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Research Article

Potential of Using Nanocarbons to Stabilize Weak Soils

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Soil stabilization, using a variety of stabilizers, is a common method used by engineers and designers to enhance the properties of soil. The use of nanomaterials for soil stabilization is one of the most active research areas that also encompass a number of disciplines, including civil engineering and construction materials. Soils improved by nanomaterials could provide a novel, smart, and eco- and environment-friendly construction material for sustainability. In this case, carbon nanomaterials (CNMs) have become candidates for numerous applications in civil engineering. The main objective of this paper is to explore improvements in the physical properties of UKM residual soil using small amounts (0.05, 0.075, 0.1, and 0.2%) of nanocarbons, that is, carbon nanotube (multiwall carbon nanotube (MWCNTs)) and carbon nanofibers (CNFs). The parameters investigated in this study include Atterberg's limits, optimum water content, maximum dry density, specific gravity, pH, and hydraulic conductivity. Nanocarbons increased the pH values from 3.93 to 4.16. Furthermore, the hydraulic conductivity values of the stabilized fine-grained soil samples containing MWCNTs decreased from $2.16E-09$ m/s to $9.46E-10$ m/s and, in the reinforcement sample by CNFs, the hydraulic conductivity value decreased to $7.44E-10$ m/s. Small amount of nanocarbons (MWCNTs and CNFs) decreased the optimum moisture content, increased maximum dry density, reduced the plasticity index, and also had a significant effect on its hydraulic conductivity.

1. Introduction

For a long time, soil stabilization has been one of the best ways to improve the effectiveness of subgrade soils. Compacted cohesive soils with low hydraulic conductivity are commonly used as a landfill cover barrier and bottom liner material. Regarding the long-term performance of the cover barrier system, the desiccation cracking of compacted clay liners is the central relevancy as desiccation will cause cracks in the compacted soil liner and consequently reduce the sealing effect of the cover system dramatically [1, 2]. Additionally, hydraulic conductivity increases with about three orders of magnitude due to desiccation cracking [2]. A few have considered soil additives (lime, sand, and cement) to increase the soil strength and resistance to cracking [3–6]. However, based on the previous studies, the lime or cement additives did not sufficiently suppress desiccation cracking and the low permeability of clayey soils with high water contents. Additionally, the effects of artificial cementation with quicklime on the microtexture and mineralogy of marine clays from eastern Canada were studied by Choquette et al. [7]. They determined that the addition of lime results in abrupt agglomeration of clay particles and that the flocculated structure is maintained with the growth of cementitious bonds. They also found that lime stabilization results in the production of platy minerals, which partition the interaggregate space within the soil material and increase the volume of the micropores (porous product). They developed a correlation between the amount of structural change due to the addition of lime and the measured strength of the treated clay.

The word nanotechnology incorporates an extensive variety of advances performed on a nanometer scale for far-reaching applications. The principle distinction between a nanomaterial and a bigger scale material is the altogether bigger particular surface region, which allows for an expansion in the substance reactivity and/or a change in the physical properties of the material [8]. The properties displayed by this new class of materials have been utilised in manufacturing for a considerable time; the huge and fast incremental use of nanotechnology is due to the logical meeting of science, material science, science, and design streams [9]. Nanotechnology has opened a new world in nanoscale while civil engineering infrastructure is focused on macroscale. Despite the fact that good pavement is constructed with existing materials, applications of nanotechnology can improve pavement performance significantly. Scientists anticipate that nanotechnology may offer great potential in the fields of material design, manufacturing, properties, monitoring, and modelling for advances in asphalt pavement technology [8–15].

Nanotechnology is defined as the understanding and control of matter at dimensions between 1 and 100 nm, where unique phenomena enable novel applications [16, 17]. The application of nanotechnology to the environment and agriculture was addressed by the United States Department of Agriculture in a document published in September 2003 [18], rapidly evolving and revolutionising agriculture. Nanotechnology can play a major role in pollution sensing through surface-enhanced Raman scattering, surface plasmon resonance, fluorescent detection, electrochemical and optical detection, treatment through adsorption, photocatalysis treatment of pollutants, and reduction by nanoparticles and bioremediation.

The implications of the nanotechnology research in the environment and agriculture are developed based on the identification of the nanoresearch thematic areas of relevance to the environmental and agricultural system. Nanomaterials such as nanoparticles, carbon nanotubes, fullerenes, and biosensors play a role in controlled delivery systems. Nanofiltration finds relevant applications in agri-food thematic areas, such as natural resources management, delivery mechanisms in plants and soils, and use of agricultural waste and biomass, and in food processing and food packaging. Risk assessment is also being evaluated [19–21].

The processes affected by nanoparticles presence in soils (the role of the nanosize fraction) have gained importance recently. Sorption capacity, interfacial electron transfers reactions, mobility, and diffusive mass transfer play a major role in soil properties. Sorption capacity of the NPs is important in topics such as assessment of sorption capacity of the NPs in soils, assessment of the NPs interactions with other minerals of the soil matrix and the resulting effects on contaminant and nutrient adsorption/desorption in soils, usage of NPs for groundwater clean-up and remediation purposes, and the evaluation and quantification of the controls or effects of different variables (physical, chemical, and biological) on these processes. Environmental studies were done by a few scientists about sparing raw materials, wastewater and debased soil treatment, vitality stockpiling, and risky waste administration [20, 21]. The OECD proposes that nanotechnology can help to resolve important environmental issues such as the provision of clean drinking water and the change and detoxification of an extensive variety of contaminants such as PCBs, heavy metals, organochlorine pesticides, and solvents [22]. Nanomaterials exhibit intriguing synthetic and physical properties that make them appropriate for many applications in a field as broad as ecology [23].

The soil nanoalumina mixtures caused beneficial changes to the engineering properties of soil (i.e., compaction characteristics, volumetric expansive strain, the crack intensity factor, and volumetric shrinkage strain). These changes were mostly due to the displacement and rearrangement of soil particles by the addition of nanoalumina [22].

Nanocarbon (NC) fibers are primarily used in industrial sectors such as electronics, automotive, aeronautics, sports, marine, and concrete. NC is also a promising advanced material in the construction industry. NC fibers, especially carbon nanotubes (CNTs) and carbon nanofibers (CNFs), have promising material properties such as high tensile strength, elastic modulus, hardness, and electrical properties [23–25]. The history of carbon nanofibers goes back more than a century. Vapour-grown carbon nanofibers (VCNFs) are a type of carbon nanomaterial which was first explored in 1889 by Hughes and Chambers. It is reported that carbon filaments were grown from carbon, and its hollow graphitic structure was first revealed in the early 1950s by Radushkevich and Lukyanovich [26, 27]. VCNFs can be extensively synthesised by catalytic chemically vapour deposit (CVD) of a hydrocarbon (such as natural gas, propane, acetylene, benzene, and ethylene) or carbon monoxide using metal (Fe, Ni, Co, and Au) or metal alloy (Ni-Cu, Fe-Ni) catalysts at a temperature of 500–1500°C [28, 29].

Carbon nanotubes, first discovered by Iijima in 1991 [30], are one of the most promising classes of new materials to emerge from nanotechnology to date. Nanotubes are members of the fullerene structural family. The name is derived from its long, hollow structure with walls formed by one-atom-thick sheets of carbon called graphene. Carbon nanotubes (CNTs) are allotropes of carbon with a cylindrical nanostructure. Carbon nanotubes were found in Damascus steel from the 17th century, which may account for the legendary strength of swords made from this steel [31–33]. Carbon nanotubes have been constructed with a length-to-diameter ratio of up to 132,000,000 : 1, significantly larger than for any other material. It has an ideal structure formed by carbon atoms with one dimension [33]. These cylindrical carbon molecules have unusual properties which are valuable for nanotechnology, electronics, optics, and other fields of materials science and technology [34]. Moreover, since CNTs exhibit great mechanical properties along with extremely high aspect ratios (length-to-diameter ratio), they are expected to produce significantly stronger and tougher composites than traditional reinforcing materials (e.g., glass fibers or carbon fibers) [35]. Research has been conducted for potential use of CNT in environmental protection application. CNT is used as a selective sorbent for organic/biological contaminants in water streams to remove contaminants such as carcinogenic cyanobacterial microcystins [36]. Moreover, the use of carbon nanotubes as an efficient source and storage of hydrogen is an important research area because of CNT's adsorption characteristics, which are due to its particularly high surface area of 50–1315 m^2/g [37–39].

The main objective of this study was to investigate the effect of nanocarbons (MWCNTs and CNFs) on the physical

Table 1: Basic properties of UKM soil.

Characteristics	
Specific gravity	2.6
Passing number 200 sieve (%)	45.39
Clay content (<1 μm) (%)	23
Unified soil classification system (USCS)	SC
Chemical composition	
SiO_2 (%)	62.07
Al_2O_3 (%)	29.46
Fe_2O_3 (%)	5.7
MgO (%)	0.58
CaO (%)	0.03
TiO_2 (%)	1.17
Na_2O (%)	—
K_2O (%)	0.76
Other	0.05
Heat loss	0.18
Organic matter (%)	4.2

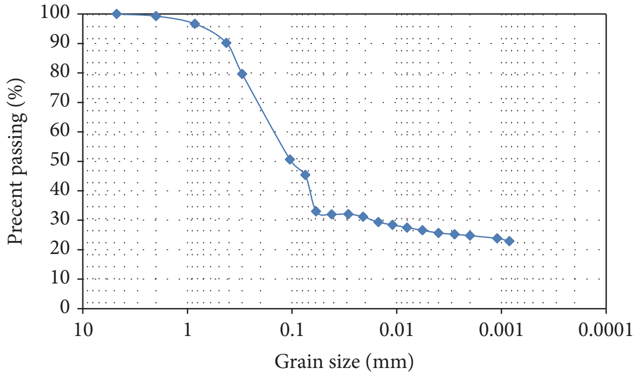

Figure 1: Grain size distributions for UKM soil.

properties of UKM soils. The parameters investigated in this study included Atterberg limits, optimum water content, maximum dry density, specific gravity, pH, and hydraulic conductivity.

2. Materials and Methods

A residual soil from the Universiti Kebangsaan Malaysia, Bangi, Malaysia campus, was chosen for the study and termed UKM soil. The soil was sampled from 0.5 to 1 m below the ground surface. The physical and chemical properties of the soil are shown in Table 1. The UKM soil was classified as clayey sand (SC) according to the Unified Soil Classification System. The UKM soil sieve analysis and particle size distribution are shown in Figure 1. Two types of nanocarbons, multiwall carbon nanotube (MWCNTs) and carbon nanofiber (CNFs) with the commercial names Graphistrength® C100 and PR-24-XT-LHT, were selected by 0.0, 0.5, 0.075, 0.1, and 0.2% content, respectively. The properties of CNTs and CNFs are listed in Tables 2 and 3, respectively. Distilled water was used to prepare solutions. Figures 2, 3, and 4 show scanning electronic microscopes (SEM) and transmission electron microscopy (TEM) images of UKM soil, MWCNTs, and CNFs as used in this study.

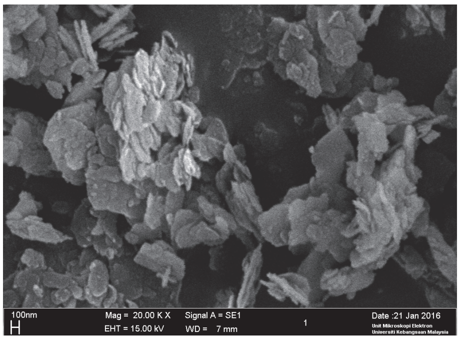

Figure 2: UKM soil particles under SEM.

Table 2: Properties of CNT (Graphistrength C100).

Property	Value
Average diameter (nm)	10–15
Average length (μm)	1–10
Carbon purity, %	>95
Apparent density (kg/mc)	50–150
Relative density (g/mL) at 25°C	2,1
Aspect ratio	600–700
Applications	Reinforcements

Table 3: Properties of CNF-PR-19-XT-LHT.

Property	Value
Average diameter, nm (average)	200
Average length (μm)	50–200
Carbon purity, %	>98
Apparent density (kg/mc)	30–300
CVD carbon overcoat present on fiber	No
Nanofiber wall density, g/cc	2–2.1
Iron, ppm	12,466
Aspect ratio	1300–1500
Applications	Mechanical and electrical

2.1. Standard Compaction Test. The purpose of any moisture-density test, commonly called compaction test, is to determine the optimum moisture content (OMC) at which the maximum dry density (MDD) of the soil is attained. It is generally desirable to increase the density in the field to enhance the strength of the soil. The standard Proctor test was conducted for both the natural soils and the soil-nanocarbons mixtures to determine the compaction parameters. The BS 1377-4:1990 standard was followed as a base for these tests. In the standard Proctor test, the soil was compacted in a mould with a 1000 cm^3 volume, also referred to as the 1-liter mould. The soil used for compaction was dried in an oven and crushed with a rubber hammer until it passed the US number 4 sieve. The soils were moistened with tap water

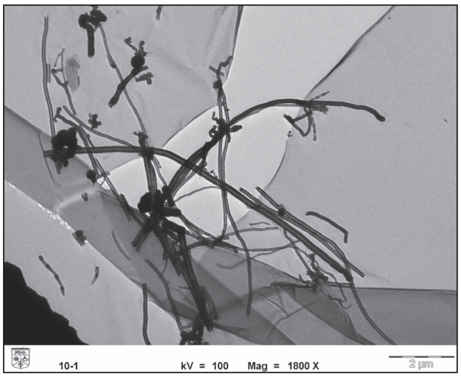

Figure 3: Multiwall carbon nanotube (MWCNTs) particles under TEM.

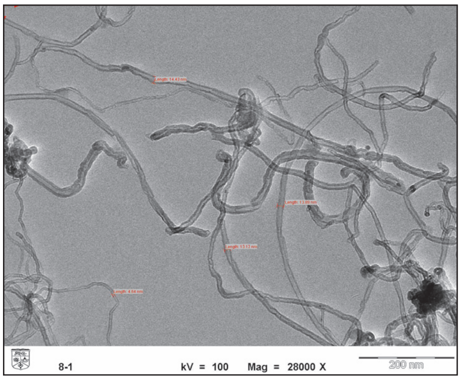

Figure 4: Carbon nanofiber (CNFs) particles under TEM.

using a spray bottle and stirred with a trowel during mixing to ensure an even distribution of water. Then, the soils were sealed in plastic bags and allowed to hydrate for at least 24 h prior to compaction. Three equal layers were compacted with 27 blows for each layer.

2.2. Atterberg Limits. The Atterberg limits (i.e., the liquid limit, the plastic limit, and the plasticity index) of each of the natural and treated soil samples were determined in accordance with BS 1377, part 2, (1990). The liquid limit tests were performed using a penetration cone assembly, which consisted of a stainless steel cone with a cone angle of 30° ± 1°. The plastic limit tests were performed using a manual method. Each sample was rolled at a sufficient pressure on a glass plate to form a thread with a uniform diameter of 3.2 mm along the full length of the sample. The plasticity index was calculated as the difference between the water contents at the liquid and plastic limits.

2.3. Specific Gravity. The specific gravity for a solid soil can be defined as a ratio of the weight of the solid at a specific volume to the weight of water at the same volume. It is actually the average value of all the mineral types found in each of the soil samples in the test. This test was conducted on control soil using a small pycnometer of 50 mL capacity. An average of three samples was taken to determine the specific gravity value of each type of soil used. This test was conducted in accordance with the procedure suggested by BS: 1377, part 2:1990, Clause 8.3.

2.4. Hydraulic Conductivity. The soil was compacted according to the standard test method (BS1377: part 4:1990 Clause 3.4) for both the untreated soil and the soil containing nanomaterials. Cylindrical specimens with a diameter of 70 mm and a height of 35 mm were prepared from the mixtures compacted by standard compaction energy at optimum water content. Then, its hydraulic conductivity was determined following ASTM D5084, that is, using flexible membrane apparatus as shown in Figure 5. Porous stones and filter paper were placed against the ends of the samples to distribute the permeated deaired water across the entire end area of the sample. Once the sample had been prepared in the test cell, the cell was filled with water and the specimen was saturated by applying pressures gradually step by step from two directions, with back pressuring from the bottom and cell surrounding the sample to force water to enter the sample for saturation until the back pressure reached 215 kPa, providing a saturation degree of more than 98% [40, 41]. After the saturation had been completed, readings of inlet and outlet burettes were taken until the measured hydraulic conductivity reached a relatively steady-state condition.

2.5. pH Test. In this study, the electrometric method (BS 1377: part 3: 1990: Clause 9) was utilised to determine the pH value of soil suspension in water as this is considered to be the most accurate method. This method requires a soil-water ratio of 1 : 2.5 and can be obtained by passing 30 gr soil through a 2 mm sieve and diluted with 75 mL distilled water for at least 8 hours. Figure 6 shows the pH meter device which was used in this test.

3. Results and Discussion

The effects of multiwall carbon nanotube (MWCNTs) and carbon nanofiber (CNFs) on specific gravity, Atterberg limit's (liquid limit, plastic limit, and plasticity index), pH, and hydraulic conductivity for clayey sand soil (UKM soil) are shown in Figures 7–15.

3.1. Effect on Specific Gravity (G_s). The test result (Figure 7) shows that reinforcing soil with MWCNTs and CNFs decreased the specific gravity from 2.604 to 2.53 for MWCNTs and from 2.604 to 2.542 for soil reinforced by CNFs.

3.2. Effect on pH. The test results showed that the pH of the stabilized soil samples increased with an increase in nanomaterial percentage for both nanocarbon materials (Figure 8) [42, 43]. However, the increase in pH was insignificant for both nanocarbons.

3.3. Effect on Compaction Characteristics. The optimum water content and maximum dry density values of reinforced soils are shown in Figures 9, 10, 11, and 12, respectively. These figures indicate that increased nanocarbon contents (at the optimum nanomaterial ratio) were associated with decreased optimum water content and increased maximum

Figure 5: Sample preparation procedures for hydraulic conductivity test in flexible membrane apparatus.

dry density. Beyond a certain nanocarbon content, any increase in the nanocarbon percentage tended to reduce the dry density [44]. The decrease in water content is related to the tendency of nanocarbons to fill pores between soil particles. In Figure 11, containing information of a soil sample reinforced by MWCNTs, it can be seen that the maximum decrease in optimum water content was 13.6% at 0.075% MWCNTs content, and dry density increased from 1.86 to 1.89 (g/cm^3). For the soil sample reinforced by CNFs, the maximum decrease in optimum water content was 14% at 0.075% CNFs content. Furthermore, dry density increased from 1.86 to 1.88 (g/cm^3); see Figure 12.

3.4. Effect on Atterberg's Limits. Atterberg limits (plastic limit "PL," liquid limit "LL," and plasticity index "PI" = LL − PL) play an important role in soil identification and classification. These parameters indicate some of the geotechnical problems such as swell potential and workability. The results of the liquid limit test of the soil samples containing various percentages of MWCNTs and CNFs used are shown in Figures 13 and 14, respectively. The results indicate that, for reinforcement soil samples, the liquid limit decreased with increasing MWCNTs and CNFs contents, especially at the optimum nanomaterial content level. Reductions in the plasticity (Figures 13 and 14) indices are indicators of

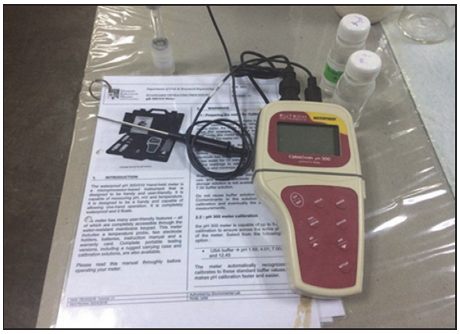

Figure 6: pH meter device used in this research.

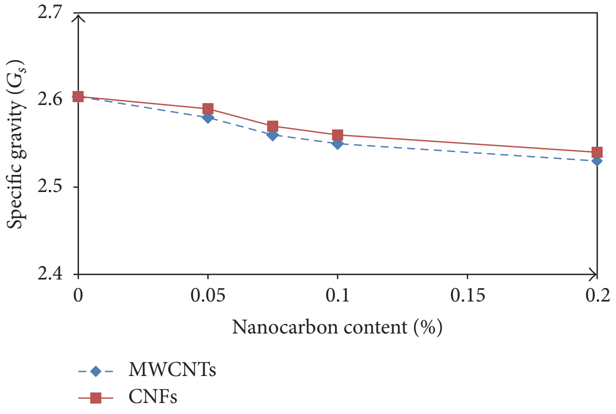

Figure 7: Effect of MWCNTs and CNFs on the specific gravity.

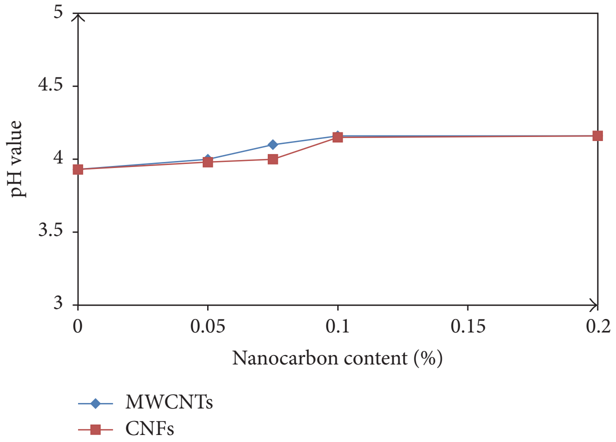

Figure 8: Effect of MWCNTs and CNFs on the pH.

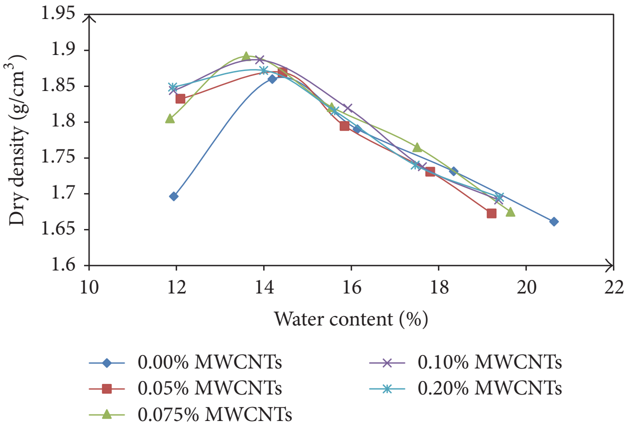

Figure 9: Compaction curves for treated UKM soil with MWCNTs.

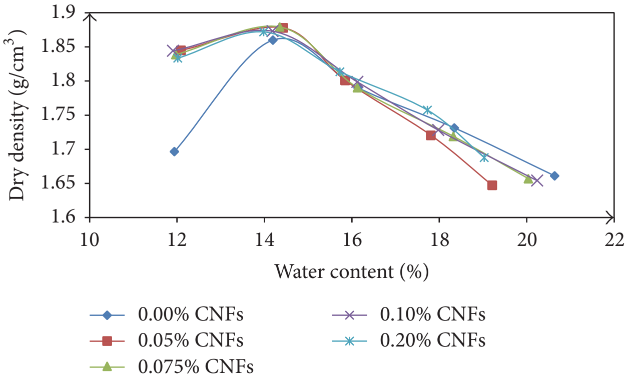

Figure 10: Compaction curves for treated UKM soil with CNFs.

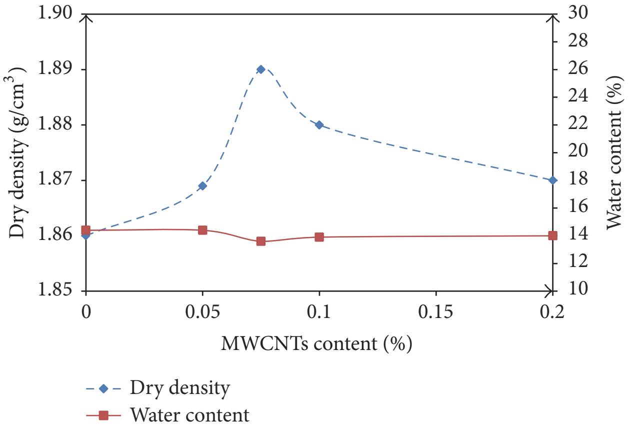

Figure 11: Effect of MWCNTs on the OMC and MDD.

soil improvement, because the plasticity index represents the range of water content over which a soil is plastic [45].

3.5. Effect on Soil Hydraulic Conductivity. The hydraulic conductivity (k) test result drawn in Figure 15 clearly shows a decrease in k value of the tested soils corresponding to an increase in the nanocarbon (MWCNTs and CNFs) percentage. Nanocarbon contents less than the optimum content significantly affected the k values. Compared with the natural fine-grained soil samples, k values of the stabilized fine-grained soil samples containing nanocarbons decreased from $2.16E-09$ m/s to $9.46E-10$ m/s for soil samples reinforced by MWCNTs and $2.16E-09$ m/s to $7.44E-10$ m/s for soil samples reinforced by CNFs.

4. Conclusion

A study was conducted to evaluate the effects of adding a small amount (less than 0.2%) of multiwall carbon nanotube

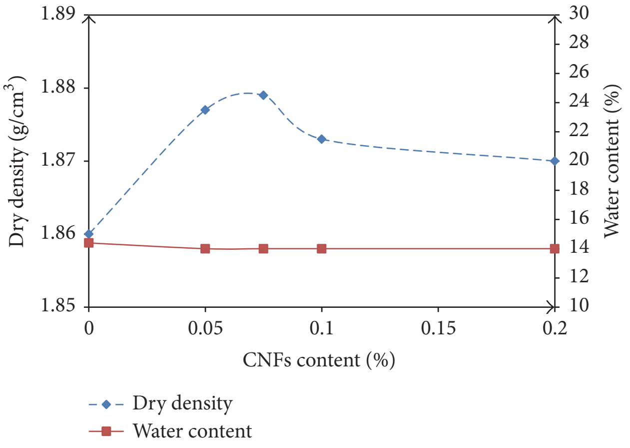

Figure 12: Effect of CNFs on the OMC and MDD.

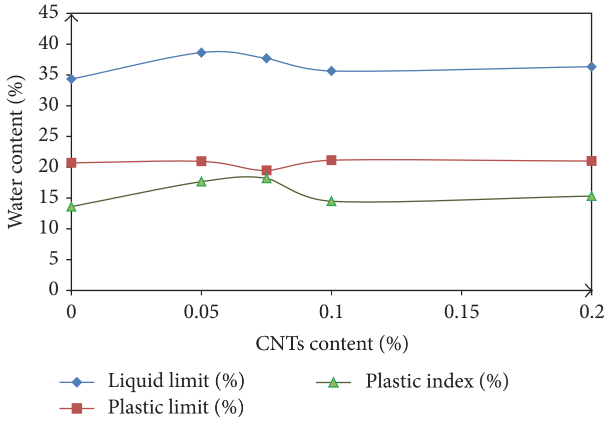

Figure 13: Effect of MWCNTs on LL, PL, and PI.

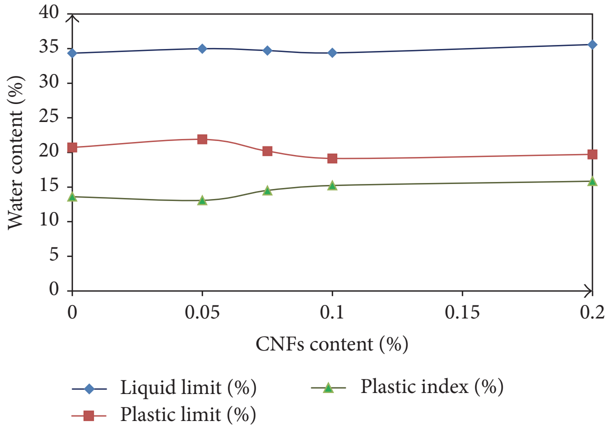

Figure 14: Effect of CNFs on LL, PL, and PI.

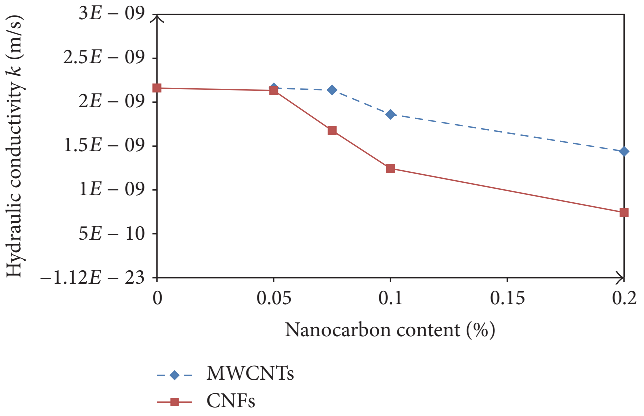

Figure 15: Effect of MWCNTs and CNFs on hydraulic conductivity.

(MWCNTs) and carbon nanofiber (CNFs) to clayey sand soil (UKM soil). The liquid limit and plastic limit increased with the amount of multiwall carbon nanotube (MWCNTs) and carbon nanofiber (CNFs) in the mixture. Moreover, the increase in the maximum dry density is due to the particle densities of nanocarbons which are greater than the particle density of natural soil. Furthermore, the nanocarbon fibers reduced porosity by filling the space between soil particles and bonded the particles together. The results showed that decreased OMC and increased MDD were for treated soil by MWCNTs at 0.075% nanocarbon content. Lastly, the result of the hydraulic conductivity test showed that nanocarbons have a significant ability to reduce k value. A comparison between the results from the two different nanocarbons (MWCNTs and CNFs) showed that the soil samples treated with CNFs had a higher reduction in hydraulic conductivity. This differs from other treatment materials like polypropylene and other types of fiber, which reduces cracks in the soil but increases the hydraulic conductivity.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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