



Investigation of geotechnical properties of clay soils mixed with recycled nano carbon black

RAHIM KAGAN AKBULUT and FATI H ISIK*

Technical Vocational School of Higher Education, Department of Construction, Ataturk University, Erzurum, Turkey
e-mail: rkakbulut@atauni.edu.tr; fatih.isik@atauni.edu.tr

MS received 10 July 2020; revised 23 November 2020; accepted 23 December 2020

Abstract. Recycled waste materials have been investigated in different ways in civil engineering applications and at these studies the usability of waste materials have been examined in concrete production, road construction and soil improvement. In this study, the effect of recycled nano carbon black (nano-CBr) on consistency limits and unconfined compressive strength properties of clayey soils was investigated. For this purpose, 4 different ratios (1%, 3%, 5% and 10%) nano-CBr were mixed to 3 different clay soils (White, Green and Red clays). In order to determine the mineralogical and chemical properties of mixtures, pH, TDS, X-Ray, SEM and contact angle tests were also performed. In this study, 1% nano-CBr ratio was generally determined as the limit value in all experiments. The consistency properties of the mixed samples have not significantly changed for the red and green clay but have importantly affected the white clay properties. Based on the 1% nano-CBr ratio, the unconfined compressive strength (UCS) values of all mixed samples increased. Addition of super hydrophobic nano-CBr to clay soils, turned clay soils into a hydrophobic material, is resulting in an increase in the contact angle values. On the other hand, pH values did not show a significant change with the increase of the nano-CBr ratio. The total dissolved solids (TDS) measurements showed a series of rise and fall steps with the increase of nano-CBr ratio and showed a tendency to stabilize at 10% nano-CBr ratio.

Keywords. Carbon black; nano material; clays; unconfined compressive strength; contact angle; geotechnical engineering.

1. Introduction

Nowadays, one of the major problems in the world is the disposal of waste materials. Due to the increase in human population and industrialization, the wastes produced by human beings have increased rapidly. The most important feature of these wastes is that they remain in nature for many years due to the chemical components they contain. This situation leads to significant environmental problems, especially in large metropolises where human population is dense. In parallel with the increase in environmental awareness in recent years, there have been important developments regarding the dispose of waste materials. Today, waste management systems are set up to reduce waste and also recycling of waste materials. The recycling process reduces the need for raw materials and ensures the sustainability of natural resources, as well as it also prevents the damage caused to the environmental problems. On the other hand, since the cost of raw materials will be

reduced by the recycling of the wastes, an economic benefit will be provided.

Recycled waste materials have been investigated in different ways in civil engineering applications and at these studies the usability of waste materials have been examined in concrete production, road construction and soil improvement. Researchers have investigated the usage of waste concrete blocks as a re-used aggregate in concrete [1–5]. Similarly, waste glass materials have been used as a concrete additive [6–8]. On the other hand, the re-use of waste asphalt coatings has been investigated by researchers [9–11].

The applicable waste materials were added as an additive to the soils and their usability in the treatment of soils was investigated in many studies. For this purpose, boro-gypsum [12–14], phospho-gypsum [15–17], silica fume [6, 18–20] and fly ash [21–23] were used.

Scrap tires existed by worn or worn-out tires are also a waste material. Scrap tires accumulate irregularly as shown in figure 1. This type of wild storage causes many environmental problems: (i) Large volumes of storage space are needed as scrap tires take up a lot of space. (ii) This type of

*For correspondence
Published online: 05 March 2021



Figure 1. Wild storage areas and scrap tires [24].

storage allows nesting of harmful reptiles and insects, and most importantly (iii) Scrap tires, a petro-chemical product, cause environmental pollution by staying in nature for many years in this type of landfill areas.

The usability of scrap tires, which were crushed and granulated, in the treatment of soils were examined by some researchers. Edil and Bosscher [25] investigated the engineering properties of granular rubber in soils. Masad *et al* [26] also examined the usability of rubber and soil mixtures as light filler materials. Edinçliler *et al* [27] investigated the effect of used tires on mechanical properties of soil embankments. Sheikh *et al* [28] also studied the slip and compressibility properties of sand and granular rubber mixtures. Brunet *et al* [29] examined the usability of recycled granular tires as seismic isolators.

Recently, pyrolysis is applied on scrap tires and they are subjected to different recycling. Pyrolysis is the process of thermal decomposition of organic substances by exposure to high temperatures (500–1000°C) in an anaerobic environment. Different products are produced from scrap tires depending on the degradation processes occurring in each phase of the pyrolysis process. These products are gas, pyrolytic oil and carbon black [24].

To the authors' knowledge, there has been no research in the literature with respect to usage of recycled carbon black at soil improvement applications. So that, authors decided to investigate the usability of nano-CBr in soil improvement. In this study, the effect of nano-CBr on some geotechnical and engineering properties of clayey soils was investigated. For this purpose, 4 different ratios of nano-CBr were mixed with 3 different clay soils. According to the results, the effect of nano-CBr on clay soils was investigated.

2. Materials and methods

2.1 Clay soils

Sedimentary deposit clay samples in Erzurum-Oltu region were used in the study. The clays taken from the reserves were named as white (W), green (G) and red (R) clay according to their colours. The geotechnical properties of clay soils are summarized in table 1.

Table 1. Some geotechnical properties of clays used in experiments.

Properties	W	G	R
Liquid Limit, LL (%)	120	55	36
Plastic Limit, PL (%)	30	27	24
Plasticity Index, I_p (%)	90	28	12
Specific Gravity, G_s	2.78	2.73	2.74
Optimum Water Content (%) [Standard Proctor]	30	27.8	21
Max. Dry Unit Weight (kN/m^3) [Standard Proctor]	13.9	14.5	17
Unconfined Compression Strength (kg/cm^2)	2.9	2.3	2.2
Clay Content (%)	61.6	60.5	34.1
USCS	CH	CH	CL
Contact Angle ($^\circ$)	22	– ⁽⁵⁾	15

2.2 Material of recycled nano carbon black (Nano-CBr)

The recycled nano carbon black used in the experiments was obtained from Prokom Co. Ltd., which recycles scrap tires in Erzincan. The company collects waste and rancidly scrap tires in the market and firstly produces steel wire and granular rubber parts via shredding and then in the second stage, it obtains pyrolytic oil and nano-sized carbon black by pyrolysis procedure. While the company uses pyrolytic oil for energy purposes, packs nano carbon black in different package sizes. Some results of analyses about nano-CBr performed by the company are given in table 2.

2.3 Preparation of nano CBr - clay mixtures

In order to investigate the effect of nano-CBr on clay soils (consistency limits, UCS, contact angle, pH and TDS), it was mixed with dry clay soils at 1%, 3%, 5% and 10% ratios. Notifications of the mixtures are given in table 3.

Table 2. Some analysis results of nano-CBr (Prokom Co. Ltd.).

Properties	Nano-CBr
View	Powder/grain
Color	Black
Particle size	40 nm
Smell	Odorless
Melting point/range	Not applicable
Boiling point/range	Not applicable
Density (20 °C)	1.7–1.9 g/ml
Bulk density	20–640 kg/m^3
Resolution (water)	Insoluble
pH	4–11
Decomposition temperature	300 °C
Self-ignition temperature	>140 °C

Table 3. Mixture percentages used in experiments.

Mixture percentages	Mixture symbols		
	White clay	Green clay	Red clay
0%	W0	G0	R0
1%	W1	G1	R1
3%	W3	G3	R3
5%	W5	G5	R5
10%	W10	G10	R10

2.4 Consistency limits

The geotechnical properties of clay soils are mainly influenced by water content. It is clearly known that the consistency limits of clay soils have a relationship between the other geotechnical properties (i.e., compatibility, swelling potential, workability, etc.). Also, the consistency limits of clay soils gives a preliminary information about geotechnical behaviour of these kind of soils. In the study, liquid limit (LL) of the mixtures was determined by the cone penetration method according to the British standard [30] and American standard [31] was used to determine the plastic limit (PL) values. The determined ratios of nano-CBr were added to the clay soil samples. In order to ensure homogeneity of the mixtures, nano-CBr was mixed with clays at dry state for 15 min duration. Water was then added to the mixtures according to the aforementioned standards and mixed again. The obtained mixtures were kept in plastic containers for 24 h in order to absorb the water. At the end of the period, the liquid limit and plastic limit tests were performed for each mixture. The images of preparation of the W5 sample are shown in figure 2.

2.5 Unconfined compressive strength (UCS) tests

In this study, nano-CBr added and not added (W0, G0 and R0) samples were loaded in the deformation controlled unconfined compressive test instrument at a loading rate of

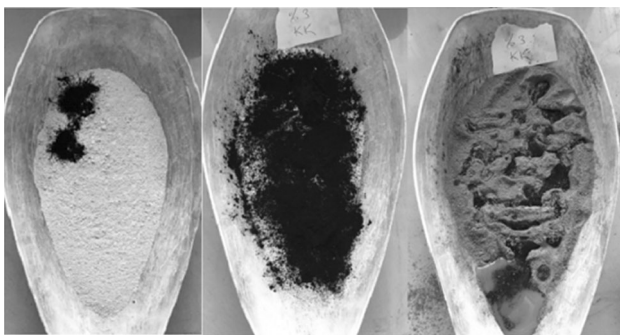
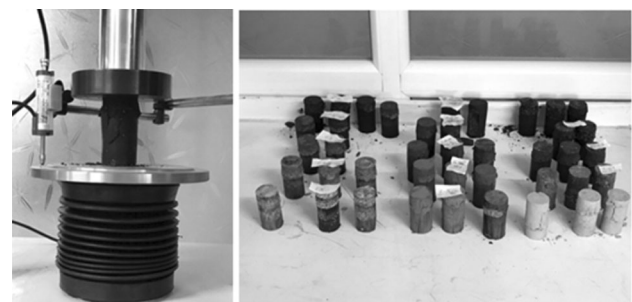
0.8 mm/min, in order to monitor the stress-deformation behavior after failure of the samples. The UCS tests were carried out in accordance with ASTM D 2166 [32]. The samples were prepared at optimum water content of Standard Proctor energy level and then compacted in a cylindrical mold (38 mm diameter and 76 mm height). All experiments were repeated on three samples to check the accuracy of the results. In figure 3, images of failed samples are given after UCS test.

2.6 Contact angle

A liquid surface in contact with a solid surface forms an angle. The magnitude of this angle, called the contact angle, depends on the relative magnitude of the attraction forces between its molecules (cohesive forces) and the liquid–solids attraction forces (adhesive forces). When the cohesion force is greater than the adhesion force results the greater contact angle value [33]. In other words, a large contact angle is an indication of the reduction of liquid–solid attraction forces (i.e., low solid surface energy and low degree of wetting), and also a small contact angle is an indication of the increment of these forces (high solid surface energy and high degree of wetting).

Contact angle is a parameter used in geotechnical engineering to measure the wettability of soils. The contact angle can be easily determined experimentally and shows the affinity of soils to water. In this respect, the contact angle has been used to examine and evaluate the soil water characteristic curves by researchers [34–36]. Contact angle is also important in evaluating different geotechnical processes (permeability, absorption, suction, capillarity, interfacial tension, etc.). In addition, the contact angle has been studied in recent years to understand the unsaturated soil mechanical behavior of soils [37–39].

In this study, the contact angles of prepared mixtures were measured using the device available in the scientific research laboratory of Atatürk University EAATRAC (East Anatolian Advanced Technology Research and Application Center) (figure 4). In order to determine the contact angle values, the powdered mixtures were pelletized with 0.6 g of

**Figure 2.** Preparation W5 sample.**Figure 3.** UCS test specimens.

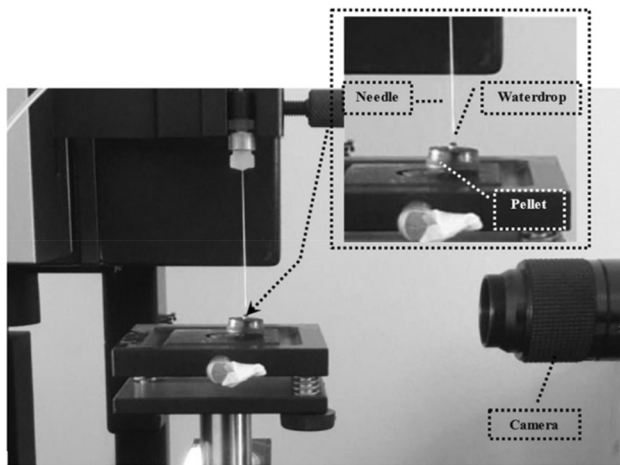


Figure 4. Contact angle measuring details.

test specimens compressed with an average pressure of 1.2 tons. The prepared pellets were placed on the device and a water drop of 3 mL volume was released from a constant drop height (figure 4). With the help of the software used, the camera was able to record at high speed with 1 s interval and the mean contact angles were measured by analyzing 5 images taken from the pellet-liquid contact surface [40].

2.7 Physico-chemical and mineralogical analyses

In the study, pH and TDS values of nano-CBr added and not added samples were examined as physico-chemical properties. On the other hand, the X-ray and SEM analyses were performed to investigate the mineralogical properties of the samples. pH is a unit of measure describing the degree of acidity or alkalinity of a solution. It's measured from a scale of 0–14. The use of pH as a measure of acidity and basicity in aqueous media has probably made potentiometric pH measurement in all disciplines perhaps the most common analytical technique [41]. It is important to know the pH of aqueous solutions of treated and untreated samples since the engineering property of most of the clay vary significantly with the pH value [40]. The pH of the aqueous solutions is generally measured by means of pH meters. This experiment was carried out in accordance with ASTM D 4972-01 [42]. The suspensions were shaken for 30 min in a temperature-controlled shaker and pH measurements were made at the end of the period. The equilibrium pH of the suspensions prepared in the experiment was determined from the pH measurements made at regular intervals. The measurement was continued until the measured pH values were fixed. In addition, the total dissolved substance (TDS) measurements of the suspensions of the prepared samples were made by the pen type TDS meter.

It is known that fine-grained soils consist of minerals and their behavior changes depending on these minerals. The XRD analysis were performed in order to identify the main minerals of nano-CBr and clay samples. The results are shown in figure 5.

In addition, SEM analyses were carried out in order to display the interference of nano-CBr between clay plates in the mixtures. EDS analysis was also performed as a function of the SEM device (figure 6).

3. Results and discussions

The consistency limits tests were performed on all samples that prepared using 3 different clay soils and 4 different nano-CBr (1%, 3%, 5% and 10%) ratios. The test results are given in figure 7.

Figure 7a shows the relationship between liquid limit (LL) and nano-CBr. White clay's LL value was determined as 119.7%. At 1% nano-CBr ratio, LL value of white clay decreased to 90.4% and after this ratio a constant trend was observed for LL values of white clay. Eventually, LL value of white clay at 10% nano-CBr ratio was determined as 82.8%.

LL value of G0 sample was determined as 54.6%. LL value of green clay mixtures insignificantly increased step by step until G5 and then a slightly decrease was obtained at 10% nano-CBr ratio (figure 7a). It is worth mentioned that considering the value of the water content, the increment and subsequent decrement trend of green clay LL values is negligible. It appears that all LL values of the green clay samples are almost constant (figure 7a). Similarly, red clay tended to remain constant at all LL values and there is no general increment or decrement tendency. In addition, it was observed in figure 7a that LL values of R1, R3, R5 and R10 samples were lower than R0 sample, however, this decrement was not valuable. As can be seen from figure 7a, nano-CBr consisted of carbon atoms. Since non-polar properties of nano-CBr, it was considered that nano-CBr particles did not adsorb on clay plates. As a result, there was no significant change in LL values with an exception of W0 sample.

It is worth mentioning that there is no study on carbon black and clay mixtures in the geotechnical literature. However, many studies have been performed on the behavior of clay soils treated with different salt solutions [43–47]. There is no generally accepted behavior in these studies. In some studies, it was determined by the researchers that LL increased with increasing salt concentration, while in others, LL decreased with increasing concentration. The reason for this is that clay soils have complex mineralogical structure.

When figure 7b is examined, it is seen that the white and green clay samples' plastic limit (PL) values increase up to 1% nano-CBr ratio and start to decrease slightly after this

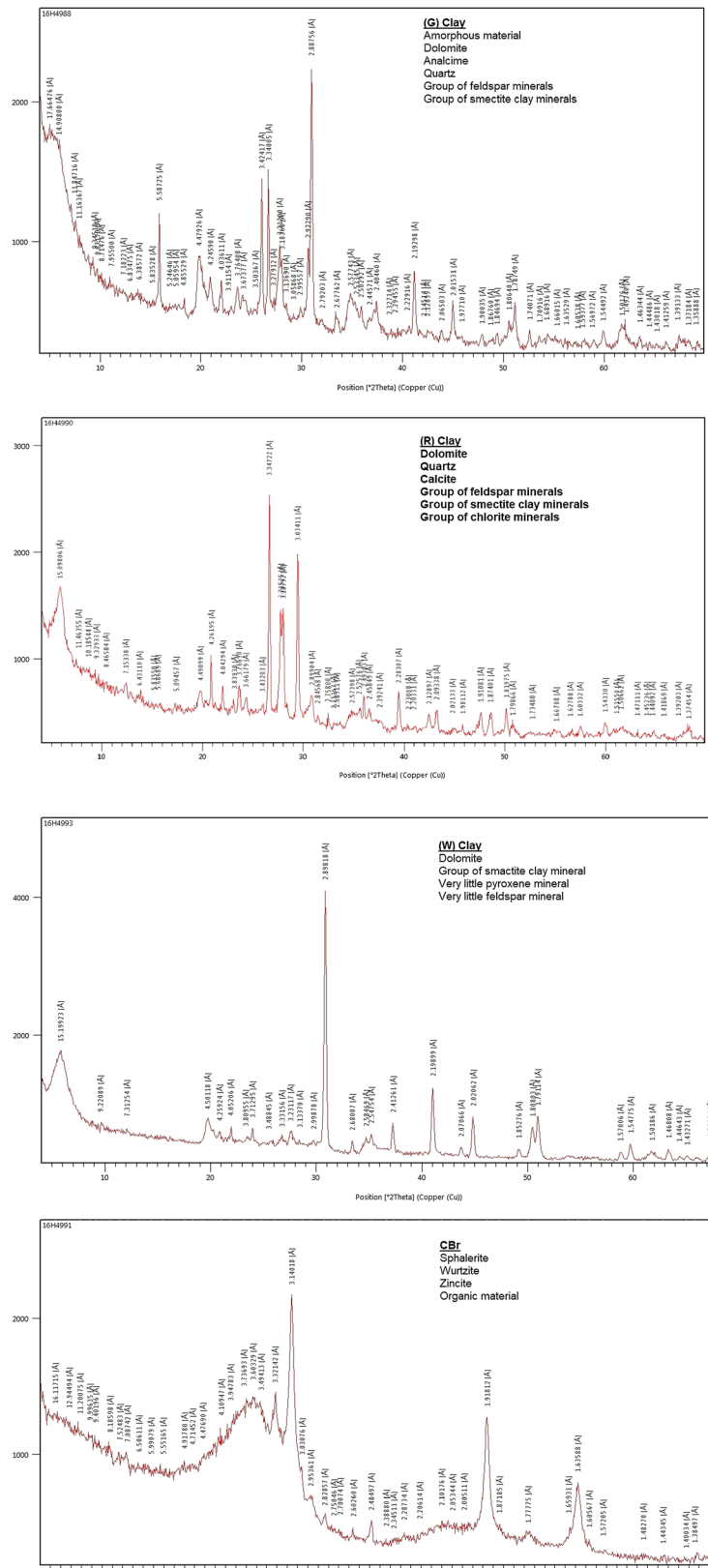


Figure 5. XRD analysis results of G–R–W clay and Nano-CBr sample.

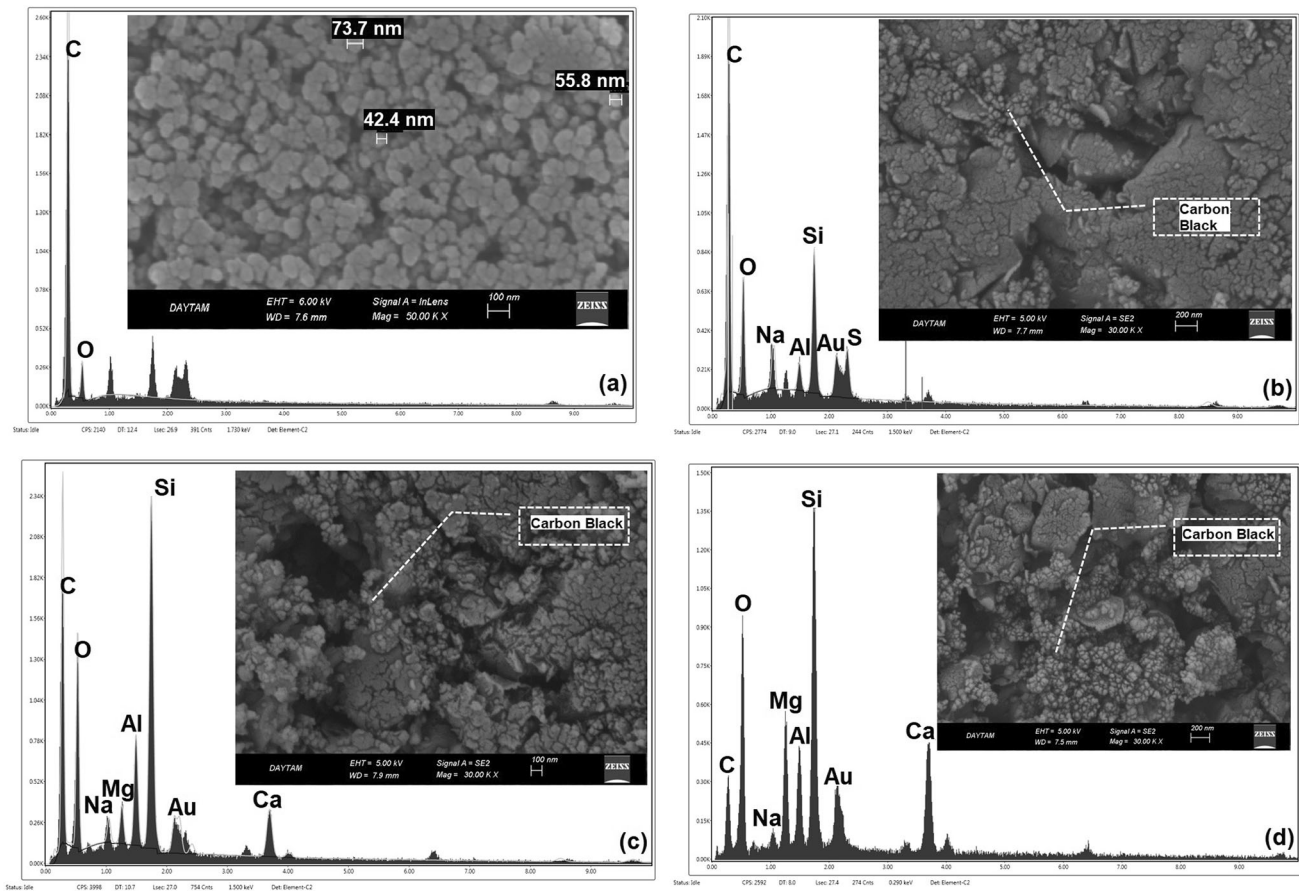


Figure 6. SEM and EDS spectrums of (a) Nano-CBr, (b) R10, (c) G10, (d) W10.

point. It is clearly seen that beyond 1% nano-CBr ratio, PL values of white and green clay samples are almost constant (figure 7b).

It is observed that there is a decrement trend on PL value of red clay samples with the increase of nano-CBr ratio. However, this decrement is not valuable in terms of geotechnical engineering. In addition, it is well known that the plasticity characteristics of clay soils depended on diffuse double layer (DDL) of clay plates. Decrement or increment in the thickness of DDL changes the soil behaviour. As a result, the addition of nano-CBr did not have appreciable effects on the thickness of DDL and so on PL of red clay samples.

Generally, the PL values of CH clays mixed with nano-CBr are higher than those pure clay samples. On the other hand, it is seen that the addition of nano-CBr to CL clay does not cause a significant change in PL values of this clay (figure 7b). When the consistency limits results were examined in view of geotechnical engineering, the effect of nano-CBr on red and green clay was negligible. On the other hand, it was determined that nano-CBr significantly affected the consistency properties of white clay (figure 7).

Clay samples and nano-CBr added samples were tested at UCS test frame. The stress-deformation graphs and peak

stress–nano-CBr relation of the test samples are given in figure 8.

The peak stresses of the mixtures, especially at 1% nano-CBr ratio, significantly increased in comparison to the pure clay samples. However, after this point, the peak stresses in all clay types decreased with the increase of nano-CBr ratio. For white clay samples, peak stresses of W3, W5 and W10 samples were determined lower than the peak stress value of W0 sample. For green and red clay samples, it was found that the peak stresses at 3%, 5% and 10% nano-CBr ratios were higher than the peak stress values of the pure clay samples. Particularly at the nano-CBr ratio of 1%, the nano-CBr particles replaced the voids between the clay plates. This phenomenon resulted, the clay plates became more compact and as a result a much higher peak stress was obtained compared to W0, G0 and R0 samples. It was thought that the reason for the decrease in the peak stresses after this critical ratio (i.e., 1% nano-CBr), the reduction of the cohesion effect between clay plates due to the super hydrophobic character of the nano-CBr. On the other hand, the nano-CBr particles at high ratios (i.e., 3%, 5% and 10%) filled the soil voids over their capacity. This situation would cause an increase in soil voids and so UCS values started to decrease after this nano-CBr ratio (i.e., 1%). As previously

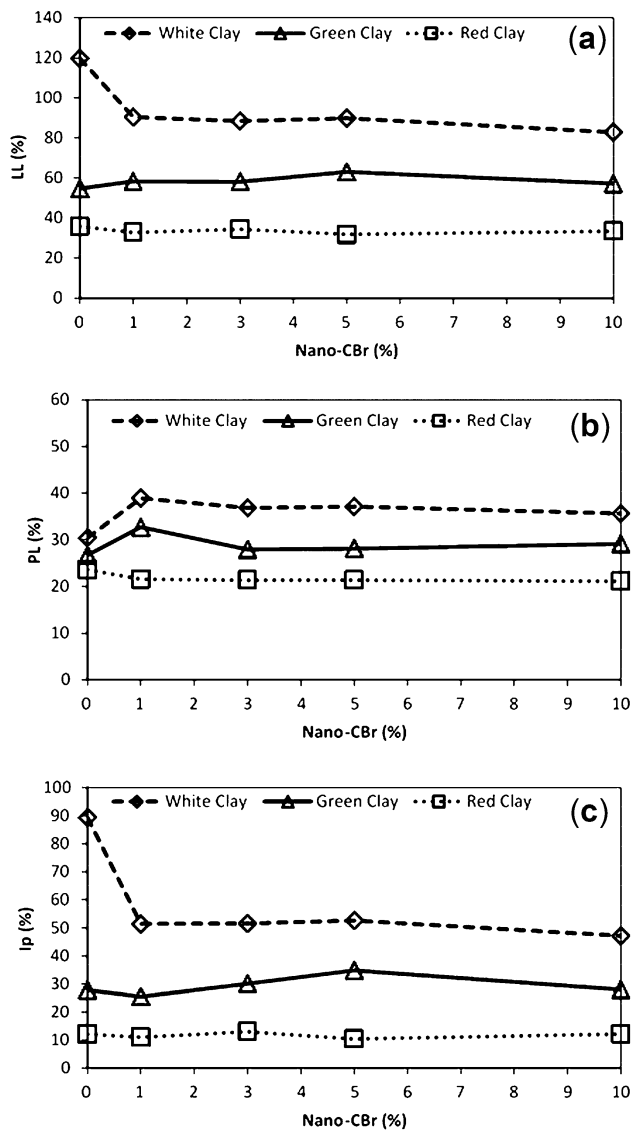


Figure 7. Results of the consistency limit tests (a) Liquid limit. (b) Plastic limit. (c) Plasticity index.

mentioned, no studies on carbon black and clay mixtures have been found in the literature. However, some studies were investigated the UCS performance of clay soils treated with different types of polyesters [48–51]. In these studies, it was determined that the UCS values increased with the use of polyester.

The contact angle values of mixtures are summarized in table 4. The contact angle—nano-CBr relation of these values is given in figure 9. As can be seen from table 4, the contact angle G0 sample could not be measured because this sample absorbs water into its structure very quickly. Also, the contact angle value of nano-CBr was determined as 146.5° , which indicates that nano-CBr was a super hydrophobic material [52]. This result showed that nano-CBr was a super-water-repellent (super hydrophobic) material. On the other hand, it was determined that the

clays used in the study were water-loving (hydrophilic) material (figure 9).

As can clearly be seen from figure 10, while the contact angle of W0 was determined as 22.7° , the contact angle values of W1, W3, W5 and W10 samples increased to 35.4° , 33.3° , 83.7° and 94.6° , respectively. In the red clay samples, the contact angle value increased until 3% nano-CBr ratio and then it decreased at 5% nano-CBr ratio and started to increase again after this point (figure 10). On the other hand, the contact angle value of green clay samples increased gradually as nano-CBr increased and reached 103.3° at 10% nano-CBr ratio. In general, it has been found that the contact angle values increase as nano-CBr ratio increase in all clay types. In other words, the increment of nano-CBr ratio caused a decrease of water affinity and wettability of clay mixtures. As expected, the addition of nano-CBr into the hydrophilic clay soils has altered the behavior of such soils and reduced their interest in water and transformed them into a hydrophobic material [34].

PH and TDS measurements in suspensions prepared to determine the physico-chemical properties of all samples were made and are shown in figure 11.

In figure 11, the pH values of W0, R0 and G0 samples were measured as 8.4, 7.1 and 7.5, respectively. In clay samples with 1% nano CBr additive, it was measured as 8.6, 7.6 and 7.2 for white, red and green clay samples, respectively. In general, at 3%, 5% and 10% nano-CBr ratios, addition of nano-CBr did not have an appreciable effect on pH values when compared with their own pure clay samples. In particular, the pH values of the suspensions of white clay samples remained in the basic medium. Other clay mixtures were still close to the basic region but exhibited a more neutral behavior. The fact that the pH values of the suspensions remain in the relatively basic region could be explained by the behavior of the oxide components such as Magnesium and Sodium in the aqueous medium, as can be seen from the XRD spectra. With the increase of the nano-additive ratio (in particular 1% excess), pH values do not change significantly. This was due to the fact that nano-CBr did not have much effect on this behavior of its oxides.

TDS measurements are associated with electrical conductivity [53, 54]. In this respect, TDS measurements showed a series of rise and fall steps with the increase of nano-CBr ratio and showed a tendency to stabilize at 10% nano-CBr ratio. The reason for the increase and decrease in these values was thought to be the removal and convergence of ion from clay matrix [30].

It is worth mentioning that the results of pH and TDS measurements are in parallel with the results of the consistency limits values. A decrement or increment trend was observed up to 1% nano-CBr ratio both at pH and TDS measurements, and after this critical ratio, pH and TDS values were going stable like the results of both consistency limits and UCS tests. This phenomenon is thought to occur due to the non-polar characteristic of nano-CBr. It could be

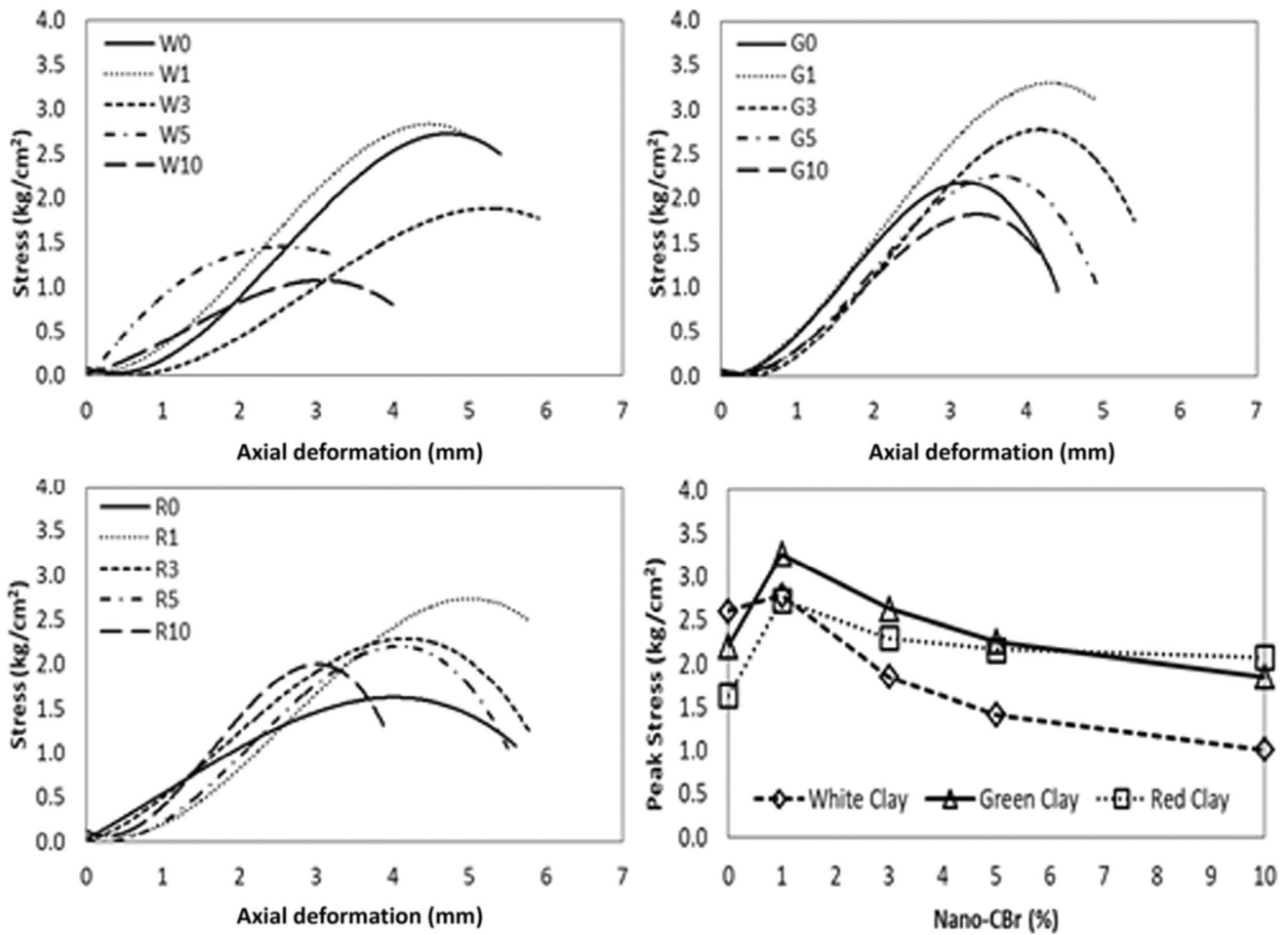


Figure 8. Stress–deformation curves and peak stress–nano-CBr relationship.

Table 4. Measured contact angle values.

Nano CBr ratio	Contact angle (°)			Nano-CBr
	White clay	Red clay	Green clay	
0%	22.7	15.9	Non	–
1%	35.4	43.6	52.5	–
3%	33.3	77.0	59.4	–
5%	83.7	69.5	70.4	–
10%	94.6	103.6	103.3	–
100%	–	–	–	146.5

explained as nano-CBr did not adsorb on clay plates and not change the thickness of DDL.

4. Conclusions

In this study, the effect of nano-CBr on some geotechnical and engineering properties of clayey soils was investigated. For this purpose, 4 different ratios (1%, 3%, 5% and 10%)

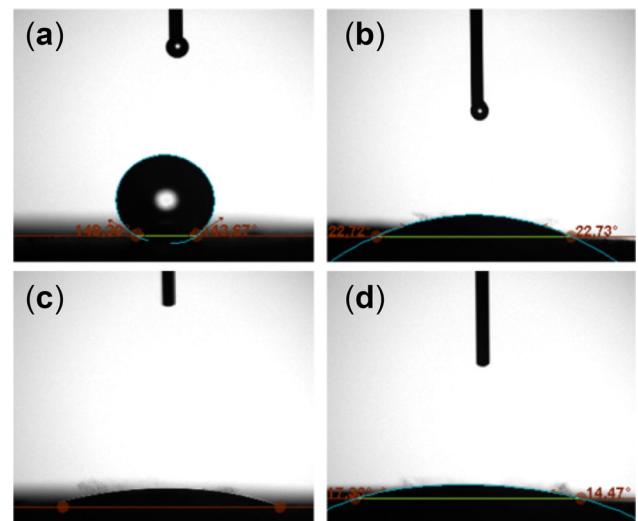


Figure 9. Images of contact angle measurements (a) Nano-CBr. (b) White clay. (c) Green clay. (d) Red clay.

nano-CBr were mixed to 3 different clay soils (White, Green and Red clays) and some experiments were

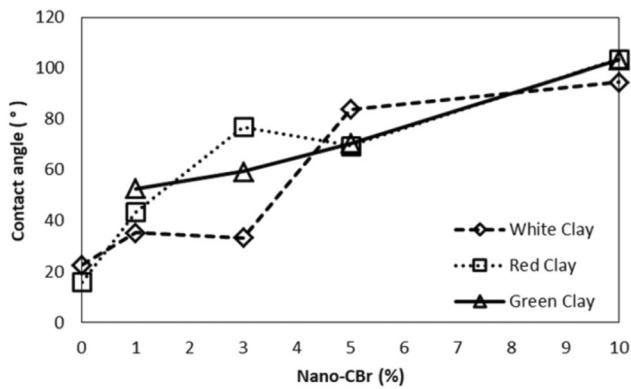


Figure 10. Relationship between contact angle and nano-CBr.

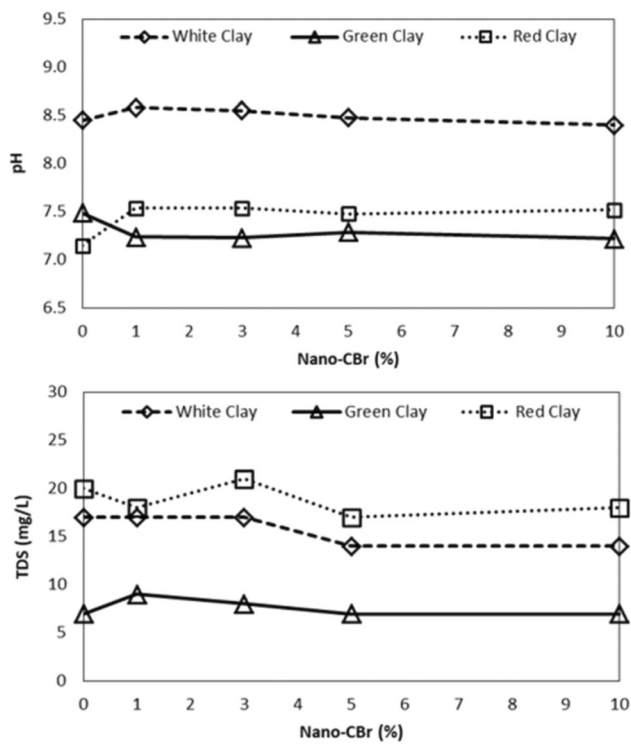


Figure 11. Effect of nano-CBr both on pH and TDS.

conducted on these mixtures. The results obtained from the experiments are described below:

- The LL value of pure white clay (W0) sample was determined as 119.7%. At 1% nano-CBr ratio, LL value of white clay (W1) mixture decreased to 90.4% and after this ratio a constant trend was observed for LL values of white clay mixtures. The LL value of green clay mixtures insignificantly increased until 5% nano-CBr ratio and then a slightly decrease was obtained at 10% nano-CBr ratio. It is worth mentioned that considering the value of the water content, the

increment and subsequent decrement trend of green clay LL values is negligible. It appears that all LL values of the green clay samples are almost constant. Similarly, red clay tended to remain constant at all LL values and a general increment or decrement trend did not observed at these mixtures.

- It was determined that the PL values of white and green clay samples increased up to 1% nano-CBr ratio and started to decrease after this point. It was observed that there was a decrement trend on PL value of red clay samples with the increase of nano-CBr ratio. However, this decrement is not valuable in terms of geotechnical engineering. Generally, the PL values of CH clays mixed with nano-CBr are higher than those pure clay samples. On the other hand, it is seen that the addition of nano-CBr to CL clay does not cause a significant change in PL values of this clay.
- When the consistency limits results are examined in view of geotechnical engineering, the effect of nano-CBr on red and green clay is negligible. On the other hand, it was determined that nano-CBr significantly affected the consistency properties of white clay.
- The peak stresses of the mixtures, especially at 1% nano-CBr ratio, significantly increase in comparison to the pure clay samples. However, after this point, the peak stresses in all clay types decrease with the increase of nano-CBr ratio. For white clay samples, the peak stresses of W3, W5 and W10 samples were determined lower than the peak stress value of W0 sample. For green and red clay samples, it was found that the peak stresses at 3%, 5% and 10% nano-CBr ratios were higher than the peak stress values of the pure clay samples.
- While the contact angle of W0 was determined as 22.7°, the contact angle values of W1, W3, W5 and W10 samples increased to 35.4°, 33.3°, 83.7° and 94.6°, respectively. In the red clay samples, the contact angle value increased until 3% nano-CBr ratio and then it decreased at 5% nano-CBR ratio and started to increase again after this point. On the other hand, the contact angle value of green clay samples increased gradually as nano-CBr increased and reached 103.3° at 10% nano-CBr ratio. When the pure clay samples and 10% nano-CBr mixtures were compared, it was seen that the contact angle values increased approximately 4 and 6.5 times for white and red clay samples, respectively. Since the contact angle value of pure green clay sample could not be measured experimentally, its contact angle increment ratio could not be calculated. Moreover, it is thought that there will be a similar increment in green clay as with the other clay types. In general, it has been found that the contact angle values increase as nano-CBr ratio increases in all clay types. This result showed that the samples changed their affinity for water from hydrophilic to

hydrophobic. When this situation is evaluated in terms of geotechnical engineering, it has been determined that the addition of recycled nano-CBr may have an effect on the engineering behavior (i.e., suction, wettability, capillarity, etc.) of clay soils.

- In particular, the pH values of the suspensions of white clay samples remained in the basic medium. Other clay samples were still close to the basic region but exhibited a more neutral behavior. TDS measurements showed a series of rise and fall steps with the increase of nano-CBr ratio and showed a tendency to stabilize at 10% nano-CBr ratio.
- 1% nano-CBr ratio was determined as the critical threshold ratio in all experiments from this study results. A decrement or increment trend was observed up to 1% nano-CBr ratio at all tests results and after this critical threshold ratio, all tests results were going stable. It could be explained as nano-CBr did not adsorb on clay plates and the nano additive physically over filled the voids of clay soils and increased these voids.

In order to achieve clearer projection about the usability of nano-CBr at soil improvement applications, tests are recommended to be continued for further studies with different soil types and experiments.

Abbreviations

<i>Nano-CBr</i>	is the recycled nano carbon black
<i>W</i>	is the white clay
<i>G</i>	is the green clay
<i>R</i>	is the red clay
<i>LL</i>	is the liquid limit
<i>PL</i>	is the plastic limit
<i>Ip</i>	is the plasticity index
<i>w_{opt}</i>	is the optimum water content
<i>γ_{dmax}</i>	is the maximum dry unit weight
USCS	is the Unified Soil Classification System
UCS	is the unconfined compressive strength
TDS	is the total dissolved solids
XRD	is the X-ray diffraction
SEM	is the scanning electron microscope
DDL	is diffused double layer

References

- [1] Pedro D, De Brito J and Evangelista L 2014 Influence of the use of recycled concrete aggregates from different sources on structural concrete. *Constr. Build. Mater.* 71: 141–151
- [2] Duan Z H and Poon C S 2014 Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars. *Mater. Des.* 58: 19–29
- [3] Silva R V, De Brito J and Dhir R K 2016 Establishing a relationship between modulus of elasticity and compressive strength of recycled aggregate concrete. *J. Clean. Prod.* 112: 2171–2186
- [4] Letelier V, Tarela E, Muñoz P and Moriconi G 2017 Combined effects of recycled hydrated cement and recycled aggregates on the mechanical properties of concrete. *Constr. Build. Mater.* 132: 365–375
- [5] Ismail S, Kwan W H and Ramli M 2017 Mechanical strength and durability properties of concrete containing treated recycled concrete aggregates under different curing conditions. *Constr. Build. Mater.* 155: 296–306
- [6] Gupta C and Sharma R K 2014 Influence of micro silica fume on sub grade characteristics of expansive soil. *Int. J. Civ. Eng. Res.* 5: 77–82
- [7] Disfani M M, Arulrajah A, Bo M W and Sivakugan N 2012 Environmental risks of using recycled crushed glass in road applications. *J. Clean. Prod.* 20: 170–179
- [8] Kampala A, Horpibulsuk S, Chinkullijniwat A and Shen S L 2013 Engineering properties of recycled calcium carbide residue stabilized clay as fill and pavement materials. *Constr. Build. Mater.* 46: 203–210
- [9] Arulrajah A, Piratheepan J, Disfani M M and Bo M W 2012 Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications. *J. Mater. Civ. Eng.* 25: 1077–1088
- [10] Hoy M, Horpibulsuk S, Rachan R, Chinkulkijniwat A and Arulrajah A 2016 Recycled asphalt pavement–fly ash geopolymers as a sustainable pavement base material: Strength and toxic leaching investigations. *Sci. Total Environ.* 573: 19–26
- [11] Ojum C and Thom N 2017 Effect of binder in recycled asphalt on cold-mix pavements. *Proc. Inst. Civ. Eng. Constr. Mater.* 170: 205–210
- [12] Tulek M 2007 *A Study of the Use of Chemical Waste Gypsums in Soil Stabilization*. Master Thesis, Balikesir University, Balikesir, Turkey
- [13] Coruh E, Hınısoglu S, Kocakerim M, Arasan S and Oltulu M 2013 Investigation of the usage of borogypsum in the subbase course as a stabilization material. *EÜFBED Grad. Sch. Nat. Appl. Sci. J.* 6: 221–231
- [14] [14] Kütük-Sert T and Kütük S 2012 Physical and marshall properties of borogypsum used as filler aggregate in asphalt concrete. *J. Mater. Civ. Eng.* 25: 266–273
- [15] Shen W, Zhou M and Zhao Q 2007 Study on lime–fly ash–phosphogypsum binder. *Constr. Build. Mater.* 21: 1480–1485
- [16] Yilmaz I and Civelekoglu B 2009 Gypsum: an additive for stabilization of swelling clay soils. *Appl. Clay Sci.* 44: 166–172
- [17] Shen W, Zhou M, Ma W, Hu J and Cai Z 2009 Investigation on the application of steel slag–fly ash–phosphogypsum solidified material as road base material. *J. Hazard. Mater.* 164: 99–104
- [18] Kalantari B, Prasad A and Huat B B 2011 Stabilising peat soil with cement and silica fume. *Proc. Inst. Civ. Eng. Geotech. Eng.* 164: 33–39
- [19] Sattar M A A, Daud K A and Al-Azzawi A A 2012 Effect of silica fume addition on the behavior of silty-clayey soils. *J. Eng. Sustain. Dev.* 16: 92–105

- [20] Negi C, Yadav R K and Singhai A K 2013 Effect of silica fume on index properties of black cotton soil. *Int. J. Sci. Eng. Res.* 4: 828-833
- [21] Edil T B, Acosta H A and Benson C H 2006 Stabilizing soft fine-grained soils with fly ash. *J. Mater. Civ. Eng.* 18: 283–294
- [22] Chauhan M S, Mittal S and Mohanty B 2008 Performance evaluation of silty sand subgrade reinforced with fly ash and fiber. *Geotext. Geomembr.* 26: 429–435
- [23] Brooks R M 2009 Soil stabilization with fly ash and rice husk ash. *Int. J. Res. Rev. Appl. Sci.* 1: 209–217
- [24] Isik F and Akbulut R K 2018 Effect of recycled carbon black on consistency limits of clayey soils. *Iğdır Univ. J. Inst. Sci. Technol.* 8: 123–130
- [25] Edil T B and Bosscher P J 1994 Engineering properties of tire chips and soil mixtures. *Geotech. Test. J.* 17: 453–464
- [26] Masad E, Taha R, Ho C and Papagiannakis T 1996 Engineering properties of tire/soil mixtures as a lightweight fill material. *Geotech. Test. J.* 19: 297–304
- [27] Edinçliler A, Baykal G and Saygılı A 2010 Influence of different processing techniques on the mechanical properties of used tires in embankment construction. *Waste Manag.* 30: 1073–1080
- [28] Sheikh M, Mashiri M S, Vinod J S and Tsang H H 2013 Shear and compressibility behavior of sand–tire crumb mixtures. *J. Mater. Civ. Eng.* 25: 1366–1374
- [29] Brunet S, De La Llera J C and Kausel E 2016 Non-linear modeling of seismic isolation systems made of recycled tire-rubber. *Soil Dyn. Earthq. Eng.* 85: 134–145
- [30] BS 1377 Part 2 1990 *Methods of Test for Soils for Civil Engineering Purposes*. Classification tests. British Standards Institution
- [31] ASTM D 4318-00 2000 *Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. ASTM International, West Conshohocken, PA, USA
- [32] ASTM D 2166 1991 *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*. ASTM International, West Conshohocken, PA, USA
- [33] Gürses A and Bayrakçeken S 1996 The empirical physico-chemistry (in Turkish) Erzurum Turkey. *Ataturk Univ. Pap.* 807: 59–65
- [34] Zhang C, Liu Z and Deng P 2016 Contact angle of soil minerals: A molecular dynamics study. *Comput. Geotech.* 75: 48–56
- [35] Fredlund D G and Rahardjo H 1993 *Soil Mechanics for Unsaturated Soils*. Wiley, Hoboken
- [36] Lu N and Likos W J 2004 *Unsaturated Soil Mechanics*. Wiley, Hoboken
- [37] Liu Z, Yu X and Wan L 2016 Capillary rise method for the measurement of the contact angle of soils. *Acta Geotech.* 11: 21–35
- [38] Duriez J and Wan R 2017 Contact angle mechanical influence in wet granular soils. *Acta Geotech.* 12: 67–83
- [39] Manahiloh K N and Meehan C L 2017 Determining the soil water characteristic curve and interfacial contact angle from microstructural analysis of X-ray CT images. *J. Geotech. Geoenviron. Eng.* 143: 04017034
- [40] Akbulut R K 2008 *Some Physical and Chemical Properties of Clay Treated with Surfactant*. Master Thesis, Ataturk University, Erzurum, Turkey
- [41] Skoog D A, West D M, Holler F J and Crouch S 2013 *Fundamentals of Analytical Chemistry*, 9th edn. Nelson Education, Toronto
- [42] ASTM D 4972-01 2001 *Standard Test Methods for pH of Soils*. ASTM International, West Conshohocken, PA, USA
- [43] Sridharan A, El-Shafei A and Miura N 2002 Mechanisms controlling the undrained strength behavior of remolded Ariake marine clays. *Mar. Georesour. Geotechnol.* 20: 21–50
- [44] Schmitz R M, Schroeder C and Charlier R 2004 Chemo-mechanical interactions in clay: a correlation between clay mineralogy and Atterberg limits. *Appl. Clay Sci.* 26: 351–358
- [45] Park J, Vipulanandan C, Kim J W and Oh M H 2006 Effects of surfactants and electrolyte solutions on the properties of soil. *Environ. Geol.* 49: 977–989
- [46] Arasan S and Yetimoglu T 2008 Effect of inorganic salt solutions on the consistency limits of two clays. *Turk. J. Eng. Environ. Sci.* 32: 107–115
- [47] Zaimoglu A S, Tan O and Akbulut R K 2016 Optimization of consistency limits and plasticity index of fine-grained soils modified with polypropylene fibers and additive materials. *KSCE J. Civ. Eng.* 20: 662–669
- [48] Al-Khanbashi A and Abdallah S W 2006 Evaluation of three waterborne polymers as stabilizers for sandy soil. *Geotech. Geol. Eng.* 24: 1603–1625
- [49] Ateş A 2013 The effect of polymer-cement stabilization on the unconfined compressive strength of liquefiable soils. *Int. J. Polym. Sci.* <https://doi.org/10.1155/2013/356214>
- [50] Arasan S and Nasirpur O 2015 The effects of polymers and fly ash on unconfined compressive strength and freeze-thaw behavior of loose saturated sand. *Geomech. Eng.* 8: 361–375
- [51] Arasan S, Bagherinia M, Akbulut R K and Zaimoglu A S 2017 Utilization of polymers to improve soft clayey soils using the deep mixing method. *Environ. Eng. Geosci.* 23: 1–12
- [52] Cabuk N 2012 *Synthesis of Superhydrophobic Nanocoatings by Using Hot Filament Chemical Vapor Deposition Method*. Master Thesis, Selcuk University, Konya, Turkey
- [53] Piper C S 1942 *Soil and Plant Analysis*. University of Adelaide, Adelaide
- [54] Rayment G E and Higginson F R 1992 *Australian Laboratory Handbook of Soil and Water Chemical Methods*. Inkata Press Pty Ltd, Melbourne