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Aluminum waste in road pavement subgrade

Residuos de aluminio en el subsuelo de las carreteras

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ABSTRACT

This paper aims to investigate the use of spiral aluminum computer numerical control milling waste (CNC-W) in the construction of road pavement subgrade. The soil (CL) was mixed with CNC-W spirals with ratios of between 0% and 20%, and 5 percent increments by dry weight with different water contents. California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and consolidation tests were conducted. The experimental results indicated that the inclusion of CNC-W spirals increased the CBR value of clay up to the 15% mixture ratio, then decreased it. Similarly, the UCS value of clay was increased to the same ratio, whilst the UCS was not able to be determined due to the failing of all specimens with a mixture ratio higher than 15%. The permeability and swelling values, as well as the consolidation characteristics of the mixtures, were defined. The swelling percentages decreased from 1,15 cm/sec to 0,81 cm/sec with an increment in the CNC-W spiral content. A reduction was observed in the coefficient of permeability (*k*) values up to 15% mixture ratio, whilst it remained constant with change in CNC-W spiral content with a 20% mixture ratio. Coefficient of consolidation demonstrated a similar pattern of behavior to the permeability changes.

Keywords: computer numerical control milling waste CNC-W, clay, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), consolidation.

RESUMEN

Este artículo buscó investigar el uso de desechos espirálicos de aluminio de fresado de control numérico por computador (CNC-W) en la construcción de subrasantes de pavimento de carretera. La tierra (CL) fue mezclada con espirales de CNC-W con proporciones entre 0 % y 20 %, e incrementos del 5 % por peso seco con contenidos diferentes de agua. Se efectuaron las pruebas California Bearing Ratio (CBR), Resistencia a la Compresión Uniaxial (UCS), y de consolidación. Los resultados experimentales indicaron que la inclusión de espirales de CNC-W incrementaba el valor CBR de la arcilla hasta el 15 % de proporción en la mezcla y después lo disminuía. Similarmente, el valor UCS de la arcilla se incrementó con las mismas proporciones, mientras que la USC no se pudo determinar debido a la falla de todos los especímenes con una proporción de mezcla más alta que el 15 %. Se definieron los valores de permeabilidad e hinchazón, así como las características de consolidación de las mezclas. Los porcentajes de hinchazón disminuyeron de 1,15 cm/sec a 0,81 cm/sec, con un incremento en el contenido de espirales de CNC-W. se observe una reducción en los valores del coeficiente de permeabilidad (*k*) con una proporción de mezcla de hasta el 15 %, mientras que estos permanecieron constantes con el cambio en el contenido de espirales de CNC-W con 20 % de proporción en la mezcla. El coeficiente de consolidación demostró un patrón similar de comportamiento a los cambios de permeabilidad.

Palabras clave: desechos de fresado de control numérico por computador (CNC-W), arcilla, California Bearing Ratio (CBR), resistencia a la compresión uniaxial (UCS), consolidación.

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Introduction

Many industrialized countries have massive sources of waste materials such as fly ash, tire rubber, and different types of metal swarf. Instead of being disposed of in landfills, such wastes can have some applications in geotechnical engineering. It is significant to note that soil does not fail in compression alone, but it always fails in shear. Soils are reinforced with waste materials, so that their performance to absorb shear stresses and tensile loads are improved. The use of waste materials for soil reinforcement has been gaining popularity primarily because of its versatility, easy and cost-effective construction. For example, different forms of waste tires have been employed in some applications in civil engineering including insulation beneath roads, slope stability, and lightweight backfill retaining walls (Mitchell and Katti, 1981; Fatani, Bauer and Al-Joulani, 1991; Ahmed and Lovell, 1992; Edil and Bosscher, 1994; Masad et al. 1996; Shahu, Yudhbir, and Kameswara,1999; Kim and Santamarina, 2008; Tanchaisawat, Bergado, Voottipruex and Shehzad, 2010; Sarkar, Abbas, and Shahu, 2012; Edincliler, Cabalar, Cevik and Cagatay, 2012; Cabalar, Karabash and Mustafa, 2014; Cabalar and Karabash, 2015; Gomes Correira, Winter and Puppala, 2016; Patel and Shahu, 2016; Seddon, Winter and Nettleton, 2018; Cabalar, Zardikawi and Abdulnafaa, 2019). In addition, investigations on plastic waste use as soil reinforcement material have proved its worth in geotechnical applications including road bases, embankments, slope stability, retaining walls by increases in shear strength, and reductions of post peak losses in soils (Maher and Ho 1994; Santoni et al 2001; Zornberg 2002; Consoli, Prietto and Ulbrich, 2007; Muntohar, 2012). Although numerous studies have been performed for use of this material, the combined use of plastic waste and steel slag can provide much more strength to the pavement constructed with certain proportions (Mishra, JhaAjachi, Satrawala and Amin, 2013). Wang (1997, 2006) studied the use of fibers from carpet waste as soil reinforcement, and observed a significant increase in triaxial strength of sandy soils. Murray, Frost and Wang (2000) reported that for every 1% increment in fiber content leads to a 1% increment in optimum moisture content. Miraftab and Lickfold (2008) indicated that carpet waste fibers could be substantially mixed with weak soil until a maximum of 10% to increase internal angle of friction and cohesion. Ghiassian, Poorebrahim, and Gray (2004) stated that randomly placed synthetic strips had an important effect on the strength and constitutive behavior of fine sand.

A Computer Numerical Control (CNC) milling machine, a specific type of computer numerical controlled device, is designed to machine any kind of metal. Spiral aluminum Computer Numerical Control Milling Waste (CNC-W) is a type of swarf, which is known as pieces of metal resulting from CNC milling machining,which is the process of physically machining objects from 3D or 2D digital information. During various steps of aluminum production within this process, a lot of CNC-W scrap is continuously generated due to machining operations (Fratila, 2009; Newman, Nassehi, AsraiandDhokia, 2012; Faludi, Bayley and Bhogal, 2015; Wang et al., 2015). Dumping of this material has become a problem for many countries. The industry in India, for example, generates around 10-20 million tons of CNC-W scrap annually, which is difficult to recycle by conventional methods (Lazzaro and Atzori, 1993; Samuel, 2003; Shinzato and Hypolito, 2005; Sevigne-Itoz, Gasol, Rieradevall and Gabarrell, 2014; Galindo, Padilla, Rodriguez, Hernandez, Andres and Delgado, 2015). After going through the literature, it is worth noting that few researchers reported that addition of CNC-W spirals in concrete mix increased the compressive strength (Shukla, 2013). Although there are several methods of CNC-W disposal, because of the environmental concerns regarding potential contamination (e.g., Hall-Héroult Process; Calder and Stark, 2010), this paper is the first toever examine the impact of CNC-W spiral content on soil behavior. An experimental study (UCS, CBR, consolidation) has been carried out on the mixtures of soil with CNC-W at percentages 0, 5, 10, 15, and 20, by dry weight.

Experimental Work

Materials

The materials used were soil and CNC-W spirals. The soil samples were collected inside the campus at the University of Gaziantep in Turkey. The Atterberg limit tests were performed, and the liquid limit and plastic limits were 49 and 23, respectively. The cohesion (c) and internal friction angle (φ) of the tested samples were measured to be 15 kPa and 22 o, respectively. The clay grains have a specific gravity of 2,65. After the sieve analysis, according to the USCS, the soil sample was classified as CL (low plasticity clay) (see Figure 1).

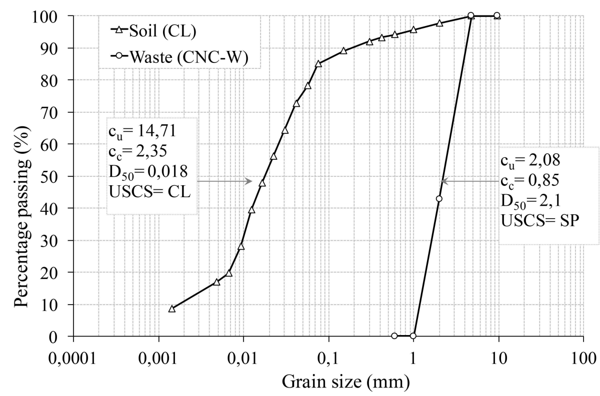

Figure 1. Grain size distributions for the soil and waste grains used during the experimental study.

The CNC-W was made of aluminum obtained from the industrial area of Gaziantep in Turkey. The density and strength of the aluminum processed for CNC-W spiral scraps were determined to be 2700 kg/m3 and 250 MPa, respectively. The CNC-W spiral scraps with a tensile strength of 24 MPa have about 9% elongation. The abundance of aluminum CNC-W scraps produced in Turkey are available at a low cost. Thus, use of this waste as soil reinforcement instead of recycling in metal industry can reduce energy consumption and make economic sense. The CNC-W scrap grains were classified as SP (poorly graded sand), and its specific gravity was found to be 2,80 (see Figure 1).

Clay grains in the scanning electron micrograph (SEM) picture seem to be consisted of smaller plates (see Figure 2). Figure 2 also indicates a photo of the CNC-W spirals, developing around an axis in a constantly changing series of planes.

Testing equipment and the preparation of specimens

The CBR testing machine employed in the laboratory had a proving ring with 28 kN capacity, and a dial gauge with 0,01 mm sensitivity. The CBR tests were performed in soaked condition according to ASTM D1883 (2016), in order to

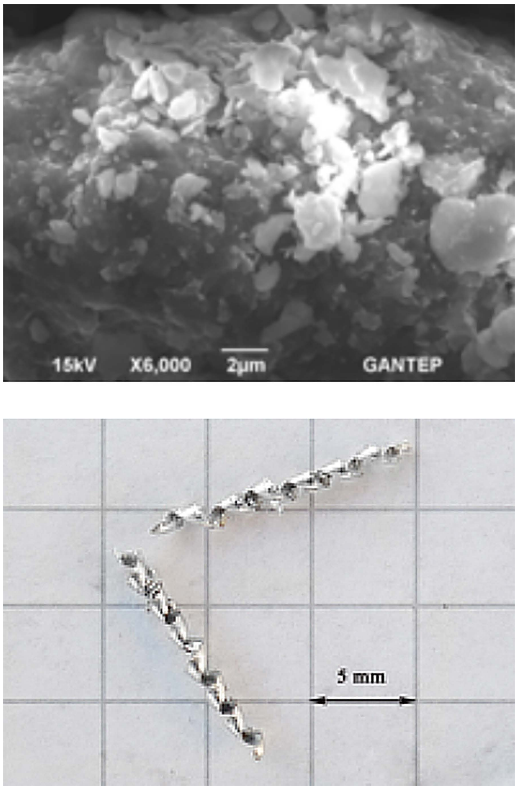

Figure 2. SEM picture of the soil (top), and photo of the aluminum CNC-W spiral (bottom).

evaluate the strength of the material and CNC-W mixtures prepared at optimum water contents (ASTM D1557, 2012). Only the soil specimens were evaluated with regard to their performance, and soil with CNC-W at the mixture proportions of 5%, 10%, 15%, and 20% by dry weight of the specimens. The weight of water, CNC-W spirals, and soil were calculated, and they were mixed uniformly. Each of these mixtures were compacted in a CBR mold in 5 layers following the instructions for modified compaction (2700 kN-m/m^3). Bottom and top surfaces of the specimens in the mold, whose diameter and height measurements were 152 mm and 178 mm respectively, were covered by paper filters in order to prevent the fines to leak out of them during the procedure. The CBR tests were carried out after a 96-hour soaking period. The piston penetrating at a rate of 1,25 mm per minute into the compacted subbase material was observed, and stresses were recorded at penetration levels of 2,54 mm, 5,08 mm, 7,62 mm, 10,16 mm, and 12,70 mm (ASTM D1883, 2016).

The samples with the same mixture ratios were studied by employing the UCS tests. Sample preparation techniques for both the CBR and UCS tests were the same. The samples were prepared by compacting them into split 43,2mm x 98,5 mm mouls (diameter x height). A hammer with a uniform pattern was employed in order to compact the samples with a certain energy, equivalent to the energy applied during the modified compaction test. After compaction, they were removed from the mold, flattened, and fixed onto the UCS pedestal (ASTM D2166, 2016).

The consolidation characteristics of these composite specimens were determined with help from laboratory consolidation tests (ASTM D2435, 2011). The oven dried soil and CNC-W samples were mixed by dry weight. The appropriate volume of soil and CNC-W were measured, and blended physically in a dry condition, up to the point where samples were noted to be uniform. They were placed in very thin layers by spooning gently into the mold. After filling the mold completely, the cap on top of the it was placed, and then the cell was periodically filled with water until the specimen was completely saturated and submerged under water. The outside ring was kept full with water for the entire period of the test. The oedometer machine used was 7,5 in diameter and 2 cm in height, which was equipped with a transducer. In the standard testing method used in this study, the submerged cell that is confined in the steel ring is subjected to a vertical loading while drainage is allowed through either the top and bottom faces. This load that is applied on the cell is increased twice its amount every day in order to measure the consolidation characteristics of the specimen.

Results and Discussion

The amount of water versus the dry unit weight of the soil only and the soil with different CNC-W inclusions were studied by traditional compaction tests, which were carried out by following the procedures defined in ASTM D1557 (2012). A comparison between the specimens prepared by conventional testing procedures is illustrated in Figure 3. The maximum dry unit weight of the specimens was observed to increase with increasing CNC-W inclusions because of relatively higher specific gravity of the CNC-W spirals. However, the optimum water content values were observed to decrease with increasing CNC-W inclusion. Certain similarities were observed between the results obtained here and the results on discrete fiber and micro grid stabilized soils (Shukla, Sivakugan, and Das, 2009). For example, Leshchinsky, Evans, and Vesper (2016) suggested using micro grids for earthworks where shallow ground improvement is required (e.g., retaining wall, surficial slope stabilization, or erosion protection).

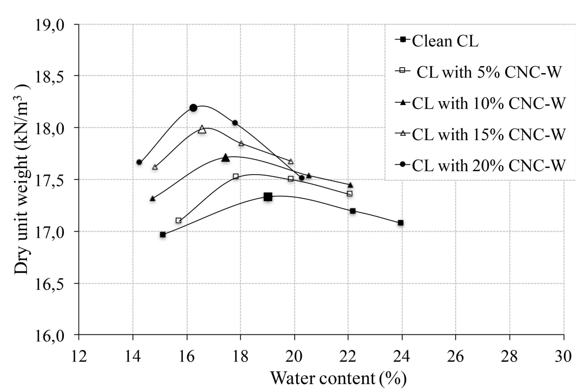

Figure 3. Compaction curves of the specimens at different mix ratios.

After determining the optimum water contents for each mixture, CBR values of soil alone, and of soil with CNC-W at different ratios were determined. Figure 4 indicates the change in CBR performance of the samples tested with CNC-W content at optimum water content (w_{opt}). The CNC-W inclusions increased the CBR performance of the mixture of soil and CNC-W up to 15%, and then a decrease was observed. The reason behind it is that either soil or CNC-W scraps govern the overall behavior of the sample. For example, 10% CNC-W inclusion to soil resulted in an approximately 2% increment in the maximum CBR performance of the mixture, whilst 20% CNC-W inclusion to soil decreased its performance by approximately 1%. The increment in the maximum CBR performance can be attributed to the increment in the maximum dry unit weights and thereby resulting increase in strength of the soil-CNC-W matrix. Similar results were obtained by employing natural and geosynthetic fiber reinforcements in soil. Actually, construction of geotechnical structures on soft soils is very much risky, given the possibility of settlement, low shear strength, and high compressibility. Fiber reinforcement in soil is accepted as an appropriate improvement technique due to its low cost and local availability (Consoli, Prietto, and Ulbrich, 1998; Rafalko, Brandon, Filz, and Mitchell, 2007; Sivakumar and Vasudevan, 2008; Pradhan, Kar, and Naik, 2012; Singh and Bagra, 2013). The strength of the compacted soil-CNC-W samples is due primarily to the mobilization of material frictional strength. Showing a similar behavior, described by Cabalar and Mustafa (2015), samples with higher quantity of the CNC-W reached the maximum dry unit weight and CBR performance with a relatively small variation in water content. However, samples with relatively less amount of CNC-W reached the maximum CBR with a relatively larger variation. This, in turn, is due primarily to the high-water intake capacity of CL type soils in the samples. When CNC-W scraps are introduced into the soil, they improve its strength. The mechanism behind this behavior is believed to be the ability of these scraps to interact with each of the soil grains through frictional force and inter-locking. Actually, the function of interlocking is to transfer the stress from soil to CNC-W scraps by mobilizing their tensile strength. This may be because of the fact that the volume filled by the CNC-W scraps is greater, leading to more interaction. Thus, influence of scraps will be predominant. CNC-W scraps eventually behave like a frictional resistance element in the soil matrix. The CBR performance of soil samples with CNC-W scraps was observed to be higher than clean soil samples. Therefore, the significant increase in the CBR performance of soil because of CNC-W scraps will substantially reduce the thickness of subgrade layer.

It has long been understood that CBR performance of a subgrade material can determine the thickness of the pavement. The design thickness and capping details for this study are shown in Figure 5. It can be seen that, for a subgrade that has a CBR performance over 15%, the thickness will be 150 mm. If the CBR performance is within a range of 2,5% and 15%, the subgrade can be designed with

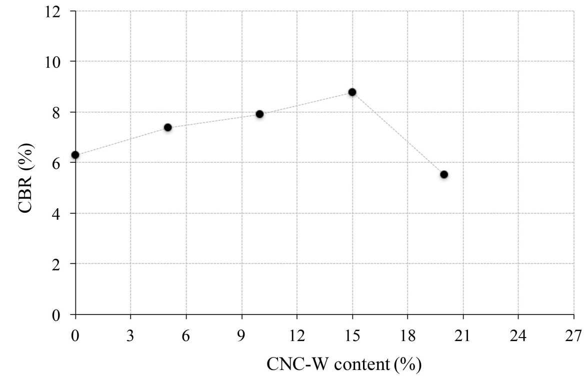

Figure 4. Variation in CBR values at wopt with CNC-W content.

(i) a 150-mm thickness with a capping of a varying thickness value, or (ii) a capping-free and a thicker subbase (HD 26/06, 2006). Table 1 lists some soil-CNC-W mixtures while also showing the capping and sub-base design thickness for each one of them.

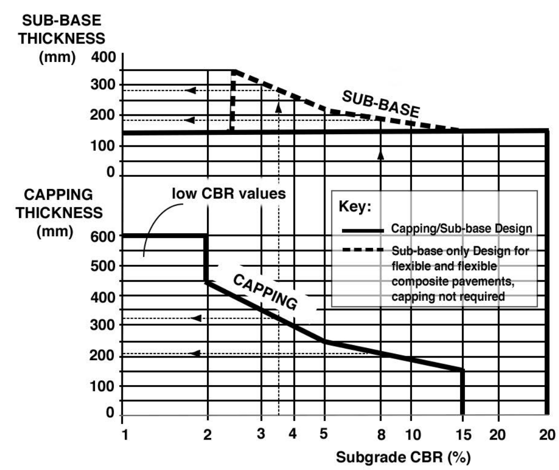

Figure 5. Capping and sub-base thickness design (HD 26/06, 2006).

The samples of soil-CNC-W mixtures were evaluated for possible swelling. The swelling potential of the sample was calculated using their expansion ratio, which is the increase in height compared to the beginning of the experiment. Samples prepared with different contents and different swelling potentials can be seen in Figure 6. It was observed that the inclusion of CNC-W in the samples was efficient in managing the swelling. The pressure that develops during swelling can be in any direction and in turn mobilize the frictional forces between the soil particles and the CNC-W, thus counteracting the swelling pressure. The presence of CNC-W inclusions reinforced the soil, and consequently decreased swelling. Eventually, the swelling ratio was seen to have decreased from 1,15% for the soil to only 0,8% for the soil with 20% CNC-W. A certain decrease in swelling percentage was also described by Vyas, Phougat, Sharma, and Ratnam (2011), and by Megeed (2012), who employed polymeric and natural fibers, respectively.

Table 1. Testing results

Specimen	CBR (%)	γ_{drymax} (kN/m^3)	w_{opt} (%)	SP (%)	UCS (kPa)	Pavement design alternatives		
						1		2
						Subbase (mm)	Capping (mm)	Subbase (mm)
CL	6,3	17,2	19,5	1,15	373	150	230	205
CL+5% CNC-W	7,4	17,5	18,7	1,06	389	150	210	190
CL+10% CNC-W	7,9	17,7	17,9	0,99	405	150	202	181
CL+15% CNC-W	8,8	18,1	17,0	0,87	470	150	195	178
CL+20% CNC-W	5,5	18,1	16,3	0,81	-	150	241	217

CBR: California bearing ratio; γ_{drymax}: Maximum dry density; w_{opt}: Optimum water content; SP: Swelling percentage; UCS: Unconfined compressive strength.

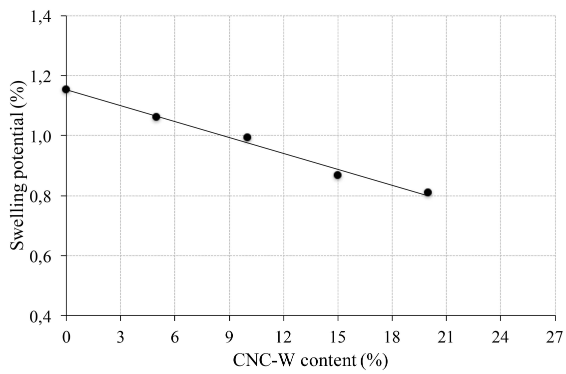

Figure 6. Variation of swelling potential vs. CNC-W content for the specimens tested at w_{opt}.

The results of the UCS show that there is a significant correlation between the stress-strain behavior of the soil samples and the amount of CNC-W in the mixtures (Figures 7 and 8). All of the samples in the study were prepared at their optimum water content (Figure 9). The samples were prepared with an increasing CNC-W scrap ratio up of to 20% in the mixture until no further test was able to be performed. The addition of the scrap materials resulted in a decrease in the peak compressive strength of the samples (Table 1). Similar findings were also reported by Chauhan, Mittal, and Mohanty (2008) for investigation of problematic soils tested with the addition of natural fibers and waste materials.

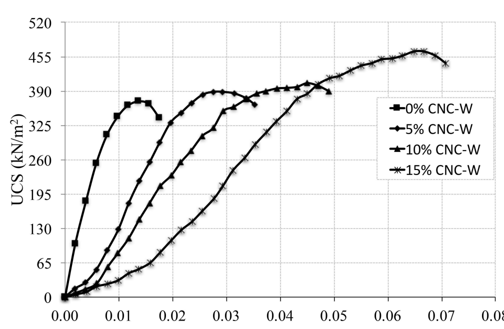

Figure 7. Variation of UCS vs. strain for the specimens with CNC-W tested at w_{opt}.

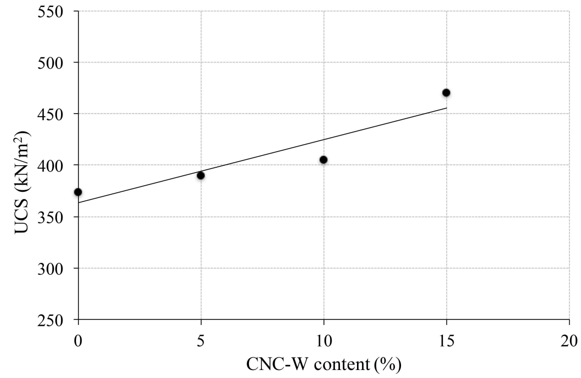

Figure 8. Effect of CNC-W content on UCS of the specimens tested at w_{opt}.

Figure 9. A picture of two tested CL with 20% CNC-W specimens.

The strength gain rate with CNC-W content was defined in terms of the strength increment index (SII) parameter as described by the expression below (Eq. 1):

$$SII = \frac{UCS_{CLwithCNC-W} - UCS_{CL}}{UCS_{CLwithCNC-W}} \cdot 100 \qquad (1)$$

A plot of the SII with CNC-W content was drawn in Figure 10, which shows that the SII increases as CNC-W content grows. Figure 10 illustrates the relative degree of strength gain due to CNC-W inclusion.

As the water pressure increases for the samples of clay (CL) and CNC-W, the change in void ratio is recorded, and its results are given in Figure 11. The figure shows that, due to the initial condition of the samples, the starting void ratios are collected within a wider range (Δe = 0,1225). After having evaluated these oedometer test results, and given the previous research of the literature, the authors concluded that the CNC-W samples used in this study could make the soil less compressible due to its ability to hinder the flow. The characteristics illustrated in Figure 11 suggest that the clean soil grains change much more freely than those tested with CNC-W, possibly as a consequence of grains packing closer to each other during sample formation,

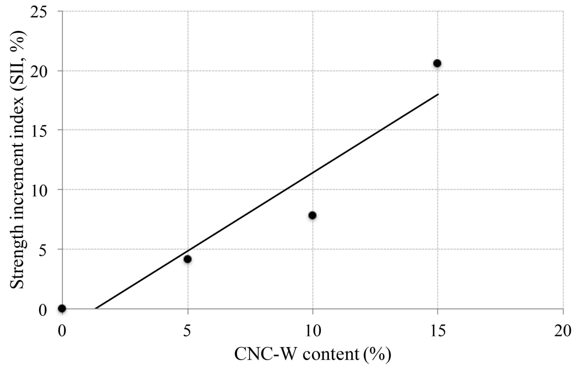

Figure 10. Effect of CNC-W content on the SII values of the specimens tested at w_{opt}.

which leads to a reduction in the voids. Then, the CNC-W spirals were thought to act as reinforcement between soil grains, and thereby result in substantial decrease in hydraulic conductivity (k) (Figure 12). Further, addition of CNC-W scraps helps in cutting of strain failure, increasing its stiffness and strength in comparison to non-CNC-W added soil. There are still many experiments to be made to be able to have more confidence in the effects of CNC-W to the soil. There are some researchers who have made contributions on this topic, including Thevanayagam (1998), Monkul and Ozden (2007), Cabalar (2010), Cabalar and Hasan (2013), and Cabalar and Mustafa (2015). In light of the readily available papers, during one dimensional consolidation, the effect of the addition of CNC-W scraps on the soil varies. One way to explain the effect of CNC-W is by using an inter-granular void ratio approach, which is hereby referredas the void ratio of the CNC-W scrap spirals with respect to the whole mixture (e_{CNC-W}).

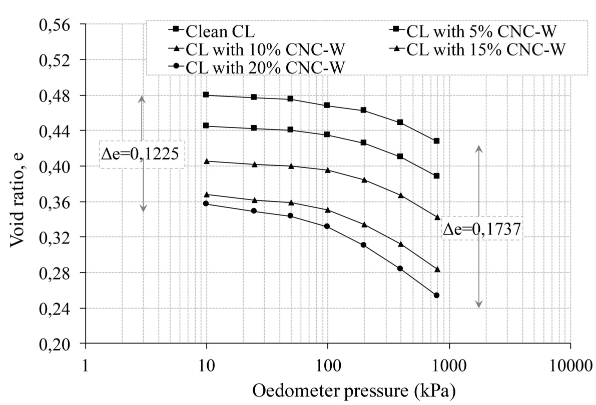

Figure 11. Variation of void ratio (e) with oedometer pressure for CL with CNC-W.

The voids of the CNC-W mixtures are due to the spiral nature of CNC-W materials (which is e_{CNC-W}) and also to the voids in the soil grains. It is understood that the direct spiral to spiral connections of the CNC-W scrap matrix start when the void ratio of the CNC-W scraps spiral to that of CNC-W alone in a mixture (i.e., $e_{CNC-W} = e_{\max}$).

Granular compression index, which is symbolized by c_{c-s}, is a definition that helps study the compression behavior of these mixtures (Monkul and Ozden, 2007). The term gives a relationship between the effective stress and void ratio, as can be seen in Eq. 2:

$$c_{c-s} = \frac{\Delta e_s}{\Delta \log \sigma'} \tag{2}$$

The change in these two compression indices (c_c and c_{c-s}) in CNC-W mixed soils is displayed in Figure 13. CNC-W inclusion caused an increase in both parameters within the same experiment. The increase in global compression index values was observed to occur in smaller proportions. Actually, with increasing clay content, the CNC-W spirals become further separated, to the point where there is almost no interaction between the spirals. At such stage, it is thought that compressive behavior is mainly due to clay particles. The difference between the two compression index parameters becomes larger as more CNC-W materials are added to the mixture.

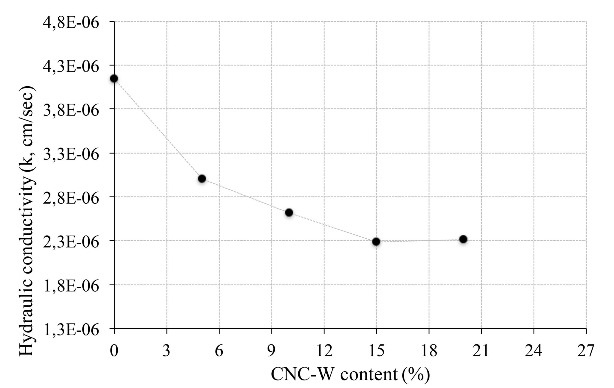

Figure 12. Effect of CNC-W content on the hydraulic conductivity (k) values of the specimens.

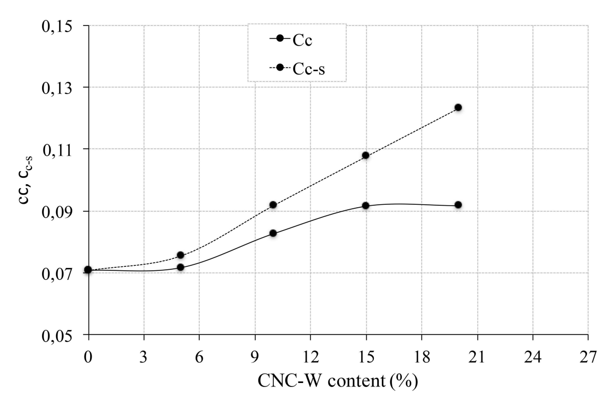

Figure 13. Variation of compression parameters for specimens with various CNC-W content.

Conclusions

A novel investigation was presented in this paper that examines the behavior of soils, which were mixed with

CNC-W scraps. An extensive series of laboratory tests were carried out on the mixtures of CL type soil reinforced with CNC-W spirals. The tests included a series of consolidation, UCS, and CBR tests. Influence of the CNC-W spirals on soil behavior was studied by adding CNC-W spirals in concentrations of 0%, 5%, 10%, 15%, and 20% by dry weight. Four new aspects of behavior can be concluded from the results of this study:

1. The increase in CNC-W content causes the maximum dry unit weight of the mixtures to increase, from 17,25 kN/m^3 to 18,25kN/m^3 by 20% CNC-W addition, whilst causing the optimum water content to decrease, from 19% to 16%.

2. The addition of CNC-W increased the CBR value of the samples up to 15%, which could lead to large reductions in thickness of highway pavement design.

3. The peak compressive strength of the samples reduced as the quantity of CNC-W content increased up to 15%, whilst no test was able to be performed with a 20% mixture ratio.

4. CNC-W scraps in the samples cause a lower compressibility (Δe_o = 0,1225 with 20% CNC-W addition), and a substantial decrease in hydraulic conductivity, from 4,3E-0 6cm/sec to 2,3E-06 cm/sec, because of their ability to reduce voids.

These conclusions suggest that specimen formation. in the way it is used here, could be considered as an alternative soil reinforcement technique for construction of road pavement subgrade.

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