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RESEARCH ARTICLE-CIVIL ENGINEERING

Plate Loading Tests on Clay with Construction and Demolition Materials

Ali Firat Cabalar[1] · Mohammed Dafer Abdulnafaa[2] · Volkan Isbuga[3]

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Abstract

This study presents a series results of plate loading tests on a clay with various construction and demolition (CD) materials conducted in a large-scale model box and a numerical verification on the use of these material mixtures. The tests have been applied to the clay with three different types of CD materials (concrete, asphalt, and brick) prepared in a reinforced concrete circular box with a diameter of 2.0 m and a depth of 1.5 m. The CD materials were added to the clay with a mix ratio of 10% by dry weight and then compacted at optimum water content (w_{opt}) and corresponding maximum dry density (γ_{drymax}). The testing results have indicated that the CD materials increased the ultimate bearing capacity of the clay with a range of 50–75%. Furthermore, a remarkable correlation between the results of plate loading tests and numerical simulations made by a commercial finite element software (Plaxis 2D) was observed for all mixtures tested.

Keywords Plate loading test · Clay · Construction and demolition materials · Finite element modelling

1 Introduction

Across the world, the volume of construction and demolition materials (CD) has been increasing as older constructions are being demolished in order to build new ones for various reasons. For example, since two devastating earthquakes occurred in Turkey (on 17 August 1999 with Mw = 7.4 and on 12 November 1999 with Mw = 7.2), the government has invested greatly in buildings and infrastructure designed to withstand earthquakes, and consequently a great amount of CD waste has been produced with many negative effects on the environment and economy. In recent years, numerous researches have been carried out to reduce environmental and economical concerns, in which various CD wastes including reclaimed asphalt, crushed concrete, and bricks were used for some geotechnical applications, such as filling materials and in unbound pavement layers [1–6]. In those studies, the CD materials were mixed with either clay or sand at different ratios and then tested in order to understand how these waste materials affected the response of the clay and/or sand. For example, Henzinger and Heyer [7] have used recycled aggregates from demolition waste for stabilization of fine-grained soil. Analysing their results proved a significant increase in shear strength values leading to high bearing capacity of treated soils. Cabalar et al. [6] have recently approved the ability to stabilize a clay for road pavement subgrade using CD materials. Cabalar et al. [8] had also studied the use of waste ceramic tiles as a raw material in the design of road pavement subgrade and concluded in a substantial decrease in design thickness of a pavement. Actually, these mixtures tested by several subsamples may suffer serious settlement and bearing capacity due to a high change in volume when they are loaded. Therefore, a plate loading test was thought to be very helpful for the selection and designing strong foundations on such mixed geomaterials with different rheological response from typical soils. The plate loading test was found to be preferable to be carried out in a model box by taking into consideration the scaling effects due to its simpler operation and lower cost [9–11], although it is usually performed in the field to determine the ultimate bearing capacity of the ground and the likely settlement under a given loading [12–14]. The fact is that, in recent decades, experimental results including plate loading tests have been

✉ Ali Firat Cabalar
cabalar@gantep.edu.tr

1 Department of Civil Engineering, University of Gaziantep, Gaziantep, Turkey

2 Department of Dams and Water Resources, University of Mosul, Mosul, Iraq

3 Department of Civil Engineering, Izmir Institute of Technology, Izmir, Turkey

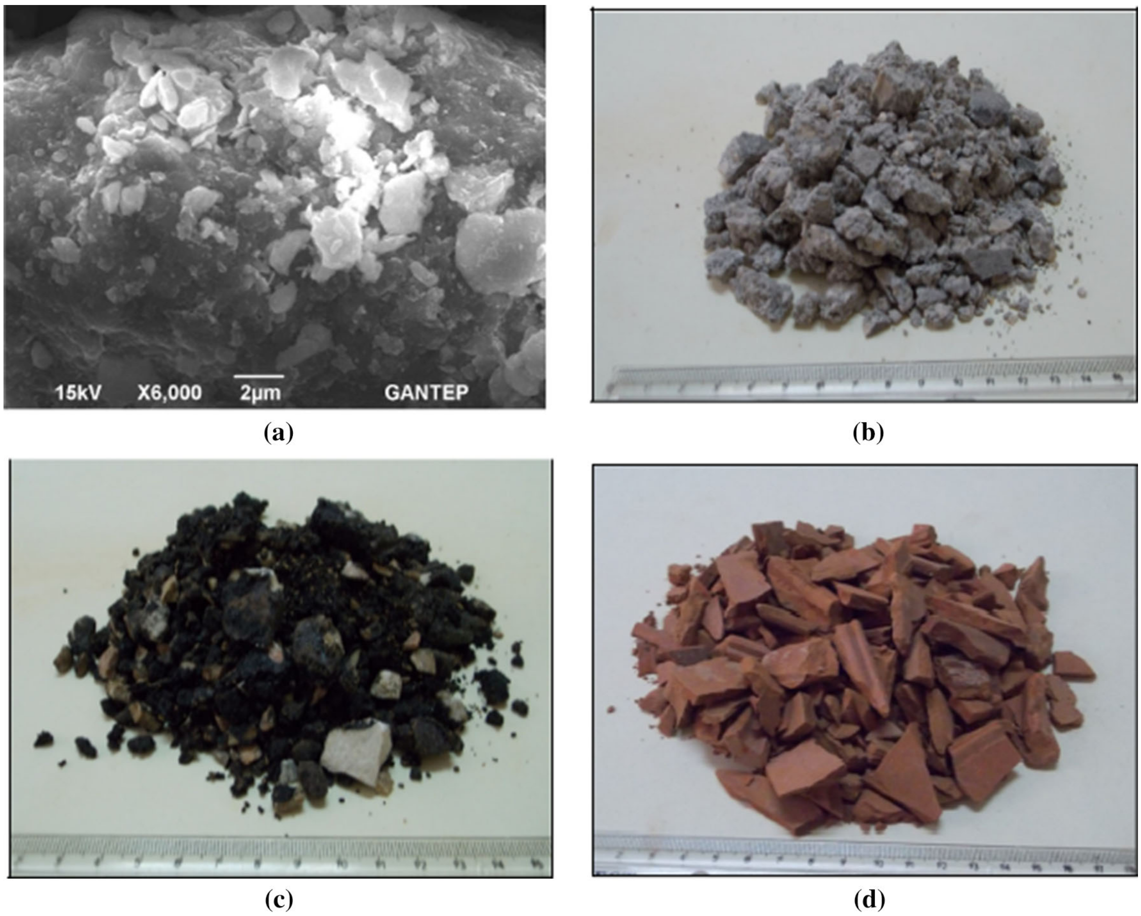


Fig. 1 **a** SEM picture of the clay, **b** crushed concrete pieces, **c** dragged asphalt pieces, **d** crushed brick pieces used during the experimental studies

modelled increasingly by the finite element methods (FEM) for analysing stress, settlement, bearing capacity, and stability in geotechnical engineering [15–17]. In those studies, the FEM analysis was an effective tool to provide reliable results using a robust constitutive model.

The main aim of the present paper was to develop an approach that can be used in order to reduce the amount of CD waste materials from building and construction projects that are considered to be clean and that have the potential to be reused. The objective of this study was to define reliable stress–settlement relationship of a clay treated with various CD waste materials using plate load tests performed in a large-scale physical model. For this purpose, a series of tests has been applied to the clay with three different types of CD materials (concrete, asphalt, and brick) prepared in a reinforced concrete circular model box with a diameter of 2.0 m and a depth of 1.5 m. Such large size of model box was specifically designed in order to reduce the boundary effects of a model container, when producing a vertical load and assessing the soil–plate interactions. The CD materials were mixed with a low plastic clay (CL) at a ratio of 10% by dry weight and then compacted at optimum water content and maximum dry density. Furthermore, a numerical model has been created in order to simulate the testing results obtained in the set-up using a commercial finite element software, Plaxis 2D. Eventually, the paper presents a pioneering numerical and experimental study on a subject that should be of great benefits for further use by researchers.

2 Experimental Study and Methodology

2.1 Materials

The clay samples used in the present research were classified as low plasticity clay (CL) according to Unified Soil Classification System (USCS). The clay samples having a 2.7 of Gs value have plastic limit and liquid limit values of about 23% and 42%, respectively [18]. A series of direct shear tests was carried out on the samples obtained by pushing a cutter into the soil in the model box [19] (ASTM D3080-04). Then, the internal friction angle (φ) and cohesion (c) of the clay samples were found to be 29° and 20 kPa, respectively. The scanning electron microscopy (SEM) picture of

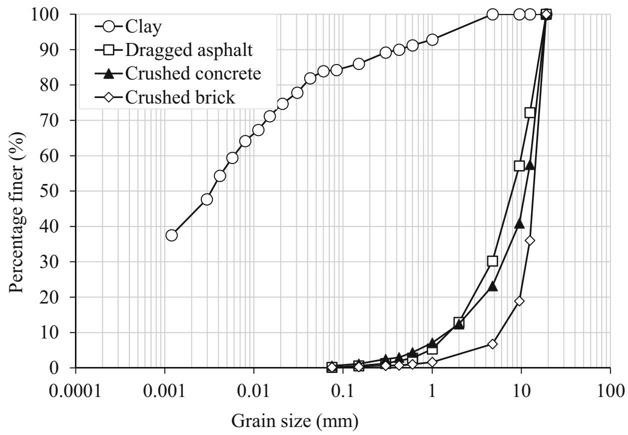


Fig. 2 Gradation of the materials used during the experimental studies

the clay is presented in Fig. 1. Three types of CD materials, crushed concrete, crushed brick, and dragged asphalt aggregates, were mixed with the clay at a ratio of 10%, which was determined by a series of index tests (Fig. 1). Dragged asphalt aggregates were obtained from the repaired and/or renewed roads and highways. Crushed bricks were obtained from the destroyed/repaired buildings, while the crushed concrete aggregates were obtained from the paving slabs used in the city of Gaziantep, Turkey. The asphalt aggregates, bricks, and paving slabs were originally produced in accordance with the KTS [20], TS EN771-1 [21], and TS2824 EN1338 [22], respectively. All the aggregates with a size less than 19 mm were chosen to have uniformity during the experimental studies. Figure 2 shows the sieve analysis results for the materials used in the laboratory works.

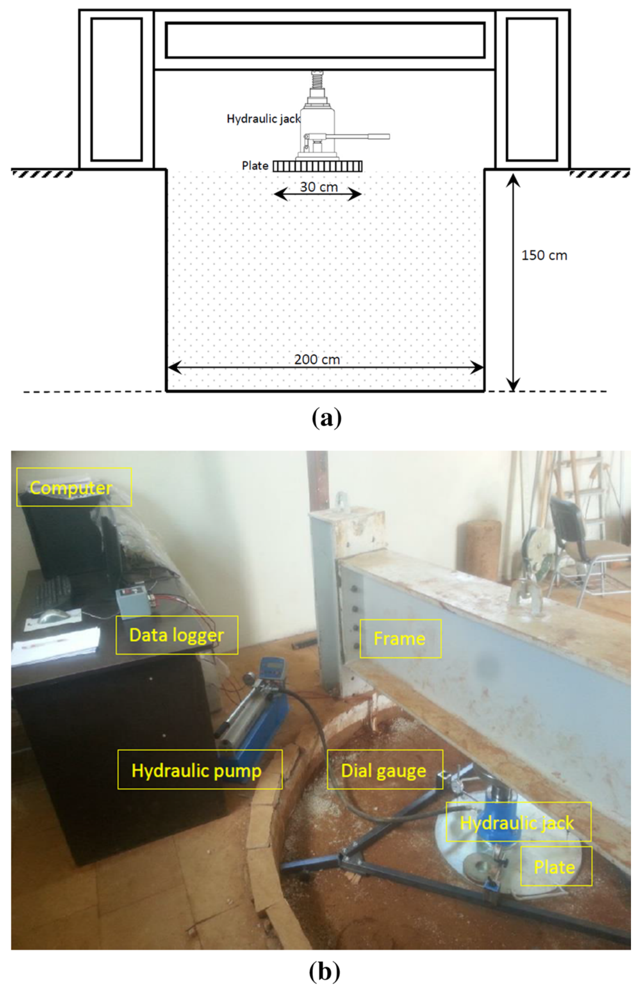


Fig. 3 **a** Schematic drawing and **b** photograph of experimental set-up

2.2 Testing Apparatus and Experimental Procedures

Tests were carried out in a 2.0-m-diameter and 1.5-m-high model box with a 400 kN axial loading frame. The model box was equipped with three linear displacement sensors with a range of 0–50 mm and two soil pressure gauges each 200 mm outside diameter with a range of 0.5–1.0 MPa for the measurement of pressure in the soil and to monitor the behaviour of filling in the model box (Fig. 3). The one with larger capacity was placed at the bottom-centre of the box (gauge 1), while the other one was placed at the bottom-quarter of the box (gauge 2). Both gauges were placed in the soil about 10 cm above the base of model box. The pressure readings were recorded at every 15 min.

Tests were conducted on the same percentage of CD (10%) waste materials in mixtures. This is attributed to the tests described previously by considering the shear strength characteristics and the internal friction angle for various mixture ratios. Cabalar et al. [23] introduced the various testing results of the clay mixed with CD materials at different percentages (0%, 5%, 10%, 20%, and 30%) and found the 10% mixture ratio as the most optimal composition and management of CD wastes in order to use effectively in geotechnical applications. Each specimen was prepared by mixing the soil with a prescribed CD quantity at optimum water content. Prior to compacting the specimens, two soil pressure gauges had been placed inside the model box. Then, each mixture was compacted in layers, typically about 100 mm thick, with respect to their maximum dry unit weight and the optimum moisture content. Field density tests and moisture contents were measured in the model box after filling out each layer completely. The results indicated the relative compaction values ranged about 90%. Such values were found to be acceptable. This is because numerous researchers recommended a field density less than 95% in many earthworks by considering the swelling potential of clay [24–26]. Table 1 presents the details for the materials filled in the model box. Finally, a 30-cm-diameter plate was placed accurately in the centre of model box and then a load is applied by using a jack under the frame. The loading was applied according to ASTM

Table 1 Materials used for filling the model box

Material properties	Clay	Clay + 10% brick	Clay + 10% asphalt	Clay + 10% concrete
Optimum moisture content (%)	18.0	17.5	12.6	16.3
Maximum dry unit weight (kN/m^3)	17.30	17.21	17.92	17.70
Weight of the CD (kg)	0	614	639	632
Weight of the dry soil (kg)	6172	5526	5754	5684
Weight of the mixture (kg)	6172	6140	6394	6315
Weight of the water (lt)	1111	1075	806	1029

Table 2 Input parameters used in the Plaxis 2D simulation of the plate load test

Material properties	References	Clay	Clay + 10% brick	Clay + 10% asphalt	Clay + 10% concrete
Unsaturated field density, γ_{unsat} (kN/m^3)	ASTM D1556/D1556M-15e1 [31]	18.37	18.20	18.16	18.52
Saturated field density, γ_{sat} (kN/m^3)	ASTM D2980-17e1 [32]	19.13	18.67	18.98	18.97
Horizontal permeability (m/day)	ASTM D5084-03 [33]	3.814E−08	6.082E−8	4.726E−8	7.417E−8
Vertical permeability (m/day)	ASTM D5084-03 [33]	7.136E−09	1.138E−8	8.842E−9	1.388E−8
Modulus of elasticity, E (kN/m^2)					
Top layer	Das and Sobhan [24]	2500	11,000	2500	2500
Middle layer	Cabalar et al. [6, 23]	3500	13,000	5500	6000
Bottom layer		4500	15,000	8500	9500
Poisson's ratio, ν	Cabalar et al. [34, 35]	0.34	0.305	0.33	0.305
Cohesion, c' (kN/m^2)	ASTM D3080-04 [19]	20.0	5.0	5.0	12.0
Effective angle of internal friction, ϕ' (°)	ASTM D3080-04 [19]	29.0	34.0	30.5	34.0

D 1194-94 [27] specifications. The load increment adjusted during the tests was no more than 1.0 ton/ft^2 (95 kPa). Each load increment was applied to the plate when the settlement measurements stayed constant at least 2 h. Settlement measurements, recorded just before and after each load increment, were made by using three strain gauges fixed on the fan blades located with 120° apart from (Fig. 3). The tests were continued until a well-defined failure load was observed, or up to the plate went through 25 mm settlement.

2.3 Numerical Approach

A finite element package, Plaxis 2D Version 8, was used during the numerical analysis. Numerical studies were conducted using Mohr–Coulomb material model, which best represents the method applied in the experimental set-up. The material properties presented in Table 2 were used as input parameters in the Plaxis 2D analysis. Particular attention was paid to the selecting modulus of elasticity (E), which has been increased at every 0.5 m depth towards the bottom of model box (Fig. 4). The reasoning behind this assumption is due to the fact that stiffness of the lower layers in soil will have higher elasticity modulus since the lower levels are compacted more under the weight of the upper portion. The increase in density due to compaction will increase the stiffness of the soil, resulting in a higher elastic modulus of a soil which varies with loading condition, soil type, and packing, thereby reducing the settlement under loading [28, 29]. The E values used in the numerical studies were determined experimentally and justified by a standard textbook of Das and Sobhan [26]. The numerical analysis has been conducted by considering the axisymmetric loading geometry

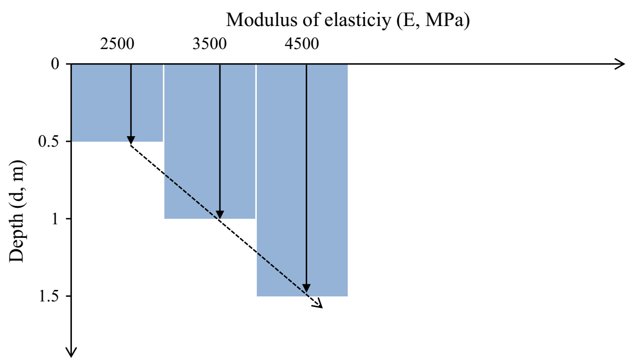


Fig. 4 The modulus of elasticity (E) variations in the Plaxis 2D

and using a fine mesh for the domain (Fig. 5). The axisymmetric boundary condition (BC) at $x = 0$, which constrains the displacements in horizontal direction, is applied on the left edge. Similarly, the right edge BC is the standard BC which constrains the horizontal displacements as well. The displacements on the base of the soil domain are constrained in both vertical and horizontal directions. As well known, 2-D axisymmetric models are the representations of 3-D domains with axisymmetric features. This kind of approach is often used in the finite element modelling when 3-D software capabilities are not available or when numerical simplifications are necessary due to a high computation demand in numerical analysis. Although the computational power need is not an issue for the present work, there is a rotational symmetry with respect to its central axis (cylindrical symmetry); this simple geometry and comparatively small punch depth of bearing plate would not require a 3-D FE model use. Plaxis 2D is a finite element software package and widely used for geotechnical engineering; it provides us with a 2-D model capability that can be applied for various geotechnical engineering analyses. We think that a 2-D axisymmetric model will be sufficient to represent the simple geometry without considering 3-D effects which could have been important, if the bearing plate were reaching a considerable punch depth to create finite strains. Then, it might cause a meaningful difference in state-of-stress with 2-D and 3-D models [30].

The elasticity modulus of soil layers has been determined experimentally and justified by Das and Sobhan [26]. However, the values close to the upper limits of the range given in Table 4 for different clay types are used since the CD construction waste materials are expected to contribute to the stiffness of the layers. For instance, the CD materials involving concrete pieces have already higher E values compared to the clean soils. The increased stiffness of CD–clay mixture has also been proven by Cabalar et al. [6]. The rigid foundation assumption is carried out for the FE analyses, as the steel plate has a multiple times higher stiffness (about 200 GPa) compared to the top soil layer where the maximum displacements take place.

3 Results and Discussion

3.1 Experimental Results

The maximum stress and the maximum settlement were governed by the properties of the samples placed in the model box. The stress applied and the associated average settlement readings for each load increment/decrement, as well as the ultimate bearing capacity values for each sample, have been listed in order to evaluate the impact of CD materials on the clay under loading. Table 3 gives the summary of the results in four tests reported here. The settlement readings in the clay only were found to have a sudden change. Considering a sharp increment in the settlement values indicating the early stage of failure in soils [36], the sample with clay only was the material which failed faster than the samples with CD materials. Then, the sample with 10% brick aggregates exhibited the earliest increment in settlement, during the loading phase. The observations showed that the amount of stress occurred on the samples with asphalt and concrete aggregates was found to be the highest for the same level of settlement (25 mm). Actually, the stress and displacement contours diminishing in magnitude when close to the boundaries in Fig. 5 confirm that the dimensions of the experimental set-up were sufficient to prevent the boundary effects on the simulations. Comparing the stress–settlement curves, it is seen that all types of CD materials improved the response of the compacted samples (Fig. 6). This response is consistent with the California bearing ratio (CBR) testing results for the same mixtures [23], in which the CBR performance of the samples increased. The load corresponding to the settlement of 25 mm is considered as an ultimate load for the plate [37–39]. Furthermore, the boundary effect was negligible, since the distance from plate edge to the model box was 2.83 times plate diameter [40]. From these points, the value of ultimate bearing capacity (q_u) and safe bearing capacity of soil for foundation can be determined. Equation (1) developed for the clayey soils by Terzaghi and Peck [37] implies that the q_u is not dependent on the size of plate used in the tests.

$$q_{u(F)} = q_{u(P)} \tag{1}$$

where $q_{u(F)}$ is the ultimate bearing capacity of a proposed foundation and $q_{u(P)}$ is the ultimate bearing capacity of the

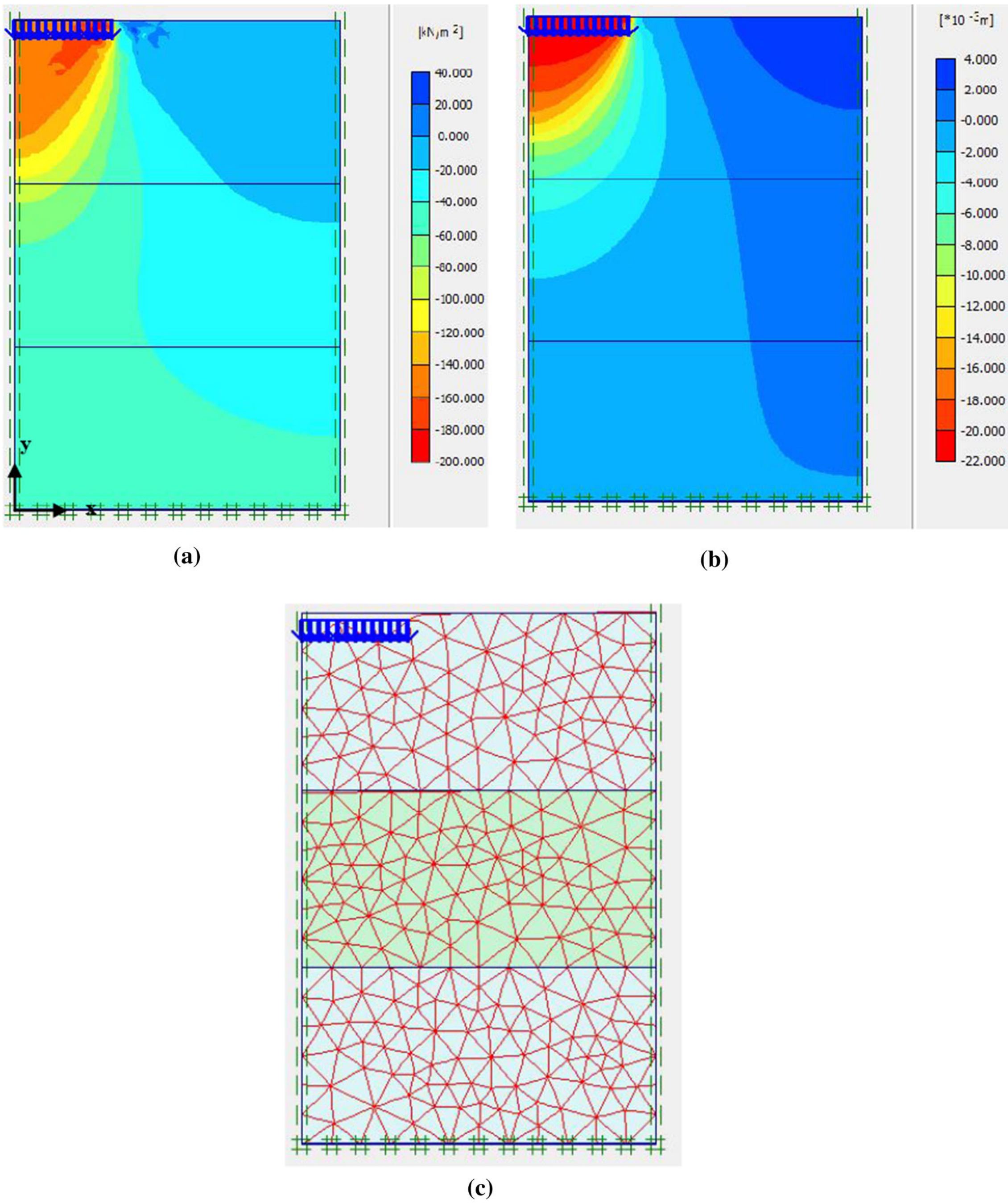


Fig. 5 Plaxis 2D outputs for applied vertical displacement $u_y = -2.162$ cm for the natural clay. **a** Total vertical stress contour plot, **b** vertical displacement contour plot, and **c** deformed mesh without any scaling factor

test plate. Hence, ultimate bearing capacity (q_u) values were found to be around 200 kPa for clay only, 300 kPa for clay with brick aggregates, and 350 kPa for clay with asphalt and concrete aggregates, respectively. Consequently, addition of CD materials improved significantly the response of soil, which is about 50% improvement for brick addition and about 75% improvement for addition of both asphalt and concrete aggregates. Similar observations were made by Consoli et al. [41]. The fact is that type of the additive materials in the soil may affect the soil fabric and structure, which leads to changes in stiffness, strength, and amount of settlement taken place in the soil [42]. Considering Fig. 7, which shows the variation of settlement as a function of time for the clay with different CD materials under 300 kN/m^2 stress, it was clearly noted that amount of settlement measured in the clay with concrete aggregates was about 5 mm, while the amount

Table 3 Average settlements for clay and clay with CD materials under plate loading

Load (kN)	Stress (kN/m^2)	Clay (mm)	Clay + 10% brick (mm)	Clay + 10% asphalt (mm)	Clay + 10% concrete (mm)
0.00	0.00	0.00	0.00	0.00	0.00
1.23	25.00	0.44	1.17	1.69	1.69
2.45	50.00	0.93	1.88	2.47	2.47
4.91	100.00	4.13	4.58	5.57	5.42
7.36	150.00	10.02	–	–	–
9.81	200.00	22.89	12.14	13.38	13.02
14.72	300.00	–	28.71	24.09	18.57
17.17	350.00	–	–	27.04	24.24
9.81	200.00	–	27.46	–	–
8.59	175.00	–	–	25.93	22.97
4.91	100.00	22.71	27.02	–	–
4.29	87.50	–	–	25.67	22.74
2.45	50.00	22.50	26.81	–	–
2.15	43.75	–	–	25.45	22.37
0.00	0.00	21.61	26.60	25.05	22.05

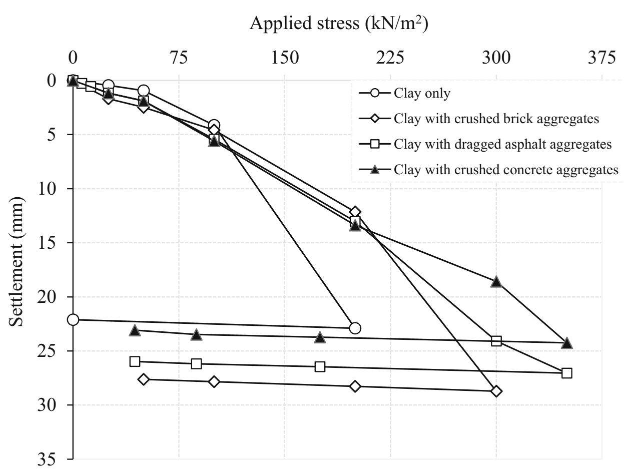


Fig. 6 Stress–settlement behaviour for plate loading tests

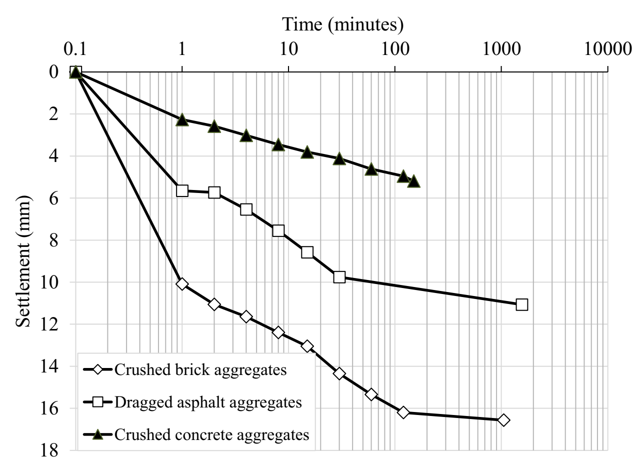


Fig. 7 Variation of time settlement for 300 kN/m^2 stress on clay with different CD materials

of settlement measured in the clay with asphalt aggregates was about 10 mm, and that with brick aggregates was found to be 16 mm at the end of 100 min loading. This suggests that basic properties of original CD materials including composition, crushing value, abrasion value, absorption, and bulk density were the main reason of various settlement findings. It is important to bear in mind that brick as a building material is composed of fire-hardened clay-bearing soil with a relatively low strength and sudden brittle rupture, while the concrete mixtures are designed in order to provide a strong compressive strength. However, dragged asphalt aggregates are bound together with bituminous materials, with a relatively ductile response under load [43–46].

Besides, stress created at the bottom of model box by the load on top varies depending on the type of the CD materials mixed with clay. Actually, for numerous problems of field applications, it is required to measure settlements due to induced stress variations. Analysis of these problems includes accurate measurements of initial stress states in the soil and of the changes in the stresses during loading stages. The methods employed to determine the bearing capacity of a foundation are limit equilibrium, limit analysis, and method of characteristics, in which the stresses causing failure are estimated and the applied stresses are compared with the failure stresses to define a safety factor against complete failure. Since the plate loading tests in the present study were performed using a circular plate with 30 cm diameter, it is an elemental procedure to adopt Boussinesq's approaches [47] developed for point loads to estimate the stress at certain depth beneath a circular area. Following the studies by Cummings [48] and Krynine [49], Kezdi [50] presented Eq. (2) to obtain stress under a loaded circular area, as follows:

$$\sigma_z = P\left[1 - \left(\frac{1}{1+\left(\frac{R}{z}\right)^2}\right)^{3/2}\right] \tag{2}$$

where R is the radius of the loaded area, z is the depth, and P is the stress at top.

Differences between the calculations using Eq. (2) and actual measurements using the soil pressure gauge located in the centre of the model box varied with respect to the type of samples tested. As the difference between calculation and measurement for the clay only was about 5%, it was found to be 20% for the clay with brick aggregates, 15% for the clay with asphalt aggregates, and 25% for the clay with concrete aggregates. The calculated values are lower than the actual measurements. The authors have considered that the differences between calculated and measured induced stress values increase as the heterogeneity in soil increases, such as increasing E values by depth. The stress data recorded in both the soil pressure gauges (gauge 1 placed at bottom-centre and gauge 2 placed at bottom-quarter), which had been commenced as soon as the first layer of sample was placed in the model box and continued up to the end of loading stage, in which a well-defined failure load was observed, are shown in Figs. 8 and 9. The bar charts illustrate the amount of stresses created at the bottom-centre and bottom-quarter of the model box. The same-coloured bars give information about how much geostatic stress (lower) and total stress (higher) were measured at the bottom of a specific sample. For example, the first pair of bars in Fig. 8 shows a geostatic stress of 22 kPa and a total stress of 40 kPa, respectively. Overall, it can be seen that geostatic stress as well as total stress values measured have a clear upward trend, while various CD materials at same content (10%) were added to the clay. This could be mainly attributed to the increase in both (i) maximum dry density and (ii) ultimate bearing capacity due to CD addition into the clay.

3.2 Numerical Results

In addition to the experimental studies, a numerical study was also carried out. Plaxis software was used to obtain the settlement values in each sample using a three different elasticity modules selected among the values shown in Table 4.

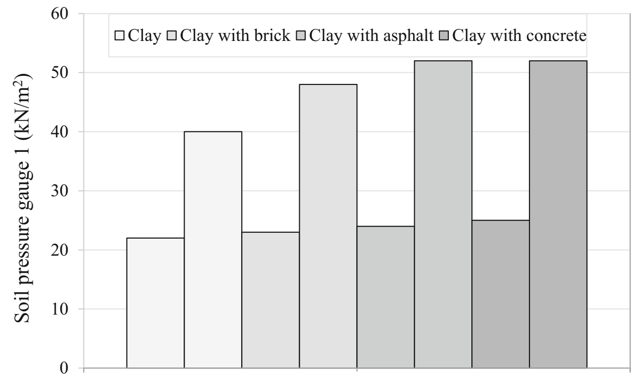


Fig. 8 Pressure cell transducer 1 reading before and after plate load test

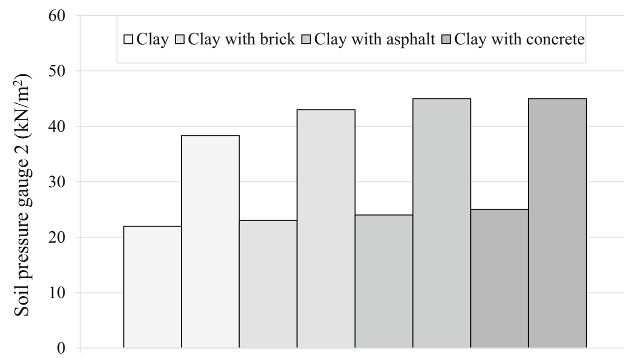


Fig. 9 Pressure cell transducer 2 reading before and after plate load test

Table 4 Typical values of the elasticity modulus [26]

Type of soil	Elasticity modulus, E (kN/m^2)
Soft clay	1800–3500
Hard clay	6000–14,000
Loose sand	10,000–28,000
Dense sand	35,000–70,000

Figure 10 compares the actual and predicted stress–settlement responses for the (a) clay only, (b) clay with 10% brick aggregates, (c) clay with 10% reclaimed asphalt aggregates, and (d) clay with 10% crushed concrete aggregates by using different E values selected for each 1/3 of the total thickness in the model box. As shown in Figs. 10 and 11, the results of the numerical analyses were found to be very close to those obtained from the plate loading test for all the mixture types. The elasticity module, selected as 2500 kN/m^2, 3500 kN/m^2, and 4500 kN/m^2 in the light of Das and Sobhan [26], captured the overall trend obtained in the experiments (Fig. 10 and Table 2). Similarly, Fig. 11 presents the correlations between the experimental and numerical results in order to show how strongly pairs of variables are related.

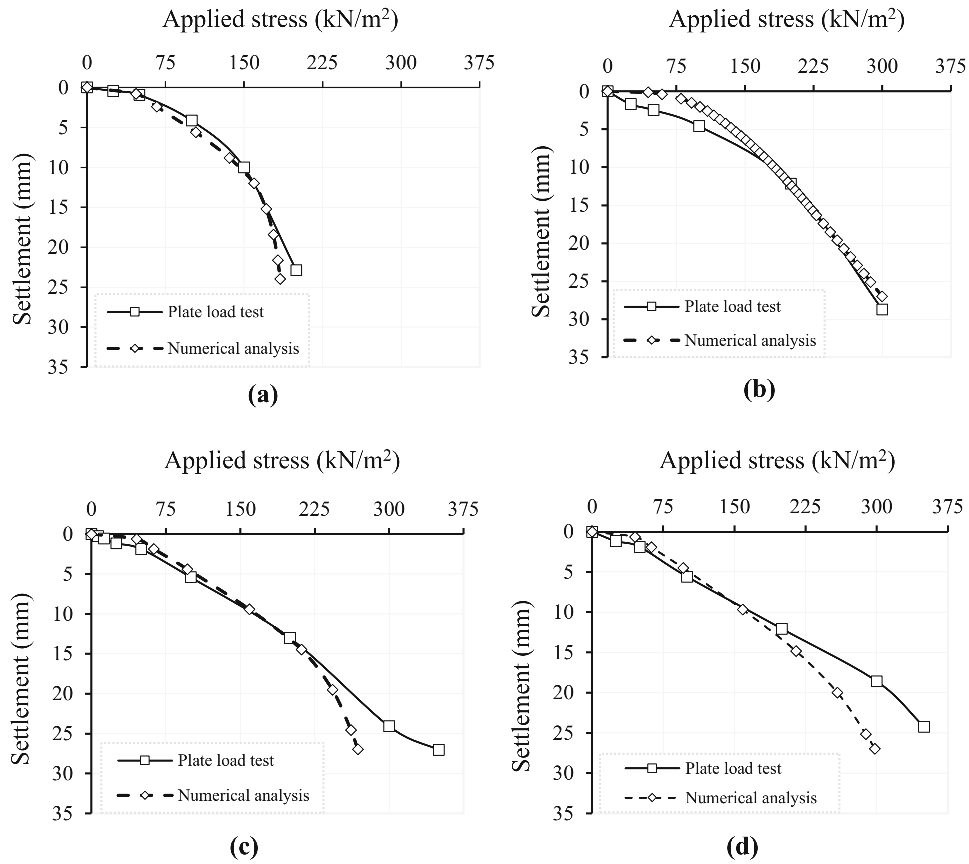


Fig. 10 Comparison of pressure–settlement responses between numerical and measured results for **a** clay only, **b** clay with 10% brick aggregates, **c** clay with 10% reclaimed asphalt aggregates, **d** clay with 10% crushed concrete aggregates

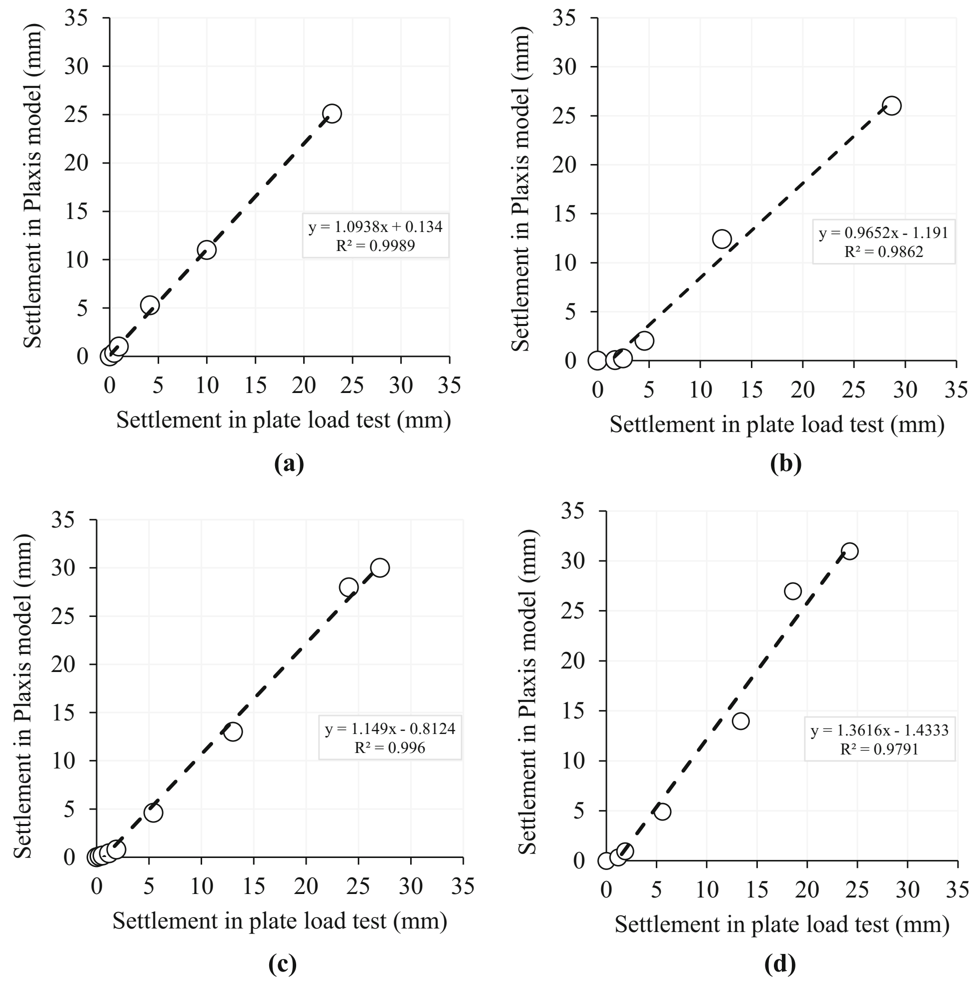
4 Conclusions

Utilization of construction and demolition (CD) materials in geotechnical engineering applications has increased recently in order to achieve sustainable waste management. However, accurate settlement and bearing capacity predictions for foundations on clay with different CD materials, which are difficult to assess, have not been extensively studied yet. The tests reported in this paper show three new facets of behaviour:

1. The results of the plate load tests performed in a large-scale model box indicate that the settlement predictions were differently affected by each type of CD materials. The sample with brick aggregates exhibited the lowest improvement, while the sample with crushed concrete aggregates provided the highest improvement in settlement observed during the tests.
2. Addition of CD materials has significantly improved the ultimate bearing capacity (q_u) of soil, which is about 50% improvement for brick addition and about 75% improvement for addition of both asphalt and concrete aggregates.
3. The finite element models were compared with the experimental results to achieve a more effective investigation. The results showed evidence that the consistency between the observed behaviour and the predicted ones by FE model yields relatively high correlation coefficients ($R^2 = 0.998$ for clay only, $R^2 = 0.986$ for clay with brick aggregates, $R^2 = 0.996$ for clay with asphalt aggregates, and $R^2 = 0.976$ for clay with concrete aggregates).

Evidently, the study was intended to serve as a reference for more advanced applications and to stimulate discussion and suggestions on the use of CD materials in geotechnical engineering applications (e.g. reinforcing problematic soils

Fig. 11 Relationship between numerical and measured settlement values on **a** clay only, **b** clay with 10% brick aggregates, **c** clay with 10% reclaimed asphalt aggregates, **d** clay with 10% crushed concrete aggregates



in road constructions, highway embankments, backfilling in retaining structures) in order to achieve sustainable waste management.

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