



Improvement in Field CBR Values of Subgrade Soil Using Construction-Demolition Materials

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Accepted: 5 May 2021/Published online: 17 May 2021

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Abstract

Many countries suffer from the stacks of construction and demolition (CD) materials as they cause environmental and health problems in society. The city of Mosul in Iraq suffers from a huge amount of demolition materials resulting from destruction of most of the infrastructure. In the present study, attempts have been made to assess the influence of three types of CD materials (dragged asphalt, DA; crushed brick, CB; and crushed concrete, CC) on the response of a low-plasticity clay (CL) for use as a road subgrade layer. An intensive series of both experimental and numerical studies on the CL with 10% CD materials was carried out using field California bearing ratio (CBR) tests performed in a large-scale model box. The results showed significant improvement in the CBR values upon the addition of CD materials to the CL soil. The CBR values increased by 12.4, 13.7, and 49.7% with the addition of DA, CB, and CC, respectively. The CBR values improved between 1.1 and 1.7 times, corresponding to an increase in the layer thickness from 50 to 100 cm. Further increases in CBR values range from 1.5 to 1.8 times attendant with increasing the thickness of layer from 50 cm to 150 cm. The addition of CC is more active and gives higher CBR values. A good match was observed between the CBR values obtained from the experimental results and the numerical analysis using the PLAXIS 2D package.

Keywords Clay · Construction and demolition materials · Field CBR test · Soil subgrade

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1 Introduction

A large amount of waste solid materials, which causes many environmental problems, is produced daily throughout the world. Some of these wastes are by-products of construction and demolition (CD) materials. It is estimated that there will be about 19 billion tons of waste building material by 2025 (Yoshizawa et al. 2004) and about 2.51 billion tons produced in the European Union (Eurostat 2014). Huge quantities of demolished building materials were accumulated in Mosul City during the war of 2014–2017 when most of the infrastructures were destroyed (see Fig. 1) (UN-Environment Technical Note 2017). Many studies have been carried out to evaluate the reusing and recycling of such materials in construction activities (Taha and Pradeep 1997; Mckelvey et al. 2002; Cyr et al. 2004; Aqil et al. 2005; Kumar and Singh 2008; Diagne et al. 2015; Fattah and Al-Waily 2015; Fattah et al. 2015; Missaoui et al. 2016; Bassani and Tefa 2018; Li et al. 2019; Oluremi et al. 2019; Shariati et al. 2019; Al-Baidhani and Al-Taie 2020; Bagriacik and Mahmutluoglu 2020). Work began by using the CD materials as substitutes for or with raw materials in the construction operations, and the researchers concluded that it can be reused or recycled in the road constructions (Hansen 1992; Corinaldesi et al. 2002; Evangelista and De Brito 2007; Saride et al.

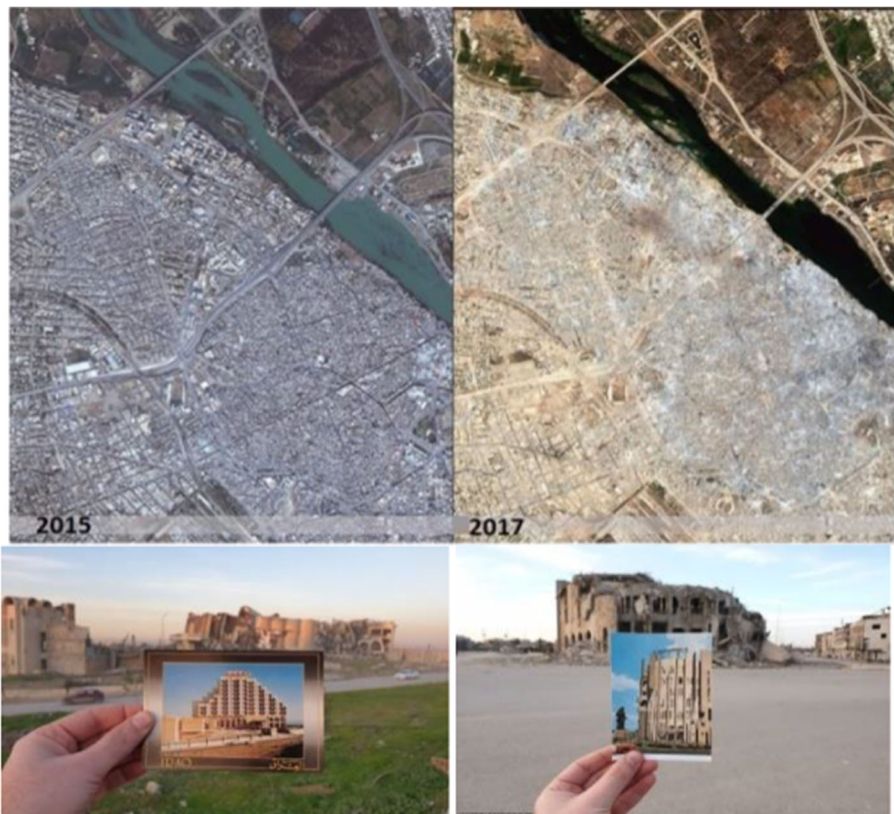


Fig. 1 Mosul infrastructure demolition

2010; Yang et al. 2011; Toghroli et al. 2018; Norsati et al. 2018; Trung et al. 2019; Bassani et al. 2019; Beja et al. 2020; Godoy et al. 2020).

The California bearing ratio (CBR) test is the most commonly used tests in road design, particularly for flexible pavements. It can be relied upon when assessing the use of the CD materials as a stabilizer of the subgrade layer. The pavement thickness depends on the subgrade modulus derived from CBR tests. The most important parameters introduced in the design of pavement are elastic modulus and resilient modulus, which can be found using the CBR values. The CBR values are a function of the moisture content, dry density, soil type, and plasticity of soil (Kumar 2014). Arshad (2019) proposed an empirical equation to relate resilient modulus with CBR values. The equation was obtained by testing 52 remolded samples treated with natural aggregate and reclaimed asphalt pavement and recycled concrete aggregate. Lakshami et al. (2019) related the resilient modulus with CBR values of different subgrade soils such as clayey sand (SC), silty sand (SM), and well-graded sand (SW). Recently, Srihandayani et al. (2020) related the bearing capacity of the soil with CBR values.

Rezende and Carvalho (2003) studied the application of quarry wastes as a base layer under the flexible pavements. A segment road of 80-m length was constructed from such materials as subgrade, base, and surface treatment in Brasilia. After 5 years of road construction, field CBR, dynamic cone penetration, and plate load tests were carried out. The suitability of the use of quarry wastes as a construction material for the base layer of low volume road capacity is evident. The CBR values of natural soil are lower than those of all types of recycled aggregate. Zabielska-Adamska and Sulewska (2015) found a good correlation between the CBR values and the compaction characteristics and concluded that the compaction of the embankment and subgrade layers can be controlled by CBR field test. Cardoso et al. (2016) stated that the strength of soil treated with CD materials can be evaluated from CBR values. Thakur et al. (2016) added 10–50% crushed (CC) mixed with 0–6% cement to strengthen the clayey subgrade soil under the flexible pavement. The CBR values increased by 6.5 and 9.5 times with the addition of the CC + cement mixture by 10% + 6% and 50% + 6%, respectively. Accordingly, the thickness of the pavement layer is reduced by 11.5%. Besides, highly increased in the maximum dry density associated with increases CC up to 10%, beyond exhibits insignificant increases. Henzinger and Heyer (2018) studied experimentally the effect of adding recycled aggregate that produced from demolition waste to fine-grained soils. The recycled aggregate is added by 50% to clay soils with low, medium, and high plasticity. Both dry density and bearing capacity increase. The results revealed that the recycled aggregate becomes more effective with low-plasticity soil. Patel et al. (2019) stated that 30% of fine admixture is the optimum percentage of replacement soil to obtained maximum dry density and CBR values. The experimental program comprises laboratory CBR, unconfined compressive strength (UCS), and swelling tests conducted by Cabalar et al. (2019) who demonstrated a suitable utilization of CD material with clay for road pavement subgrade. A similar conclusion was found by Cristelo et al. (2019) using a fine portion of CD particles. Alnunu and Nalbantoglu (2020) selected three types of CD materials including shredded bricks, crushed waste stone, and crushed old concrete to construct stone columns in the loose sandy soil (SP). The results showed that the largest effect was evident when adding crushed old concrete, as it reduced the settlement and increased the stiffness modulus, while the bricks showed

less effect. The addition of CD materials to a highly plastic clay enhanced the strength substantially (Sharma and Sharma 2019). Moreira et al. (2020) treated silty soil for use as a subgrade under pavement with 40–60% CD consisting of granular materials (sand and gravel). The UCS, tensile strength, and resilient modulus increase by 72, 92, and 552%, respectively, over the natural soil, with increasing CD material. A total of 60% of CD was found to result in the best soil properties. Mehrjardi et al. (2020) evaluated the CD waste as a subbase material through a series of experimental tests. These materials were found to be suitable for use as a subbase in road construction. The strength of the subbase was improved by using the geocell with the CD material. Similar conclusions about the use of CD materials in shoulders and unpaved roads were reported by Huber et al. (2020). Sheikh and Shah (2020) carried out static plate load tests on the base layer of reclaimed asphalt pavement (RAP) that reinforced with geocell and geosynthetic. Results show that the strength and deformation improved when reinforced the base layer compared to unreinforced layer. The bearing capacity increases up to 96% of the base thickness of 20 cm. It is concluded that the use of RAP as a base course material can significantly improve by stabilized with geosynthetic materials.

Many studies have been carried out to evaluate the use of CD materials as stabilizers for subgrade soil based on the results of laboratory CBR values and compaction characteristics. However, the field CBR values reflect the actual field conditions and it is essential to verify the actual improvement in the behavior of subgrade soil. Therefore, the present study carried out field CBR tests on soil treated with various CD materials to evaluate the suitability of such waste materials as a stabilizer for the subgrade layer. A comparison of the results of the field CBR tests and numerical values from the PLAXIS 2D package was carried out.

2 Experimental Study

2.1 Materials

Natural clayey soil (CL) with the engineering characteristics shown in Table 1 was used in this study. The soil is classified as ‘CL (clay of low plasticity)’ according to the Unified Soil Classification System (USC) and ‘A-7-6 (7)’ according to American Association of State Highway and Transportation Office (AASHTO 1993) classification systems, respectively.

Three types of solid waste materials that are produced from the construction and demolition (CD) processes of buildings were chosen. The first of these wastes is construction-demolition asphalt waste (DA), which results from the destruction of old asphalt or the crushing of road pavement. It consists of aggregate particles coated with asphalt. The second type is construction-demolition crushed bricks (CB) produced from the demolition of brick masonry. Its composition is a mixture of clay and silt soil with other compounds. The third type of material is from construction-demolition waste for concrete that is generated from the old cast of crushed concrete (CC). Some of the engineering properties of these waste materials are listed in Table 1.

Table 1 Index properties of the materials

Properties	Material type				
	CL	CL+10%DA	CL+10%CB	CL+10%CC	
Liquid limit (%)	41	34	38	36	
Plastic limit (%)	25	22	25	24	
Plasticity index (%)	16	12	13	12	
Specific gravity	2.69	2.64	2.66	2.66	
Grain-size distribution	Gravel (%)	2.5	11.5	8.5	10
	Sand (%)	42	39	42	40.5
	Silt (%)	23	20.5	20.5	20.5
	Clay (%)	32	29	29	29
Compaction characteristics	Dry unit weight (kN/m ³)	17.3	17.8	17.1	17.6
	Optimum moisture content (%)	18.4	12.3	16.5	15.4
Classification system	USCS	CL (lean clay with sand)	CL (lean clay with sand)	CL (lean clay with sand)	CL (lean clay with sand)
	AASHTO	A-7-6 (7)	A-6 (3)	A-6 (3)	A-6 (3)

2.2 Laboratory Compaction Tests

Natural clayey soil (CL) and crushed CD materials were cleaned and sieved on #4 and 19-mm sieves, respectively. The soil and specific amounts of CD materials were mixed dry, until they formed a homogenous mixture. Thereafter, a required amount of water was added and the mixture was thoroughly re-mixed until obtaining a homogeneous wet mixture. The modified Proctor compaction test (ASTM (D4429), 2014) was performed on five to six samples with different moisture contents to obtain the compaction curves of the three types of soil-CD mixtures in addition to the natural soil. The optimum moisture contents and maximum dry unit weights were obtained from the compaction curves. The selection of the CD percentage of 10 was based on the results of the shear test conducted by Abdulnafa'a et al. (2019), which showed that the highest angle of internal friction of the soil is at 10% of the same CD materials. Likewise, Thakur et al. (2016) found that 10% of the CD is the optimal percentage for the maximum dry density.

2.3 Field CBR Test

Work was done in the laboratory on a large model to simulate the CBR test in the field, taking into account the effect of boundary conditions. The model consists of a cylindrical concrete box with a diameter of 2.0 m and a height of 1.5 m. The field CBR test equipment consists of a steel frame that was installed above the model to apply the load through using a hydraulic jack (see Fig. 2); a penetration plunger has a circular section of 50 mm in diameter and 102 mm in length; and a surcharge steel plate with a circular section of 254 mm in diameter has a hole in the center of 50.8 mm in diameter, and the surcharge weights (ASTM (D4429), 2014).

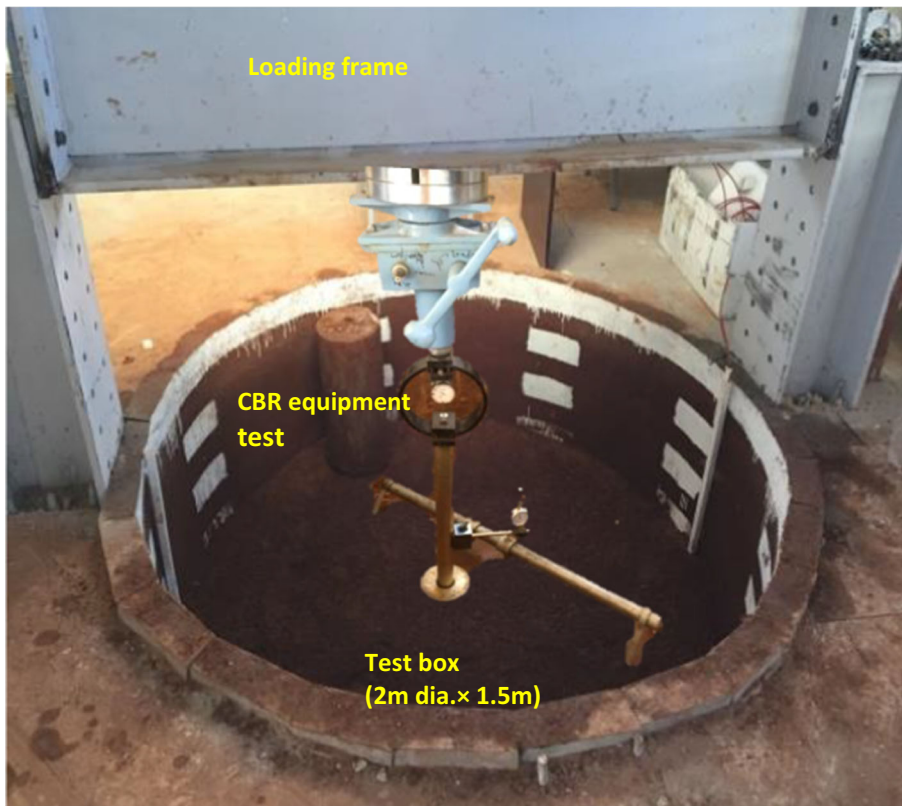


Fig. 2 Field CBR test setup

The amount of soil used for the field CBR tests in the study was approximately 16.5 m^3 after it was passed through a #4 sieve. The amount of each type of CD material used was approximately 0.5 m^3 after it was passed through a 19-mm sieve. A quantity of dry soil was mixed with 10% of one of the CD materials to achieve a layer thickness of 10 cm with a specific dry unit weight. Then specific amount of water was added that is equivalent to the optimum moisture content resulting from the compaction curve. Re-mixing again until a homogeneous mixture is achieved. To verify this, the moisture content was checked by taking samples of the mixture after an hour of mixing. The height of the model was divided into 15 layers, each layer achieving a thickness of 10 cm soil after compaction. Compaction was carried out at 90% of the maximum dry unit weight using a hammer with a steel rod. In addition, a concrete cylinder was used to obtain a regular plane surface. Several samples were taken from different locations for each compacted layer to test the uniformity of density and percentage of moisture in each layer throughout the model with a permissible deviation of 1%.

Four test models were prepared, one for the natural soil (CL) and three for the soil treated with three types of CD materials (DA, CB, and CC). The field CBR test was carried out according to ASTM specification (ASTM (D4429), 2014). Before each test, the CBR instrument was calibrated. The penetration rate is approximately 1.3 mm/min. The load was applied manually with the aid of the steel frame and using a hydraulic jack during the test. Figure 3 shows the test setup and device installation.

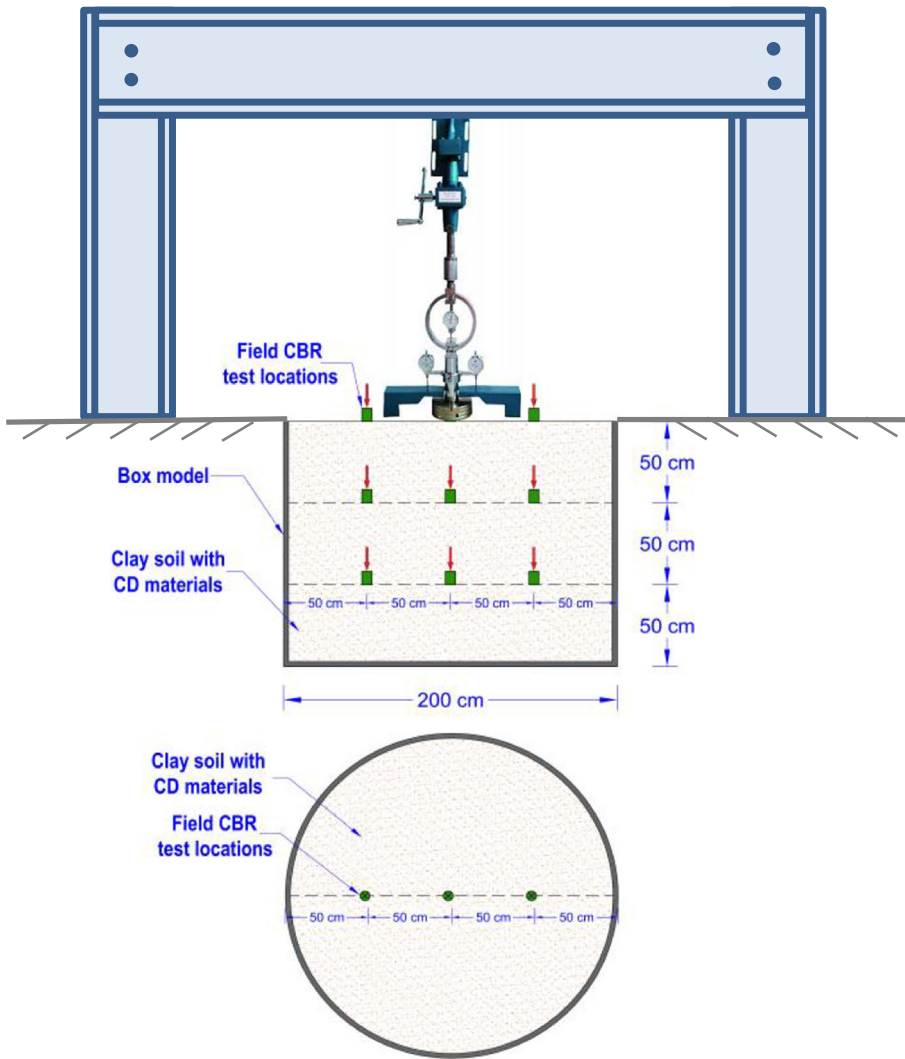


Fig. 3 Arrangement and locations of field CBR tests

The test was performed on three levels (50, 100, and 150 cm) which represent the thickness of the studied layers. The CBR value for each level is an average of three CBR tests arrangement as shown in Fig. 3. Accordingly, the total of field CBR tests is 36 tests conducted during the study. In each test, sequential readings of stress and penetration were taken, and the values for CBR were taken at penetration depths of 2.5 and 5.0 mm.

3 Numerical Analyses

Numerical analysis was performed using the PLAXIS 2D package to simulate the field CBR test. The simulation included natural soil (CL) as well as soils treated with 10%

Table 2 Input parameters used in the PLAXIS 2D simulation

PLAXIS model properties	CL	CL+10% DA	CL+10% CB	CL+10% CC
Materials model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
$\gamma_{unsat.}$ (unsaturated field density) kN/m^3	18.40	18.27	18.14	18.27
$\gamma_{sat.}$ (saturated field density) kN/m^3	19.1	19.13	18.5	18.48
E (modulus of elasticity) kN/m^2	Estimated from equations proposed by previous studies (see Table 4)			
ν (Poisson's ratio)	0.342	0.328	0.314	0.319
* C_{ref} (cohesion) kN/m^2	18.0	7.0	6.5	13.0
* ϕ' (effective angle of internal friction) degree	28.5	30.7	33.0	32.0
ψ (angle of dilatancy) degree	0.0	0.0	0.0	0.0

*after Abdulnafa'a et al. (2019)

CD materials (DA, CB, and CC). Based on that, 56 axisymmetric models were built to simulate the experimental tests as well as to compare practical and theoretical results.

The parameters to be included in numerical models were obtained either from experimental tests or from empirical equations. The Mohr-Coulomb criteria were adopted to represent natural soil (CL) behavior and soil treated with CD materials. The input parameters required in numerical models were obtained from either experimental tests or empirical equations. The Mohr-Coulomb criteria were adopted to simulate the behavior of CL and soil with CD materials. Table 2 presents the input parameters and the engineering properties of the soil layers used in the numerical analysis. The plane triangular elements with 15 nodes and 12 stress points were used to represent the soil to obtain accurate results.

Figure 4 shows the typical model used in numerical analyses of the three layers with thicknesses of 50, 100, and 150 cm. The results were obtained from the numerical analyses in the form of the deformed shape and the deformation. The CBR values for natural and treated soils with CD were calculated from the stress-strain curves resulting from the numerical analysis for each case.

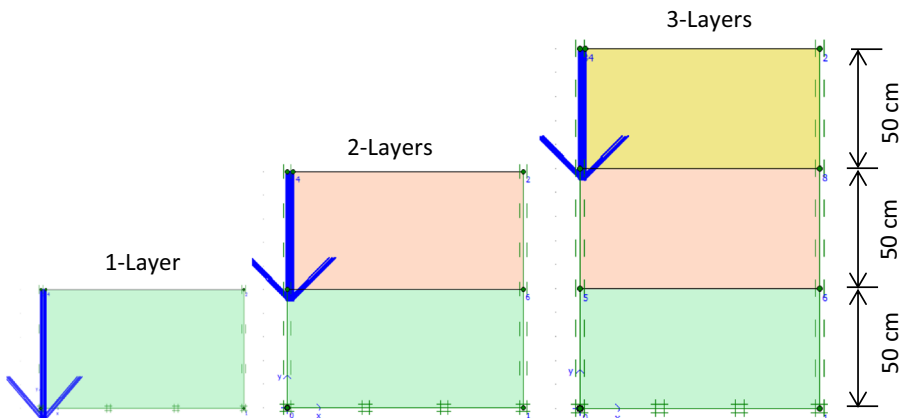


Fig. 4 Typical models used in numerical analyses

Six equations obtained from previous studies were used in calculating the modulus of elasticity (E) value. These equations depend on the CBR values obtained from experiments to estimate the value of E . For each value of the E , a corresponding CBR value was calculated, and then the numerical results were compared to the experimental results to obtain the best equation that represents the field CBR tests.

4 Results and Discussions

4.1 Grain-Size Distribution

The grain-size analyses of natural soil (CL), CD materials, and mixtures of the soil-CD materials are shown in Fig. 5. The addition of 10% CD materials to clay soil improves its grain-size distribution of the soil. According to AASHTO specifications (1993), clay soil are classified as {A-7-6 (7)} and becomes {A-6 (3)} after treatment with 10% of DA, CB, and CC. This means that with the addition of the CD materials, the soil becomes more graded in accordance with the grain-size distribution and increases the group index decreases about twofold, which indicates that there is potential for the use of such waste material to enhance soil subgrade layers.

4.2 Compaction Characteristics

The results of compaction tests are presented in Fig. 6, and a summary is presented in Table 1. The optimum moisture content decreases upon the addition of the CD materials. A significant reduction is associated with DA material while other waste materials CB and CC show a slight reduction in optimum moisture content relative to the natural clay soil. Due to the coating of particles with asphalt in DA, less water is

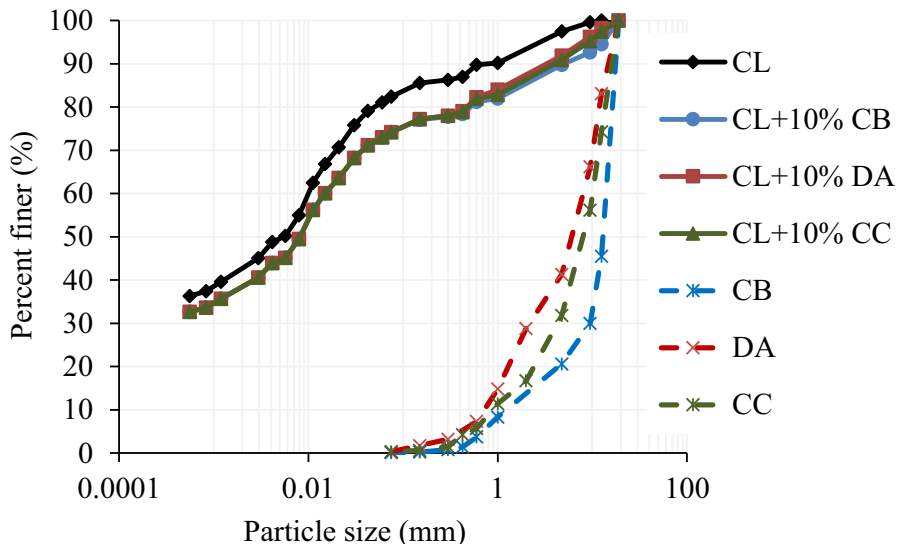


Fig. 5 Grain-size distribution curves

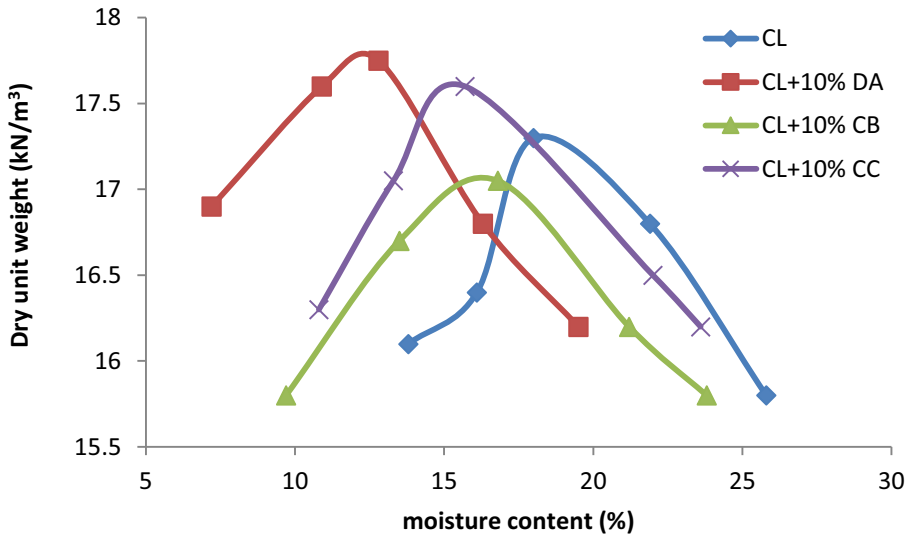


Fig. 6 Laboratory compaction characteristics curves

required to achieve the maximum dry unit weight than with natural soil (CL). Both CB and CC can adsorb water like natural soil particles but have less absorption activity than that exhibited by clayey particles. Vegas et al. (2011) found a reduction in the optimum moisture content of soil with DA.

In general, the maximum dry unit weight increases with the addition of CD materials, except for CB, which shows a slight reduction of 1.15% that may be due to the presence of a relatively high voids in the block pieces and possess a lower specific gravity value (2.64) than soil clay particles (2.69) while DA and CC have solid pieces and low void ratios. The natural soil (CL) and that treated with CD materials have a typical trend of soil compaction curve. Also, the addition of 10% CD materials led to minor variations in dry unit weights of 2.9, 1.1, and 1.7% over the CL for soil treated with DA, CB, and CC, respectively. However, Vegas et al. (2011) observed a reduction in the unit weight upon the addition of CD materials.

4.3 Stress-Penetration Behavior

By reading the stress level at each specific penetration, the stress-penetration relation has been plotted in Fig. 7 for layer thickness 50, 100, and 150 cm. Although these plots do not represent the actual stress-strain relation, the CBR values and the modulus of elasticity of the subgrade layer can be estimated from these curves, which are essential values in the design of pavement thickness. All mixtures of soil and CD, as well as the natural soil (CL), exhibited similar trends. The stresses increased with thickness, and the only exception was detected in the behavior of CL because the rate of increases in stress reduced significantly and almost became insignificant changes at 150 cm of thickness.

Further penetration of the plunge into the soil occurs with an increase in the applied load. This is reasonable as the confinement effect on the soil increases with the plunger penetrates the soil as in the case of the CBR test. The addition of CD materials

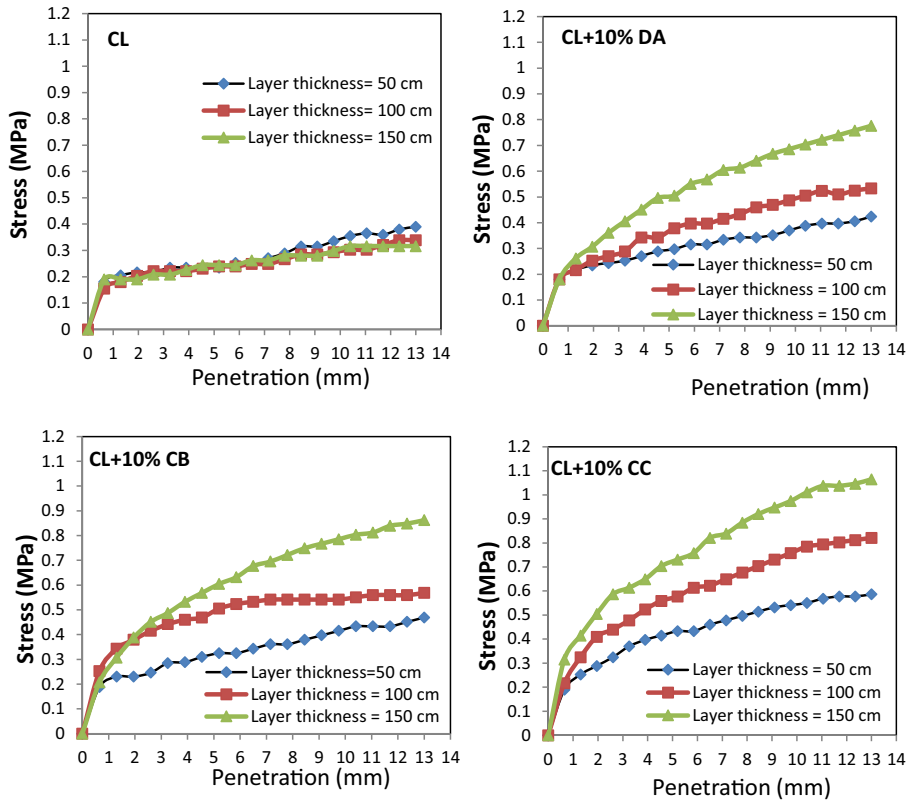


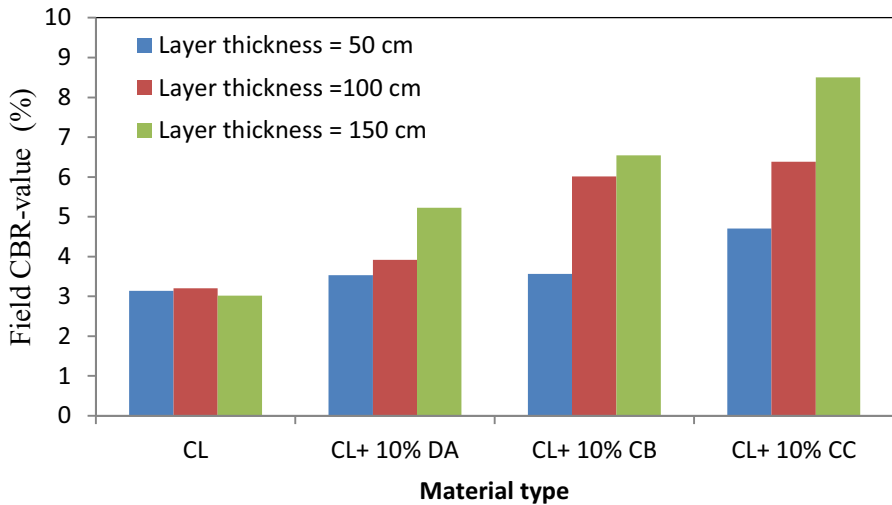
Fig. 7 Stress-penetration relationships

enhances the strength of the soil and the stress increases. The CC materials show the highest stresses of order 324.7, 440.1, and 586.3 kPa at 2.5 mm penetration, respectively, which reflect the improvement of the soil stiffness compared to natural soil (CL) values of 208.3, 221.2, and 221.5 kPa. Other CD materials (DA and CB) also improved the stiffness of soil but at a lower rate. An experimental study was carried out by Kianimehr et al. (2019) to examine the strength properties of clay soils by recycled concrete aggregate. The addition of recycled concrete aggregate enhanced the strength of the soil while the density decreases and it can be used as a subbase or subgrade of road pavements. However, Ok et al. (2020) stated that the CD materials exhibited lower CBR values and UCS by about 25% compared to the natural aggregate.

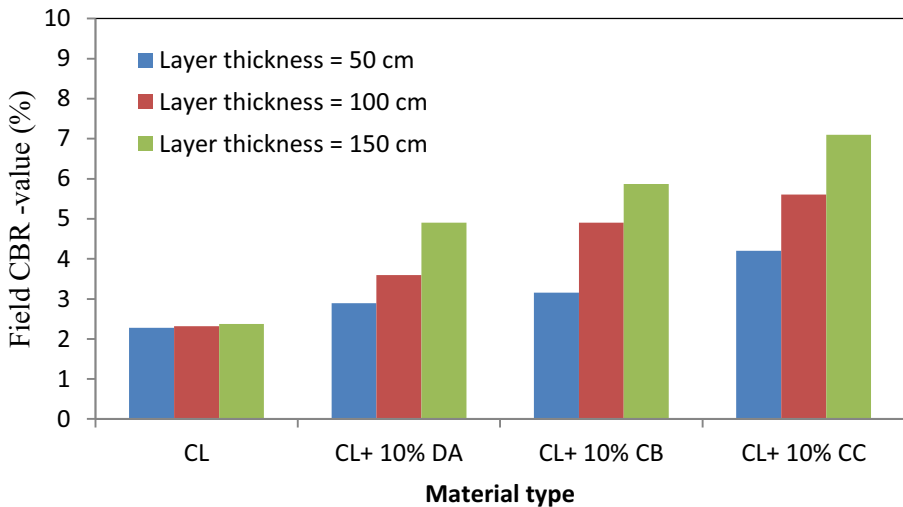
From the stress-penetration relation, the CBR values can be derived at 2.5- and 5.0-mm penetrations. Furthermore, the modulus of elasticity can be calculated with the aid of stress-penetration curves.

4.4 CBR Values of Soil Treated with CD

The effect of the addition of construction-demolition waste materials (CD) on the field CBR values of the clayey soil is shown in Fig. 8. The addition of CD materials to the soil improved the CBR values. As shown in Fig. 8, the CBR values increased with the addition of CD.



(a) Penetration= 2.5 mm



(b) Penetration= 5.0mm

Fig. 8 Effect of CD materials on CBR value-field tests

Table 3 gives a summary of the results of the CBR values for different mixtures and depths. The results of the first tested layer with a thickness of 50 cm showed improvement in the CBR values of soil (at penetration 2.5 mm) with DA, CB, and CC by 12.5, 13.6, and 49.7% over the natural soil (CL), respectively. These increases became 22.2, 87.8, and 98.5% with a layer thickness of 100 cm and 73.2, 117.0, and 182.1% for a 150-cm layer thickness. Great improvements in the CBR values in the soil with CC material were identified while the addition of DA material was found to result in relatively less improvement. Similar findings were reported by Vegas et al. (2011) while Bennet and Maher (2008) reported a reduction in the CBR values of DA

Table 3 Field CBR values for natural and treated soil

Displacement (mm)	Layer thickness (cm)	CBR values (%)			
		Material type			
		CL	CL+10% DA	CL+10% CB	CL+10% CC
2.5	50	3.14	3.53	3.57	4.70
	100	3.20	3.91	6.02	6.38
	150	3.01	5.22	6.54	8.50
5.0	50	2.28	2.89	3.15	4.20
	100	2.32	3.59	4.90	5.61
	150	2.37	4.91	5.87	7.10

materials. This behavior reveals the activity of the addition of CD materials as additives to improve the engineering properties of the subgrade soil layer. The addition of CD materials enhanced the gradation of the soil as well as provides more stiffness to the soil through the increasing friction between soil particles and CD materials.

The CBR values reflect some limits of the actual stiffness of the different mixtures. Therefore, the variation in the improvement of the CBR values for different CD materials belongs to the nature of their particles. The particles of CC materials are more stiff and higher strength compared to the DA and CB materials. On the contrary, the DA particles are coated with asphalt and, hence, provide less friction than the other two waste materials. It believes that the addition of more amount of waste asphalt (DA) or other CD materials may enhance the CBR values considerably. However, this is the limitation of this study which depends on the optimum percentage of CD materials as 10% obtaining from shear strength tests results (Abdulnafaa et al. 2019). It is believed that the optimum percentage of CD materials that led to the maximum CBR values depends on the gradation of such materials. The percentage increases with finer waste materials.

At 5.0 mm of penetration, lower improvement gains in CBR values were achieved than those exhibited at 2.5 mm, as shown in Fig. 8. Accordingly, the CBR values at 2.5 mm should be adopted in the design calculation.

4.5 Variations in CBR Values with Varying Layer Thickness

Figure 9 shows the trends of CBR values versus thickness of the subgrade clayey layer. Increasing the thickness of the natural clay layer from 50 to 100 cm and then 150 cm had insignificant effects on the CBR values. The trends of relation at 150 cm denoted a slight reduction in CBR values around 5%. The high CBR values with the clay layer thickness of 50 cm can be attributed to the high stiffness layer located under the first layer, and as the thickness was increased, the effect of the underlying layer vanished.

For soil treated with 10% CD materials, Fig. 9 shows an increase in the CBR values with increasing subgrade clay layer thickness from 50 to 100 cm and 150 cm. A maximum increase in CBR values was found to be associated with CC material. It is increased by 1.4 times for increasing thickness from 50 to 100 cm and 1.8 times for

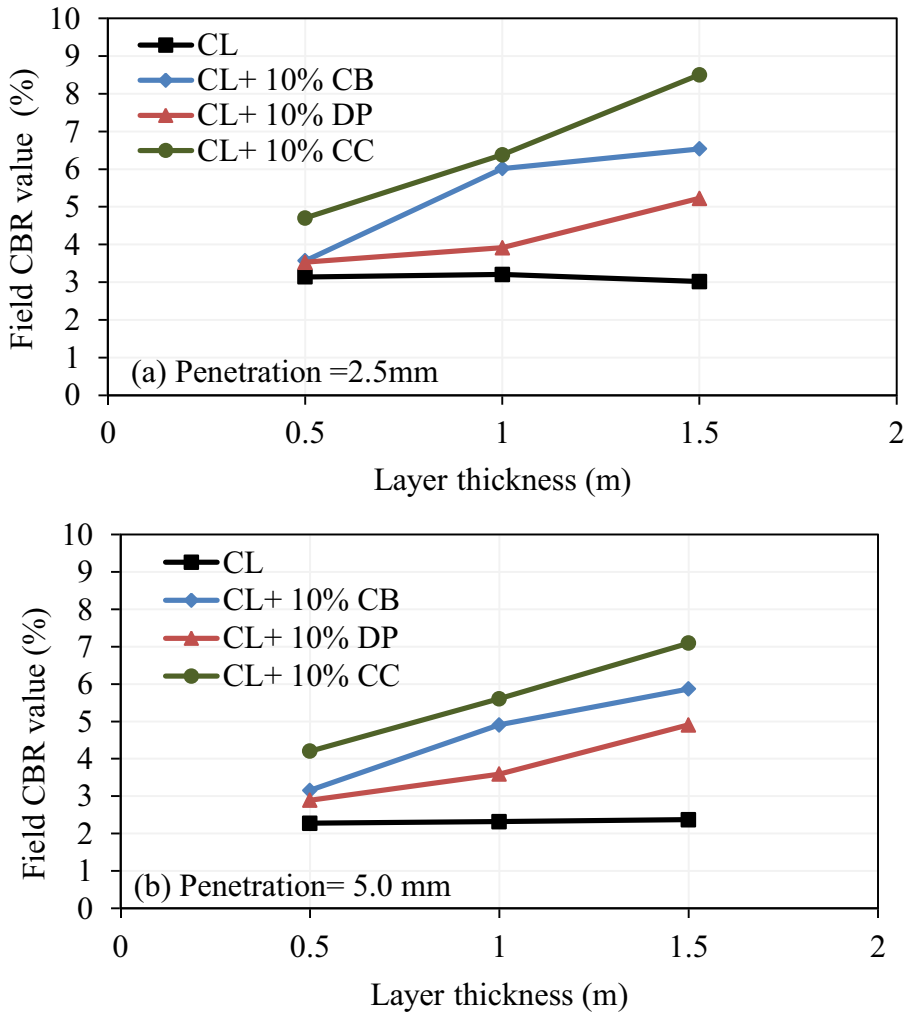


Fig. 9 Effect of layer thickness on CBR value

thickness increases from 50 to 150 cm at penetration 2.5 mm. Lower increases recorded at 5.0-mm penetration. The increases in CBR values are 1.1 times and 1.7 times for thickness increases from 50 to 100 cm for soil with DA and CB materials, respectively, over the natural soil (CL). It becomes 1.5 times and 1.8 times for thickness increases from 50 to 150 cm. This increase can be attributed to the additional resistance layers achieved with increasing thicknesses of treated soil, which led to reductions in stress concentrations due to the distribution of the load over a large area. Thus, the higher rate of increases in the CBR values with the thickness associated with the soil that treated with CC because it is provide more stiffness layer. A similar observation reported by Moayed et al. (2012) obtained from a CBR test on the subbase layer consists of sandy soil overlying a cohesive soil as a subgrade layer. Three different thicknesses of the sandy layer were considered, and the results revealed that the CBR values varied with the thickness of sandy layers.

4.6 Relation Between Modulus of Elasticity and CBR Values

Several relationships have been proposed for use in identifying the modulus of elasticity (E) value of soil. Some of these relationships depend on the results of the CBR test. From the relationship between stress-penetration obtained from experiments, the E value can be calculated using the proposed equation from Kameswara Rao (2000) while other equations involve the use of CBR values (Heukelom and Klomp 1962; Powell et al. 1984; Look 2007; Shukla and Sivakugan 2011; Putri et al. 2012). Table 4 contains a summary of the computation of E computed from several equations. A large difference between the E values is computed from those equations. This is expected because the assumptions for these equations differ. However, the best E values were obtained using the equations of Kameswara Rao (2000) and Putri et al. (2012) because their hypotheses are similar to those in the present study. It is believed that the results obtained from the Kameswara Rao (2000) equation are more logical than those obtained from the Putri et al. (2012) equation because they depend on the stress-penetration relation derived from the field CBR test.

Table 4 Values of modulus of elasticity from various equations

Material type	Depth (cm)	Field CBR values	Estimated values of modulus of elasticity (kN/m ²)					
			Equation number					
			<i>Eq. 1</i>	<i>Eq. 2</i>	<i>Eq. 3</i>	<i>Eq. 4</i>	<i>Eq. 5</i>	<i>Eq. 6</i>
			Heukelom and Klomp (1962)	Powell et al. (1984)	Kameswara Rao (2000)	Look (2007)	Shukla and Sivakugan (2011)	Putri et al. (2012)
			$E = 10300 \times CBR$	$E = 17.6 CBR^{0.64}$	$E = \frac{p(1-\mu^2)\sqrt{A}}{1.13 \delta}$	$E = 5000 \times CBR$	$E = 2000 \times CBR$	$E = 840.5 \times CBR$
CL	50	3.14	32,318	36,588	3119	15,688	6275	2637
	100	3.20	32,990	37,073	3184	16,014	6406	2692
	150	3.01	31,049	35,662	2996	15,072	6029	2533
CL+ 10%DA	50	3.53	36,363	39,457	3509	17,652	7061	2967
	100	3.91	40,319	42,153	3891	19,572	7829	3290
	150	5.22	53,798	50,698	5192	26,116	10,446	4390
CL+ 10%CB	50	3.57	36,737	39,716	3545	17,833	7133	2998
	100	6.02	61,964	55,497	5980	30,080	12,032	5056
	150	6.54	67,353	58,539	6500	32,696	13,078	5496
CL+ 10%CC	50	4.70	48,425	47,396	4673	23,507	9403	3952
	100	6.38	65,711	57,622	6342	31,899	12,759	5362
	150	8.50	87,550	69,237	8449	42,500	17,000	7144

4.7 Numerical Results

Fifty-six numerical models were built to simulate the field CBR tests carried out in the present study. From the stress-penetration curve obtained from the numerical analysis, the CBR values were found at 2.5 mm of penetration. For every estimated modulus of elasticity value (Table 4), there is a corresponding CBR value (Table 5). The results of the CBR values obtained from the numerical analyses are presented in Fig. 10 and Table 5. Generally, Eq. 3 suggested by Kameswara Rao (2000) gives CBR values with an 85% match with the CBR values obtained in the experimental work in the present study. Also, Eq. 6 provides CBR results that are close to the experimental results with an average 80% match, while Eqs. 1, 2, 4, and 5 exhibited higher CBR values than those from the matching experimental tests. As mentioned earlier, Eq. 3 depends on the stress-penetration relation, so it is a more reliable formula than other equations for use in numerical analysis.

The CBR results obtained from the numerical analysis indicated that the CBR values of the soil treated with CB are greater than those of soil that was treated with DA, and both of them give a greater CBR value than the natural soil (CL). In all cases, soil with CC gives the highest values of CBR while soil with CA gives the lowest values, particularly in the case of lowest layer thickness (50 cm). The reason for this is attributed to the model used in numerical analysis, which is Mohr-Coulomb, which depends on the values of shear strength parameters (C and ϕ). Therefore, the effect of these coefficients is limited to the CBR values because the stress level remains below the level of failure. The same results were reported by Mendoza and Caicedo (2018).

Table 5 CBR values from numerical analysis

Material type	Depth (cm)	Field CBR value (%)	CBR values from numerical analysis (%)					
			Equation number that values of E calculated and used in numerical analysis					
			<i>Eq.1</i>	<i>Eq.2</i>	<i>Eq.3</i>	<i>Eq.4</i>	<i>Eq.5</i>	<i>Eq.6</i>
			Heukelom and Klomp (1962)	Powell et al. (1984)	Kameswara Rao (2000)	Look (2007)	Shukla and Sivakugan (2011)	Putri et al. (2012)
CL	50	3.14	4.12	13.1	3.26	5.90	5.66	3.75
	100	3.20	5.34	13.2	3.82	9.73	6.53	3.93
	150	3.01	7.81	18.07	4.20	13.08	7.11	4.11
CL+ 10% DA	50	3.53	3.07	8.32	2.94	6.41	4.23	2.66
	100	3.91	8.40	8.45	3.22	6.76	4.64	3.72
	150	5.22	12.71	12.58	4.80	10.30	7.09	4.30
CL+ 10% CB	50	3.57	9.05	9.21	3.08	6.91	4.53	2.63
	100	6.02	10.20	9.98	4.11	8.64	6.05	3.85
	150	6.54	14.43	14.07	5.74	12.17	8.10	5.08
CL+ 10% CC	50	4.70	14.46	14.38	4.31	10.70	7.06	4.02
	100	6.38	15.50	14.92	8.16	12.24	8.23	5.35
	150	8.50	23.61	22.34	8.83	18.61	12.50	7.81

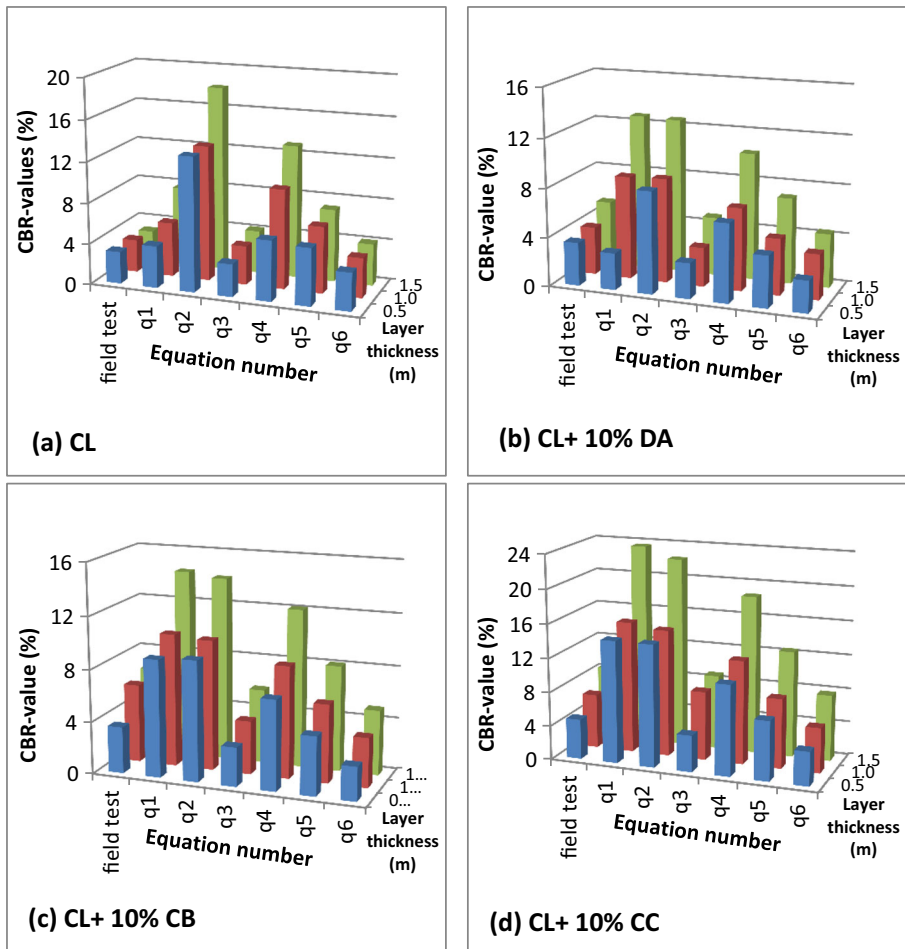


Fig. 10 CBR values from various equations and numerical analysis

Although the angle of friction of clay soil (ϕ) treated with DA is greater, the cohesion is less than that of CL and the E values of natural soil (CL) are higher than those in soil treated with DA, which indicates that cohesion (C) is more effective than friction at a lower range of applied stress.

A good match was found between the CBR values obtained from the experimental work and numerical analysis if Eqs. 3 and 6 were applied. The differences between the CBR values from numerical analyses depend on the use of different equations, which are based on multiple hypotheses. Accordingly, it is possible to rely on numerical analysis in finding CBR, but consideration must be given to the careful selection of the variables.

Figure 11 shows the typical deformed shapes in case of soil treated with 10% CC. It is clear that the behavior is the same for all thicknesses of the layers. Also, natural soil (CL) and that treatment with other CD materials (DA and BC) showed the same trend.

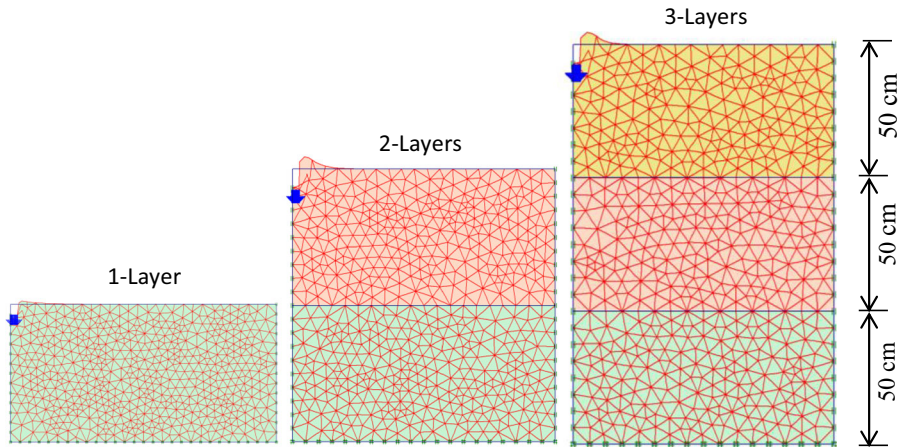


Fig. 11 Typical deform shapes of CL + 10% CC

5 Conclusions

From the experimental and numerical results, the following conclusions can be drawn:

- A slight reduction in optimum moisture content occurred upon the addition of CD materials by 10.3 and 16.3% for CB and CC, respectively, while the DA exhibited the highest reduction by 33.2%.
- The dry unit weight increases upon the addition of CD materials by 1.7 to 2.8%, with the exception of CB, which shows a dry unit weight reduction of 1.2%.
- The grain-size distribution of clayey soil was modified by the addition of CD materials. The natural soil (CL) which is classified as {A-7-6 (4)} according to the ASSHTO classification system becomes {A-2-6 (8)} after treated with CD materials.
- There was improvement in the field CBR values upon the addition of CD materials. The CBR values increase by 12.4, 13.7, and 49.7% for DA, CB, and CC, respectively, over the natural soil for (CL) the 50-cm layer thickness.
- The CBR values increased with increasing layer thickness. It increases by 1.1 times to 1.7 times when thickness increases from 50 to 100 cm and by 1.5 times and 1.8 times for thickness increases from 50 to 150 cm.
- There is a wide variation in the modulus of elasticity when applying many of the formulas proposed from previous works. Under the conditions of the present study, it was found that some equations give an acceptable elastic modulus and in turn CBR values.
- There is a good match in CBR values between experimental and numerical results.
- It is believed that the addition of more than 10% of CD materials will improve the CBR values and other engineering properties of subgrade soil.

Declarations

Conflict of Interest The authors declare competing interests.

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