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Hydraulic conductivity and undrained shear strength of clay-construction and demolition solid waste materials mixtures

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Article

Keywords
Clay
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Undrained shear strength
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Abstract

The study aims to investigate the effects of three different construction and demolition materials (CDMs), including crushed waste asphalt (CWA), crushed waste bricks (CWB), and crushed waste concrete (CWC), on some geotechnical properties of low plastic clayey soil, particularly, the undrained shear strength (S_u) and the hydraulic conductivity (k). A set of experimental tests were performed on clayey soil and on clayey soil-CDM mixtures at mixing ratios of 5%, 10%, 15%, and 20% by dry weight. The results show that the soil plasticity decreases as the CDMs increase. Quantitatively, it is found a maximum of 12%, 6%, and 6% decrease in the liquid limits (LL) and a maximum of 9%, 4%, and 6% decrease in the plasticity limit (PI) of the mixtures with 20% of CWA, CWB, and CWC, respectively. The results of the S_u estimated empirically from the fall cone tests show that the S_u decreases as the CDMs increase. The S_u reduces by approximately 10% and 2% of the mixtures with 20% CWA and CWB, respectively. But the S_u is not affected by the CWC additive for water content lower than approximately 35%. The k value increases as the CDMs increase. The results show that the reported k value increases by 75%, 79%, and 247% of the mixtures with 20% of CWA, CWB, and CWC, respectively. Additionally, the k values obtained from the consolidation test confirm the findings of the effect of the CDMs on the coefficient of hydraulic conductivity.

1. Introduction

The excessive increase in construction activities causes a significant increasing generation of construction and demolition materials (CDMs). Obaid et al. (2019) report that 1.3 billion tons of construction and demolition waste are generated worldwide yearly. This quantity is anticipated to increase up to approximately two times by 2025. Disposing of these materials in landfills will reflect economic and environmental problems. Recently, studies have been done to consider investing and recycling these materials in real projects and studied the engineering properties of these materials (Arulrajah et al., 2011, 2012, 2013; Cristelo et al., 2016; Park, 2003; Yoshizawa et al., 2005). From a geotechnical perspective, studies have been done to investigate the possibility of using these materials additives to enhance the engineering properties of soils and to avoid economic and environmental problems.

Various percentages of crushed bricks, dragged asphalt, and crushed concrete paving slabs were used as additives to reduce the swelling potential of clayey soil (Cabalar et al., 2016). A plasticity index (PI), which is a strong indicator of swelling potential in clayey soils, was found to decrease as the amount of CDMs increases in the mixtures. It was reported that the PI reduced by 28%, 39%, and 43% for an additive of 15% of dragged asphalt, crushed bricks, and concrete paving slabs, respectively. Mohialdeen et al. (2020) investigated the effects of CDMs on expansive soils from Mosul, Iraq, on soil consistency limits. The liquid limit and PI were found to reduce by approximately 16 and 25%, respectively, and the demolition type controls the reduction percent.

Researchers have performed strength tests to investigate the effect of the CMDs on drained shear strength of various soil types (Abdulnafaa et al., 2019; Abhijith et al., 2014; Arulrajah et al., 2014; Jia et al., 2015). In geotechnical design, drained shear strength does not always replicate the field conditions. Therefore, the undrained shear strength should be used in design and analysis. This criterion is applied mainly

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to low permeability soils such as clayey soils. Undrained shear strength can be measured in the laboratory using consolidated undrained (CU) or unconsolidated undrained (UU) triaxial tests, vane shear test, or fall cone test. Very few studies have been performed on the assessment of effects of CDMs on the undrained shear strength of fine-grained soils mixed with CDMs. These studies are limited on assessing the undrained shear strength from unconfined compression tests (Cabalar et al., 2016; Lukiantchuki et al., 2019). The current study used an alternative method for estimating the undrained shear strength (S_u), which is the fall cone testing method. This method has an advantage over other methods (unconfined compression test, direct shear test, triaxial test, and vane shear test) for being a very fast method, using relatively small specimen, and performing over a wide range of water content (Canelas et al., 2018).

Hydraulic properties of soils are as important as the mechanical properties of soils. There are a few research studies on the effects of CDMs on the hydraulic properties of soils, and they are limited to coarse-grained soils. Poon & Chan (2006) studied the effect of self-cementing properties of fine CWC on the properties of unbounded sub-base materials. The results showed that the sub-base aggregate-CWC mixtures exhibited higher hydraulic conductivity than the natural sub-base aggregate by approximately one order of magnitude when it was measured immediately after compaction. Bennert et al. (2000) studied the hydraulic conductivity of natural aggregate and aggregate with varying percentages of CWC and CWA. The results showed that the hydraulic conductivity of aggregate mixed with 75% of CWC became closer to the hydraulic conductivity values of natural aggregate. Kang et al. (2011) evaluated the suitability of four recycled materials with aggregates as base and sub-base layers for roads. They found that the coefficients of hydraulic conductivity of the mixtures were higher than that of the natural aggregates. All the above-mentioned studies have suggested investigating the effects of CDMs on the hydraulic conductivity of fine-grained soils and, it is important to note that they agree that the hydraulic conductivity coefficients of soil-CDM mixtures are generally higher than those of natural soils.

The main objective of the current research was to investigate the impacts of the CDMs on the soil Atterberg limits, the undrained shear strength, and the hydraulic conductivity of low plasticity clayey soil. Undrained shear strength (S_u) was evaluated for various water content and the effect of the CDMs was assess quantitatively. The hydraulic conductivity using two different techniques (falling head tests and consolidation tests) was evaluated for both clayey soil and clayey soil-CDMs mixtures.

2. Materials

The soil used for the current research was classified as a brown clayey soil (ASTM, 2000) with pieces of $CaCo_3$ fragments. Physical properties of the clayey soil were measured according to ASTM standards and the results are tabulated in Table 1.

Three construction and demolition (CDMs) materials illustrated in Figure1 (CWA, CWB, and CWC) were used in this study as additive materials mixed with the clayey soil. The CWA material was produced from the destruction of old and under maintenance crushed asphalt roads and highways, the CWB material was produced from the demolition of buildings, and the CWC material was accumulated in large piles from old plain concrete of building, pavement, and sidewalks.

Atterberg limits tests of clayey soil and clayey soil-CDMs mixtures were performed according to ASTM D4318 (ASTM, 2005) and the results are presented in Table 2. The results of sieve analysis performed on clayey soil and CDMs are shown in Figure 2. Compaction tests following the modified Proctor method were performed on clayey soil and clayey soil-CDMs mixtures according to ASTM D-2216 (ASTM, 1998), and the compaction characteristics were presented in Table 2.

3. Methodology

3.1 Atterberg limits tests

The clayey soil and CDMs were sieved on No. 40 (0.425 mm) for performing the Atterberg limits tests. The tests were performed for both clayey soil and clayey soil-CDM mixtures in accordance with the ASTM D4318 (2005). The liquid limit test was performed using British fall cone equipment according to BS 1377 (BSI, 1990). The results were adopted to empirically estimate the undrained shear strengths (S_u) of soils.

The soil samples of clay and clay-CDM mixtures were prepared using oven-dried clayey soil and CDMs. The required amount of clayey soil and CDMs for each test were weighed and mixed thoroughly in a dry state until homogeneity was achieved. Then the mixture was

Table1. Index properties of clayey soil.

Soil properties Clayey soil		Soil type
Specific gravity, *Gs*		2.7
Atterberg limits	Liquid limit, LL (%) as per BSI standard	42
	Plastic limit, PL (%)	25
	Plasticity index (%)	17
Grain size analysis	Sand (%)	40
	Silt (%)	43
	Clay (%)	17
Classification	Unified soil classification system (USCC)	CL
	AASHTO	A-7-6(14)

Table 2. Atterberg limits and classification of clayey soil and soil-CDMs mixtures.

Mixture type	CDMs (%)	Compaction Characteristics		LL (%)	PL (%)	PI (%)	Classification	
		OMC (%)	$\gamma_{d\,max}$ (kN/m^3)				USCS	AASHTO
Clayey soil	0	18.0	17.30	42	25	17	CL	A-7-6(14)
CWA [a]	5	13.5	17.58	41	27	14	ML	A-7-6(12)
CWA	10	12.6	17.92	40	28	12	ML	A-7-6(11)
CWA	15	12.0	18.00	36	25	11	ML	A-6(9)
CWA	20	11.6	18.26	30	22	8	ML	A-4(5)
CWB [b]	5	18.2	17.25	41	28	13	ML	A-7-6(12)
CWB	10	17.5	17.21	39	27	12	ML	A-6(10)
CWB	15	17.6	17.22	38	28	10	ML	A-6(9)
CWB	20	17.1	17.10	36	27	9	ML	A-4(8)
CWC [c]	5	16.6	17.30	41	29	12	ML	A-7-6(11)
CWC	10	16.3	17.70	40	30	10	ML	A-4(9)
CWC	15	15.8	17.80	37	30	7	ML	A-4(6)
CWC	20	15.2	17.93	36	30	6	ML	A-4(60)

[a] Crushed waste asphalt (CWA), [b] Crushed waste bricks (CWB), [c] Crushed waste concrete (CWC).

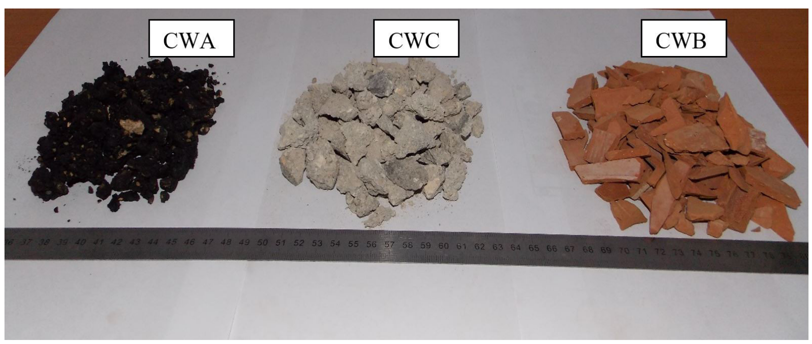

Figure 1. Construction and demolition materials.

mixed with a required amount of water to become like a workable paste and cured for 24 hours in plastic bags before testing.

A British fall cone device with a 30° cone and 0.785 N weight was used. The fall cone cup diameter was 55 mm, and the height was 40 mm. The prepared sample was placed into the fall cone cup using a spatula ensuring no air was trapped during the process. A leveled side of the straight edge was used to remove the excess soil on the cup surface to obtain a smooth surface. Finally, the sample was placed in the device with the cone tip barely touching the surface of the tested sample. After five seconds of penetration, the penetration distance was measured. Three trials were performed to check the repeatability of the tested samples. After test completion, the sample moisture content was determined. The same testing procedure was repeated for all clayey soil and soil-CDMs mixtures at different moisture contents.

The empirical Equation 1, proposed by Hansbo (1957), was adopted to estimate the undrained shear strength (S_u) of soils from the measured consistency limits.

$$S_u = k_{cone} \frac{m}{d^2} \tag{1}$$

where m is the cone mass (in g), d is the cone penetration depth (in mm), and k_{cone} is a constant that is a function of the cone angle (for a cone angle of 30°, k_{cone} = 0.85). This equation was used by many researchers to estimate the undrained shear strength (S_u) for clayey soil and clayey soil mixed with different materials (Cabalar & Mustafa, 2015; Kumar & Muir Wood, 1999; Wood, 1985).

3.2 Hydraulic conductivity test

Hydraulic conductivity measurements on undisturbed samples are commonly performed on samples collected from the field using thin-wall sampling (Shelby) tubes (Clayton et al., 1995). However, because of the inevitable disturbance associated with the process of extracting a sample from the ground and the Shelby tube, remolded specimens were prepared at 90% maximum dry density and the optimum moisture content of premeasured compaction curves. The specimen was prepared in a permeameter with dimensions of 10 cm in diameter and 12.5 cm in height. Four sets of soil specimens were prepared for performing the hydraulic conductivity tests. Each set included five identical specimens prepared for the purpose of repeatability. The first set of specimens was for clayey soil and the other three sets were for clayey soil mixed with 10% of CWA, CWB, and CWC, respectively. The clayey soil was passed through a No. 4 sieve while the additives (CWA, CWB, and CWC) were passed through a 19 mm sieve. The latter represented the maximum particle size identified in the compaction and hydraulic conductivity tests. For each sample, water was added to the dry clayey soil-CDMs mixture until it reached its associated optimum water content. The soil was put in a sealed bag for at least one day before compaction to achieve moisture equalization. The compaction process was carried out in five equal layers; the thickness of each layer was 25 mm to get a uniform density along with the specimen. The density used for preparing hydraulic conductivity specimens in the permeameter was 90% of the maximum dry density of clay and clay-10% CDM mixtures. Before testing, the permeameters were soaked in a water tank for saturation purposes. After assembling, the hydraulic conductivity tests were performed according to ASTM D5084 (ASTM, 2010) specifications.

Another method for measuring the coefficient of hydraulic conductivity was used based on consolidation test results (Das & Sobhan, 2014). A set of compacted specimens of clayey soil and clayey soil-CDMs mixtures were prepared in an oedometer ring with dimensions of 6.2 cm in diameter and 1.92 cm in height. The specimens were compressed in the ring of the oedometer statically, using a constant rate of 0.02 mm/sec. The specimens were prepared at the optimum moisture content and 90% maximum dry density. The CDMs were mixed with clayey soil in different percentages of 5%, 10%, 15%, and 20% to investigate the effect of the CDMs on the coefficient of hydraulic conductivity of clayey soil (Abdulnafaa, 2018). The coefficient of hydraulic conductivity for clayey soil and clayey soil-CDMs mixtures were estimated from the consolidation test results at 400 kPa using Equation 2.

$$k = m_v c_v \gamma_w \tag{2}$$

where k is the coefficient of hydraulic conductivity, m_v is the coefficient of volume compressibility, c_v is the coefficient of consolidation, and γ_w is the unit weight of water.

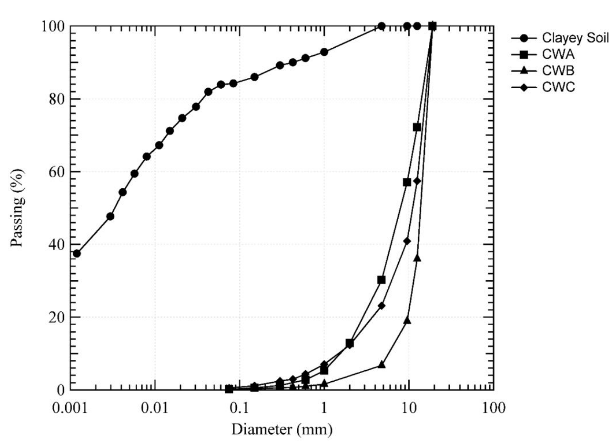

Figure 2. Grain size distributions curves for clayey soil and CDMs used in the study.

4. Results and discussions

4.1 Atterberg limits

The Atterberg limits of clayey soil and clayey soil-CDMs mixture are tabulated in Table 2 and presented in Figures 3 to 5. The table and the figures clearly show that

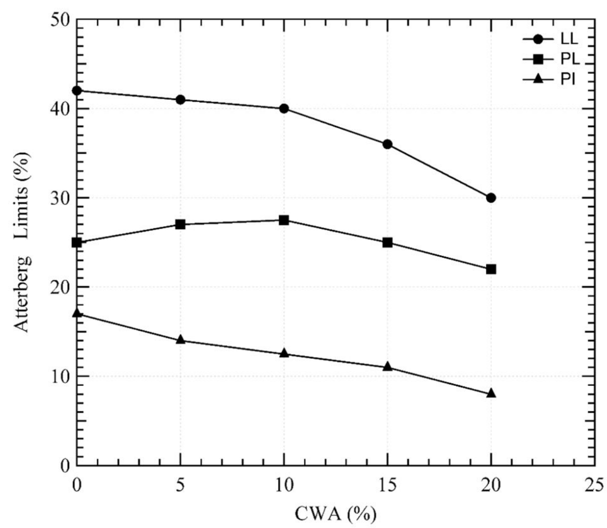

Figure 3. Atterberg limits with CWA content.

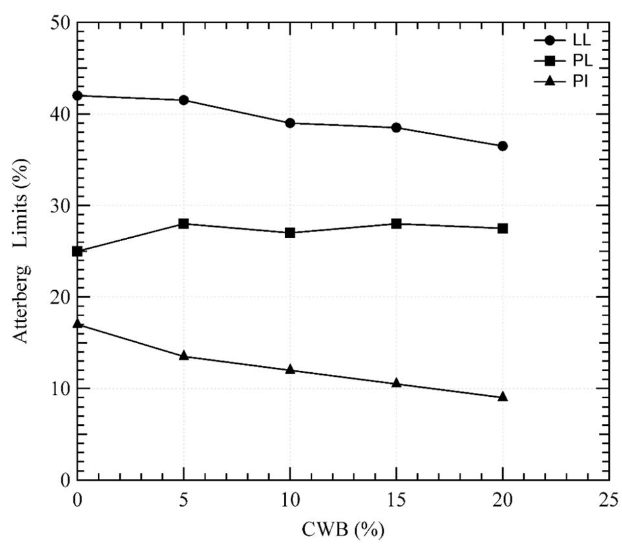

Figure 4. Atterberg limits with CWB content.

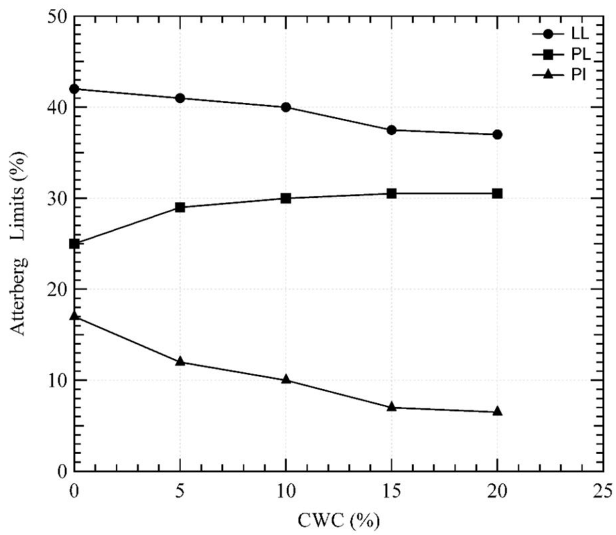

Figure 5. Atterberg limits with CWC content.

the LL decreased as the additive percent increased. For a given additive percent, the reduction in LL varied with the additive type. For instance, for 20% additive, the reduction percentages in the LL were 12%, 6%, and 6% for CWA, CWB, and CWC, respectively. The plasticity index (PI) of the mixtures decreased for all types of additives. The maximum reported reductions in the PI values were 9%, 4%, and 6% when 20% CWA, CWB, and CWC were added, respectively. The reduction in the plasticity indices can be explained by the physical compensation of a ratio of clayey soil (by weight-plasticity materials) to the CDMs (non-plasticity materials).

It is important to note that the CDMs affected the geotechnical classification of clayey soil, as shown in Table 1. The clayey soil used in this study is classified as low plastic clay (CL) according to the Unified Soil Classification System (USCS). The classification changed from CL to low plastic silt (ML) because of the clay-CDM mixtures. An alternative and more common soil classification type used particularly in road design and construction works is the AASHTO classification system. The suitability of the materials could be assessed using such a soil classification system. For instance, it was found that soil classification changed from A-7-6 for clayey soil to A-6 or A-4 for 10% CDMs-clay mixture and the group index (GI) of the mixture was lower than that of clayey soil. This finding showed that the CDM-clay mixtures became more suitable for use as a base or sub-base material than the clayey soil.

4.2 Undrained shear strength

Using Hansbo (1957) empirical equation, the undrained shear strength (Su) was estimated for the fall cone test results of both clayey soil and clayey soil-CDMs mixtures. Figures 6 to 8 display the relationship between the undrained shear strength (S_u) and water content. The results show that the undrained shear strength (S_u) of the clayey soil and

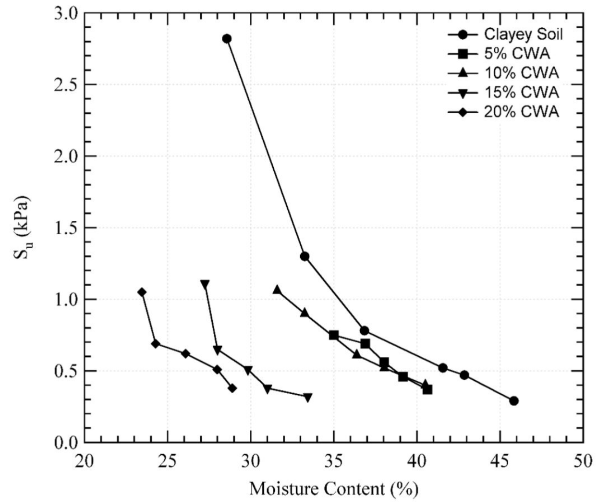

Figure 6. Undrained shear strength with water content for the clayey soil and clay- CWA mixtures.

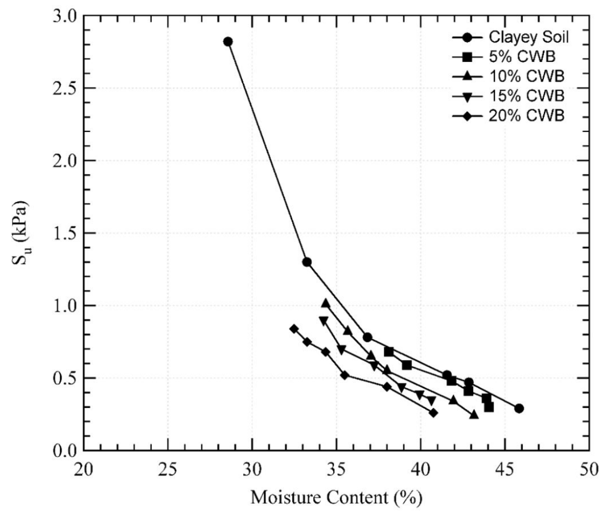

Figure 7. Undrained shear strength with water content for the clayey soil and clay- CWB mixtures.

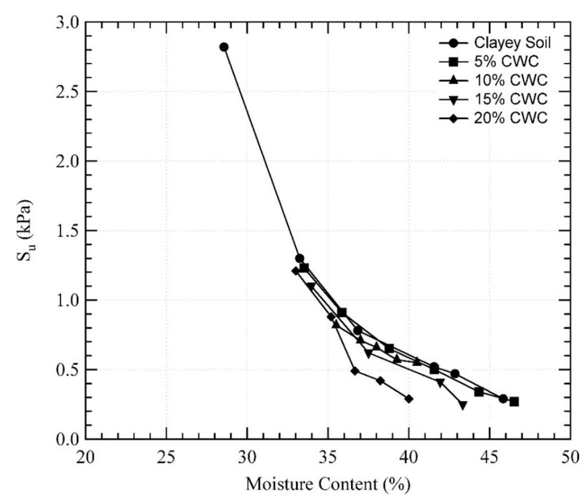

Figure 8. Undrained shear strength with water content for the clayey and clay- CWC mixtures.

clayey soil-CDMs mixtures generally decreased as the water content increased. Results presented in Figure 6 show that the undrained shear strength (S_u) decreased significantly as the CWA increased especially for the 15 and 20% of CWA and the range of water content used. For instance, in comparison to the clayey soil, the undrained shear strength (S_u) of clayey soil-20% CWA mixture reduced by 10% at moisture content near the LL. Figure 7 shows the effect of the CWB on the undrained shear strength (S_u) of the clayey soil. It was observed that the undrained shear strength (S_u) decreased only slightly as the CWB increased. For instance, for LL, the reduction of undrained shear strength (S_u) was only 2% for the clayey soil-20% CWB mixture compared to the clayey soil. Practically, this amount of reduction can be ignored as it is minimal. Figure 8 showed the effect of the CWC on the undrained shear strength (S_u) of clayey soil and the clayey soil-CWC mixtures. The results showed an insignificant different behavior between the clayey soil and the clayey soil mixed with 5%, and 10% of CWC additive for all the range of moisture content used. However, for 15% and 20% additive, the effect of CWC was significant for the range of water content higher than 35% while the effect of the CWC on the undrained shear strength (S_u) disappear for the water content lower than approximately 35%. In other words, the undrained shear strength (S_u) of clay and clayey soil-CDM mixtures merged into one curve for water content lower than 35%.

The change in undrained shear strength (S_u) of a composite matrix of cohesive and cohesionless soils can be affected by the nature of the interaction between sand-like grains and clay grains (Mitchell & Soga, 2005). The non-plastic materials (CDMs) which have a similar nature to cohesionless materials (i.e. sand) can easily reduce the undrained shearing strength (S_u) of clayey soils. From the fact that the cohesionless soil causes the plasticity of the cohesive soil to reduce when they are mixed, the cohesion between soil particles will be reduced. The undrained shear strength (S_u) is a function of soil cohesion; thus, undrained shearing strength (S_u) will be reduced. Similar findings can be found in Al Rawi et al. (2018) and Cabalar & Mustafa (2015).

4.3 Hydraulic conductivity

The hydraulic conductivity (k) for clayey soil and clayey soil-10% CDMs mixtures are shown in Table 3 and Figures 9 and 10, which show the change in k with three different additives. Because the hydraulic conductivity test is highly influenced by the variation of void ratio, pore size and pore size distribution, soil density, and additive distribution along with the soil specimens, as commented by Das & Sobhan (2014), five identical specimens of each soil type were tested to examine repeatability. The results for clayey soil show that the variations in the value of k for specimen numbers 2, 3, and 4 were minimal. However, there was some variation by approximately -10% and +10% in specimen numbers 1 and 5, respectively. The variation could be due to the non-homogeneity of the additive in the specimens, and the non-uniformity of the density along with the soil specimens. The results showed that there was no variation in the values of k for the CWA and

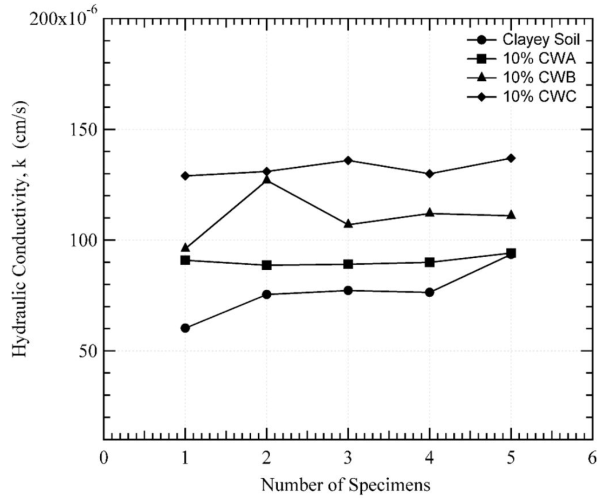

Figure 9. Hydraulic conductivity (k) for the clayey soil and clayey soil- CDMs mixtures.

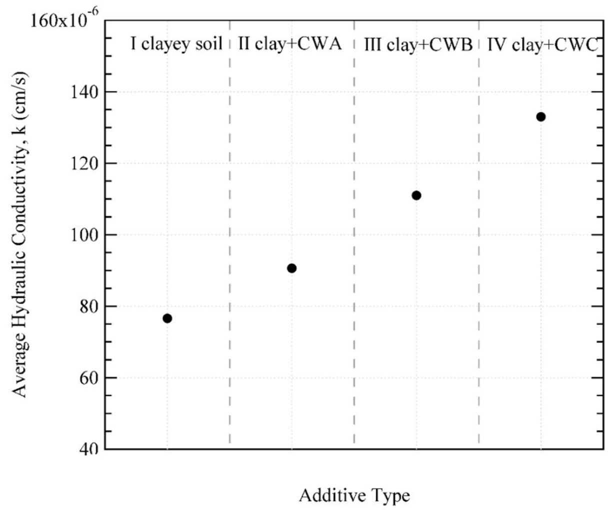

Figure 10. Average values of hydraulic conductivity, k for the clayey soil and clayey soil- CDMs mixtures.

Table 3. Coefficient of hydraulic conductivity, k of clayey soil and clay-10% CDMs using falling head test.

Specimen No.	Coefficient of hydraulic conductivity, k, (cm/sec)			
	Clayey soil	CWA	CWB	CWC
1	6.03E-05	9.09E-05	9.62E-05	1.29E-04
2	7.55E-05	8.87E-05	1.27E-04	1.31E-04
3	7.73E-05	8.91E-05	1.07E-04	1.36E-04
4	7.64E-05	9.00E-05	1.12E-04	1.30E-04
5	9.36E-05	9.42E-05	1.11E-04	1.37E-04
Average	7.66E-05	9.06E-05	1.11E-04	1.33E-04

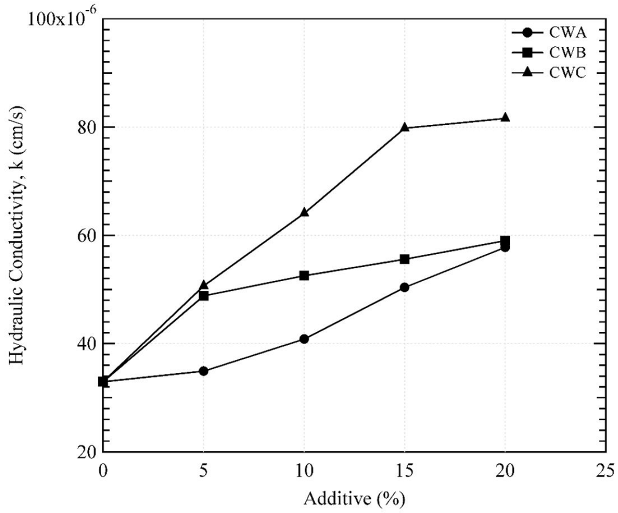

Figure 11. Hydraulic conductivity *k* for the clayey soil and clayey soil-CDMs mixtures.

CWC tested specimens. Except for specimen number 2, the values of *k* of CWB specimens were approximately the same. This finding implies that the soil specimens were well uniform and homogenous, and the additives were well distributed in the soil sample during mixing and compacting processes.

Table 3 and Figure 10 show the average values of *k*. The plot is divided into four zones I, II, III, IV for clayey soil, clayey oil-CWA, clayey soil-CWB, and clayey soil-CWC, respectively. It was observed that *k* varied with the additive type. In comparison to the clayey soil, it was noted that *k* increased by approximately 18%, 44%, and 73% for the clayey soil mixed with 10% of CWA, CWB, and CWC, respectively. The explanation for increasing the value of *k* when adding CDMs to the clayey soil was that adding materials with high granular gradients, and high hydraulic conductivity to clayey soil with very low hydraulic conductivity would increase the hydraulic conductivity of the new mixtures in proportions depending on the type and quantity of the additive.

The hydraulic conductivity levels of clayey soil and the clayey soil-CDM mixtures estimated indirectly from the consolidation tests are presented in Figure 11. The figure clearly shows that *k* increased as the additive percent increased. For instance, at 20% additive, a maximum reported incremental percentage in *k* was 75%, 79%, and 247% for CWA, CWB, and CWC, respectively. Similarly, the increments in the hydraulic conductivity can be explained by the physical compensation of a ratio of clayey soil (by weight) (cohesive materials) to the CDMs (cohesionless materials). This finding confirms the finding of the *k* values measured by the falling head method. It is observed that the two methods exhibited the same trend but different magnitudes of *k* values, which is because the testing conditions are different between the two testing techniques.

5. Conclusions

This experimental study examined the influences of three types of CDMs (CWA, CWB, and CWC) on the engineering properties of natural clayey soil. The conclusions are the following:

- The LL and PI of clayey soil decrease as the CDMs percentages increase. A maximum of 13%, 37%, and 30% decrease in the LL of the mixtures with 20% content of CWA, CWB, and CWC, respectively, and a maximum of 13%, 37%, and 30% decrease in the PI of the mixtures with 20% content of CWA, CWB, and CWC, respectively.
- The classification of the clayey soil changes from CL for clayey soil to ML for clay-CDM mixtures.
- Results indicate that the clayey soil-CDMs mixtures are more suitable for use as base or sub-base materials than the clayey soil under paving or parking area.
- The undrained shear strength (S_u) of both clayey soil and clayey soil-CDMs mixtures decreases as the moisture content increases. The greatest reduction in the undrained (S_u) of clayey soil was 10% for clayey soil- 20% CWA mixtures.
- The hydraulic conductivity (*k*) of the CDMs is higher than that of clayey soil by 75%, 79%, and 247% for CWA, CWB, CWC, respectively.
- The coefficient of hydraulic conductivity measured from the consolidation test confirms the *k* values measured by the falling head test.

Declaration of interest

The authors declare that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Authors' contributions

Nurullah Akbulut: investigation. Ali Cabalar: methodology, validation. Mohammed Abdulnafaa: data curing, writing - original draft preparation. Muwafaq Awad: writing - reviewing and editing. Burak Ozufacik: experimental work.

List of symbols

CDMs	Construction and Demolition Materials
CWA	Crushed Waste Asphalt
CWB	Crushed Waste Bricks
CWC	Crushed Waste Concrete
k	Hydraulic conductivity
S_u	Undrained shear strength
$\gamma_{d\,max}$	Maximum dry unit weight

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