 6 XRD analysis of untreated and NCs-treated soil

compacting to maximum dry density (Fig. 4(b)). The sample S1 refers to UKM residual soil, whereas S2 and S3 are samples with increased plasticity by adding 10% and 20% bentonite, respectively to UKM soil. The FESEM images in Fig. 5 show the structure of CNT and CNF-treated soil samples to explain the reinforcing mechanism of both NCs. X-ray diffraction (XRD) tests were also carried out to verify if there was any chemical reaction between the soil and NCs (Fig. 6). It can be observed that the chemical structure of untreated and NCs-treated soil remained similar due to the fact that nanocarbons are insoluble material and cannot react with soil-water mixture at ordinary conditions (Wang *et al.* 2007).

2.4 Test procedure

Soil samples with varying bentonite and NCs contents were prepared at respective maximum dry densities and optimum moisture contents determined through the standard compaction test (ASTM D698-12). These samples were used for compressive and tensile strength tests. Unconfined compression tests (UCS) were performed on 70 mm high and 34 mm diameter compacted specimens at a loading rate of 1 mm/min according to ASTM D2166M-16. Three identical samples were tested to record average unconfined compressive strength and Young's modulus (E_{50}).

Likewise, indirect tensile strength (ITS) tests were performed according to ASTM D3967-16 on 115 mm high and 105 mm diameter soil samples at a loading rate of 1.0 mm/min. Akin and Likos (2017) have shown that the loading rates ranging from 0.10 mm/min to 1.0 mm/min have no significant effects on measured tensile strength. ITS tests were conducted by applying load along the cores in between two flat parallel plates according to Indirect Brazilian Test procedure.

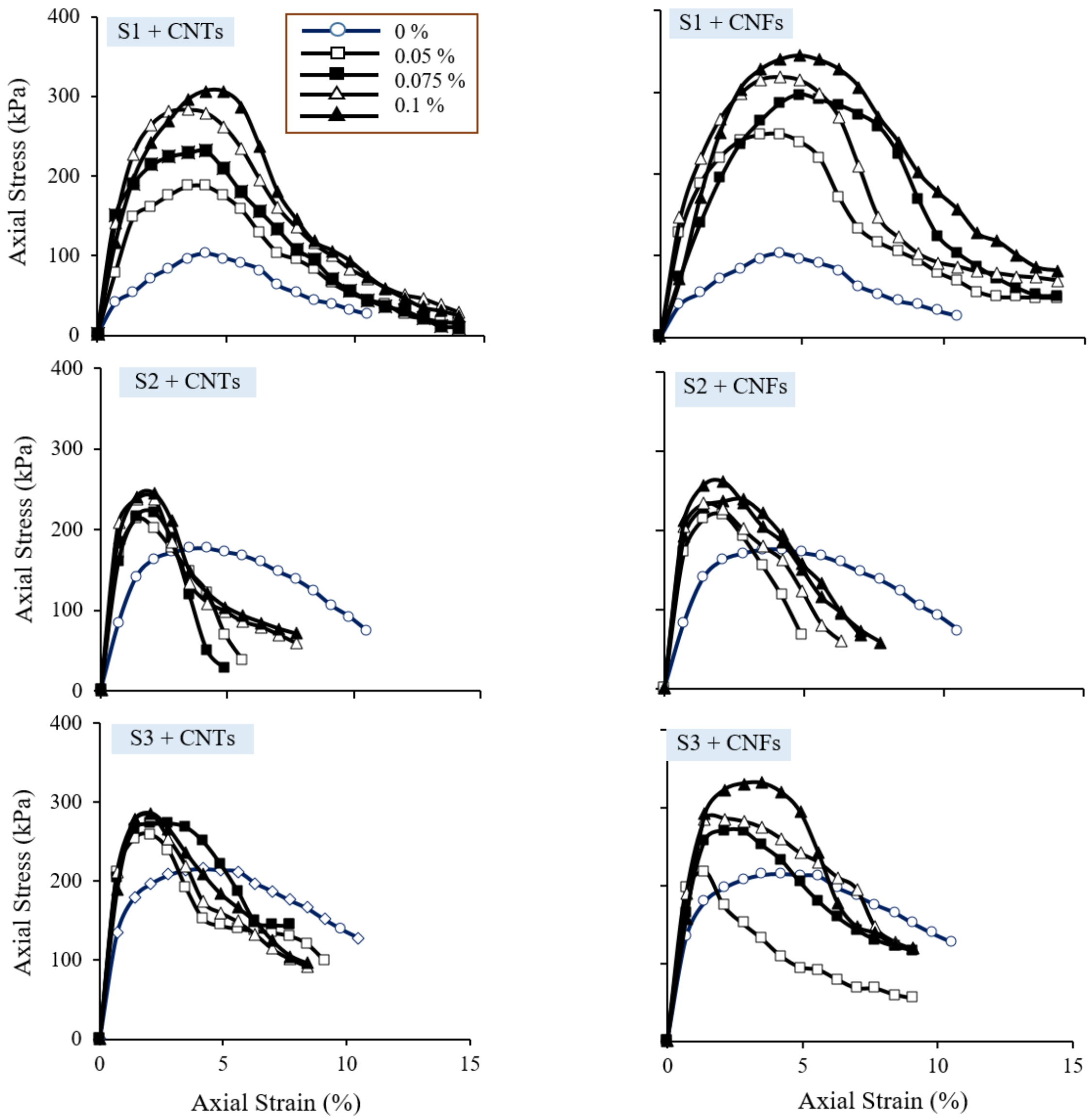
3. Results and discussions

3.1 Effects of nanocarbons on unconfined compressive strength

Effects of NCs inclusion on stress-strain behaviour of S1, S2 and S3 samples through UCS tests are presented in Fig. 7. It can be observed that soil reinforced with CNTs and CNFs exhibit stronger and stiffer response as compared to the samples with no NCs. Likewise, an increase in UCS with increased plasticity of the untreated soil samples (i.e., through S1 to S3 with no NCs) is also evident.

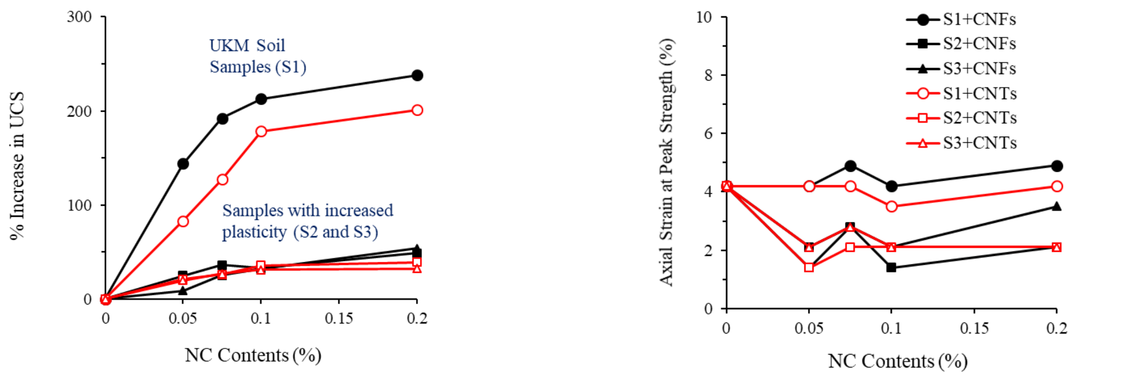
Fig. 8 shows the effects of NCs on the compressive strengths (UCS) and failure strains i.e., strains at peak stresses. It is evident that there is considerable increase in peak strengths with increasing CNT and CNF contents (Fig. 8a). A high rate of increase in strength is observed from 0% to 0.10% NC contents and the rate of strength gain decreases with further addition of NCs. The maximum increase in UCS is found to be 201% and 238% for S1 samples at 0.20% CNT and CNF contents, respectively. However, the increase in UCS for S2 and S3 samples (soil samples with relatively high plasticity) with increase in CNT and CNF contents is considerably lower than the S1 samples. The strain level at peak stress are plotted in Fig. 8(b) against the NC contents which shows that the peak stress of reinforced soil occurs at a relatively lower strain as compared to unreinforced soil i.e., the soil behaviour changes from relatively ductile to brittle. This can further be demonstrated through Fig. 9 which shows failure modes in unconfined compression of an unreinforced soil sample (S2) and a sample reinforced with 0.2% CNFs. Untreated soil sample exhibits a ductile response through bulging failure, whereas a brittle mode of failure (formation of shear plane) can be observed in CNF-treated soil because of increase in strength of treated soil and the interlocking nature of CNFs as shown previously in Fig. 5. Similar behaviour was observed for the other soil samples.

Young's modulus (E_{50}) was computed from stress-strain relationships and is plotted in Fig. 10 which shows an increase in modulus with an increase in NCs from 0% to



(a) CNT-reinforced soil (b) CNF-reinforced soil

Fig. 7 Stress-strain plots from unconfined compression strength tests

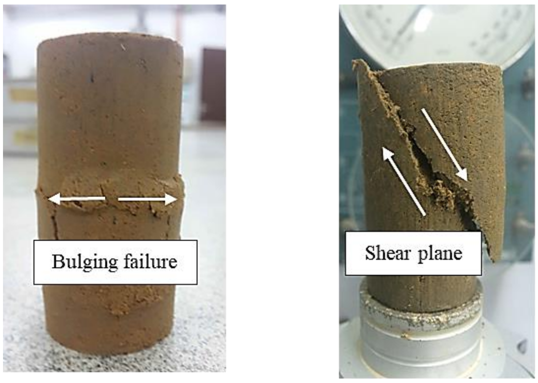


(a) NC contents versus percent increase in UCS (b) NC contents versus axial strain at peak strength

Fig. 8 Effects of nanocarbons on UCS and failure strains

0.1% and the modulus is unchanged for NCs greater than 0.1%. Fig. 11 describes the effects of increased plasticity (S1 through S3 samples) on E_{50} and it is evident that the maximum increase is for samples S2.

The improvement in strength and stiffness characteristics of NC-treated soil samples can be explained



(a) Unreinforced soil (b) With 0.2% CNFs

Fig. 9 Failure modes in UCS tests (S2 specimens)

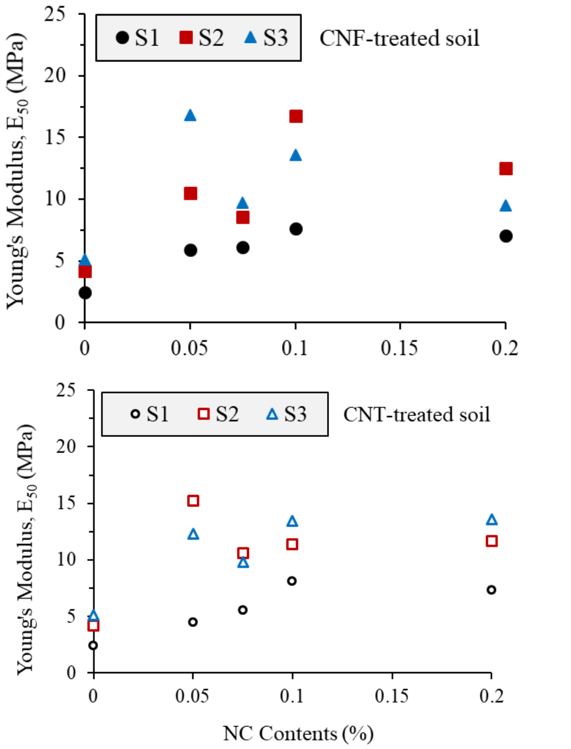


Fig. 10 Effects of NC contents on Young's modulus (E_{50})

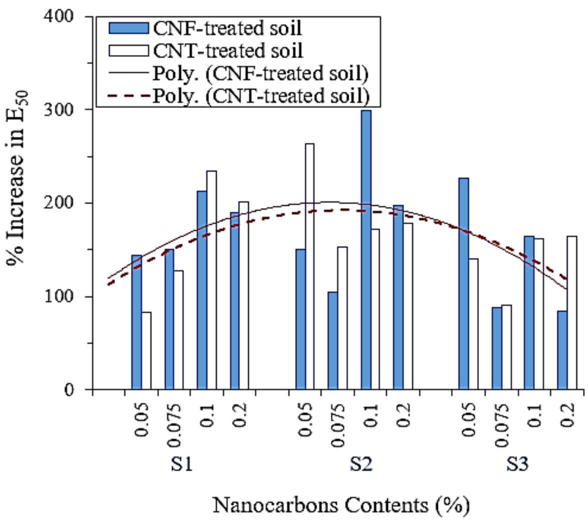


Fig. 11 Effects of plasticity on E_{50} of NC-treated soil

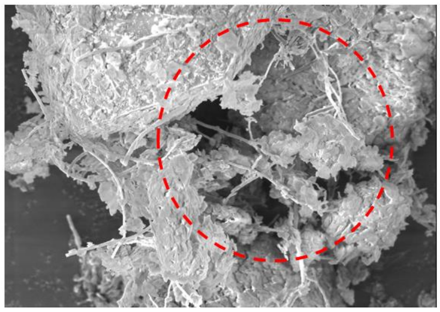


Fig. 12 Bridging of micro-cracks by the CNFs

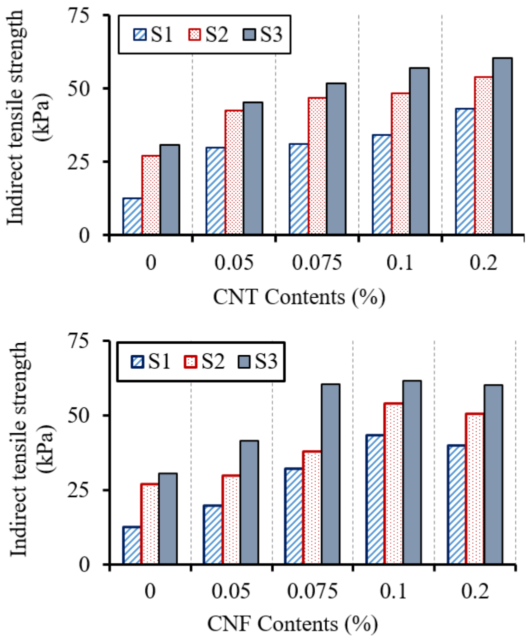


Fig. 13 Indirect tensile strength test results

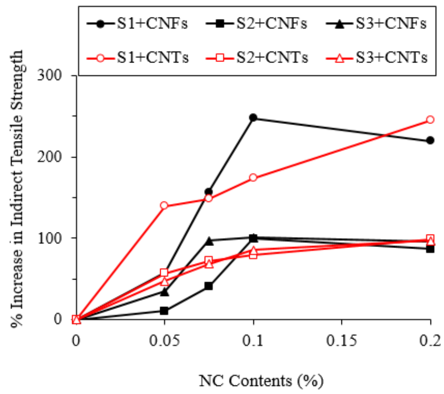


Fig. 14 Increase in tensile strength of NC-treated soil

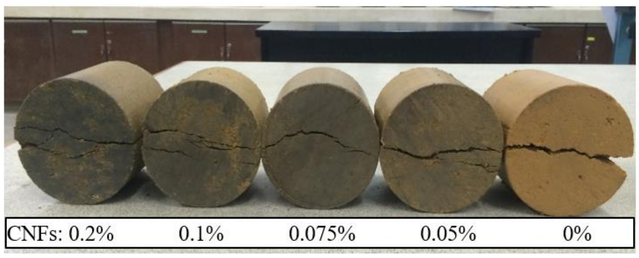


Fig. 15 Failure modes during indirect tensile strength tests

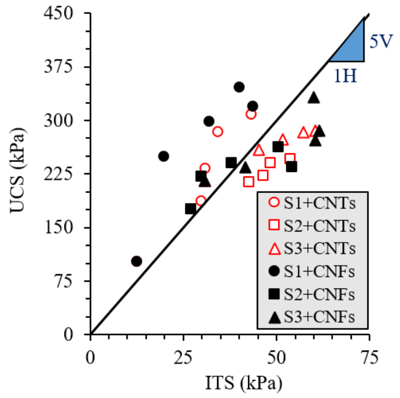


Fig. 16 Relationship between tensile and compressive strengths

by the structure of soil-nanocarbons mixture as shown in Fig. 12. The bridging-action of NCs across the void spaces assures better load-transfer in both compression and tension. This is consistent with other studies (Nochaiya and Chaipanich 2011, Chaipanich *et al.* 2010) related to the use of nanocarbons in cement composites. As presented in Table 2, the aspect ratios of CNTs and CNFs are 600-700 and 1300-1500, respectively, which indicate that CNFs should have relatively better bonding behaviour with soil as compared to CNTs. A larger aspect ratio of nanofibers produces stronger contact or bridge between the soils particles and hence improves strength and stiffness of the composite (Abou Diab *et al.* 2016).

3.2 Indirect tensile strength tests

The results of indirect tensile strength (ITS) tests performed on three soil samples (S1, S2 and S3) reinforced with nanocarbons are presented in Fig. 13. It can be observed that the tensile strength increases with increase in CNF and CNT contents as well as with the increase in soil's plasticity. Similar to UCS tests and as shown in Fig. 14, a high rate of increase in ITS is observed from 0% to 0.10% NC contents and the rate of strength gain decreases with further addition of NCs. The maximum increase in ITS is found to be 245% and 219% for S1 samples at 0.20% CNT and CNF contents, respectively. However, increase in ITS for S2 and S3 samples (soil samples with relatively high plasticity) with increase in NC contents is considerably lower than the S1 samples. As discussed earlier, such behavior can be attributed to interlocking of nanocarbons with soil particles (CNFs being better than CNTs in this aspect). With inclusion of nanocarbons to the soil, cohesion force increases due to an increase in contact surface area between soil and fibers. Thus, reinforced specimens continue to carry more loads after formation of cracks as compared to unreinforced soil. This is in agreement with the findings of Babu *et al.* (2008) who reported similar behavior while investigating the use of coir fibers to improve engineering properties of expansive soils. The failure in ITS test is caused by tensile stresses acting vertical to the loaded diameter. The effect of nanocarbons on tensile failure mode of soil samples is illustrated in Fig. 15. It can be observed that NCs efficiently retarded the development of cracks and accordingly prevented the soil samples from splitting failure.

The relationship between indirect tensile strength and unconfined compressive strength for soils treated by different types of fibers have been reported by Anggraini *et al.* (2015) and Fatahi *et al.* (2012). Such correlations as obtained from test results of this study are presented in Fig. 16.

The comparison of ITS tests with UCS tests in Fig. 16 shows that the compressive strength are generally five times higher than the tensile strengths and this ratio (1:5) tends to decrease with increased plasticity i.e., for S1 through S3 soil samples.

4. Conclusions

In this study, nanocarbons (carbon nanotubes, CNTs and carbon nanofibers, CNFs) have been proposed as promising candidates for next generation of sustainable reinforcing materials for soft soils. A residual clayey sand (UKM soil) was mixed with bentonite to prepare samples of different plasticities. These samples were treated with CNTs and CNFs to investigate their effects on the mechanical properties of the reinforced soils through a series of laboratory tests. The following conclusions are drawn from this study.

The effects of nanocarbons on stress-strain behavior were investigated through UCS tests which showed stronger and stiffer response as compared to unreinforced soil. A high rate of increase in compressive strength and Young's modulus (E_{50}) was observed up to 0.10 % NC contents and the peak strength of reinforced soil was achieved at relatively lower strains as compared to the unreinforced soil which indicates that the soil behavior changed from relatively ductile to brittle.

- The results of indirect tensile strength tests showed that the tensile strength increased with the increase in CNF and CNT contents as well as with the increase in soil's plasticity. Similar to the UCS tests, a high rate of increase in tensile strength was observed up to 0.10% nanocarbons contents. The effect of nanocarbons on tensile failure mode of the samples showed that nanocarbons efficiently retarded the development of cracks and accordingly prevented the soil samples from splitting failure.
- The relationship between indirect tensile strength and unconfined compressive strength revealed that the compressive strengths are generally five times higher than the tensile strengths and this ratio (1:5) tends to decrease with increased plasticity.
- The nanosized diameter (10-15 nm) and high aspect ratio (600-1500) of CNTs and CNFs make it possible to distribute the reinforcing materials on a much smaller scale than the commonly used reinforcing fibers. As a result, a better 'soil-reinforcing material' interaction is achieved, and hence enhances desired properties of the soil at nanolevel, CNFs being relatively better than CNTs in this aspect.

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