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Application of cement kiln dust for the stabilization of expansive soils in the region of Murcia (Spain)

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ABSTRACT

The increasing demand for the recovery of different waste materials, such as by-product materials from different industries, due to the necessity for reduction of carbon print emission, have found its usage in geotechnical engineering by its application for soil stabilization, among other applications. This study proposes the recovery of two cement kiln dust (CKD) types for the stabilization of an expansive clay with high swelling potential thus also classified as inadequate for its use as building material and discarded for construction of geotechnical structures. The mineralogical and chemical analysis of raw materials is performed for their identification prior to performance of different geotechnical laboratory tests, as well as on different mixtures of soil and CKD after the performance of tests. The study of compaction and deformational parameters for soil mixtures with different CKD content is presented to evaluate its compaction conditions, the reduction in swelling potential and improvement of deformational properties. It is confirmed that the reduction of index properties through limit liquid and plasticity index, reduction of swelling potential and reduction of compressibility by improvement of deformation properties can be achieved by the addition of 10 % of cement kiln dust of different mineralogical compositions.

1. Introduction

For environmental and economic reasons, in different transportation projects (roads, railways, ports, airports), it is advisable to reuse the soil at site itself, both for embankment construction as well as for base and subbase of infrastructures, considering fulfillment of requirements for the bearing capacity and stability under traffic loads. However, soils often do not have appropriate characteristics, thus requiring their stabilization and improvement by application of different binder material for enhancement of geotechnical properties to ensure stability, compressibility, swelling potential and resistance requirements for different geotechnical structures. The achievement of soil stabilization is traditionally performed by chemical additives such as lime and Portland cement, or alternatively by industrial by-products such as lime kiln dust, cement kiln dust, fly ash, etc., providing reduction of plasticity, swelling potential, compressibility and permeability, increase of shear strength, etc. [48].

In general, it is of great interest for soil stabilization, the application of locally available waste materials and industry by-products to reduce the quantity of materials for landfill deposition. Different industries generate millions of tons of various by-product materials that have limited use, and its recovery should be provided to reduce the quantity of materials often deposited as waste on landfills impacting negatively air, surface and groundwater, thus being necessary its recovery for enhancement of circular economy being one of the major environmental concerns nowadays [2]. According to [19], the bulk of the cement kiln dust (CKD) generated during cement manufacturing is recycled as a raw feed substitute in cement manufacturing and a portion of it is used as a secondary material for selected commercial applications that are dependent upon the chemical and physical characteristics of CKD, while the remaining CKD is often landfilled. Approximately 220 millions of tons of cement kiln dust (CKD) are collected from kilns during cement manufacturing that is the most widely used material in the construction industry, being estimated 0.06–0.07 tons of CKD generated to produce one ton of cement by Elbaz et al. (2017), and up to the quantity of 15–20 % of CKD generated during cement production [2,38,50]. CKD

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consists of fine-grained particles of clinker, unreacted and/or partially calcined raw materials generated during the high-temperature production of clinker. Main components of CKDs are the clinker phases of Portland cement, quartz, calcium oxide and calcium carbonate, and may also contain alkali sulfates, chloride and other minor components, whose proportions depend on the raw materials used, with relatively high alkaline pH value around 12 [46,51,54]. In general, it is considered that there is no average type of CKD, presenting compositional differences depending on the location of the cement factory, thus availability of different raw materials for clinker production encountered in the proximity of the factory should be considered, as well as the age of CKD deposition at stockpills, by that way varying each CKD in its chemical composition and physical properties, being necessary to study each CKD source for its application [40,46,51,54]. The recovery of CKD has been implemented for cement and mortar production, ceramic and brick manufacturing, asphalt concrete mix production, soil stabilization, etc. ([2,50,51]; etc.).

Previous use of CKD for the soil stabilization is given for different soils in [41]; and in particular for clays and silts ([20,26,54,33,37,48,4,5,27]), and sands [18,3], etc. The application of CKD provides the reduction of the cement application for soil stabilization, being CKD considered of the similar composition as Portland cement regarding high amount of oxides of calcium, silicon and aluminum with high pH alkaline value when mixed with water necessary for its effectiveness in the application for soil stabilization [40,54]. It was also studied for waste treatment of contaminated soils due to its absorptive quality and alkaline properties ([31,42]; etc.).

Previous evaluation of the effectiveness of the application of CKD to expansive clay stabilization by other researchers was performed by [58,41,46,35,49,55,44,45,24,56,1,40,28]; etc.

In general, previous studies of the application of CKD to different soils comprised the analysis of the improvement of geotechnical properties by the comparison of plasticity properties (liquid limit (LL), plastic limit (PL), plasticity index (PI)), compaction properties, strength properties evaluated by direct shear and/or triaxial tests, unconfined compressive strength (UCS) tests, California Bearing Ratio (CBR) test, durability tests (wetting-drying and freezing-thawing), of the untreated and treated samples with different dosages of CKD applied in the range between 2 % and 40 % to dry soil weight. Previous studies indicated improvements regarding reduction of plasticity properties, improvement of workability, reduction of swelling potential, increase of resistance parameters, increase in strength with curing time evaluated by UCS tests, enhancement of durability considering the reduction in weight loss, etc. Also, its chemical and mineralogical characterization has been done by X-ray diffraction, X-ray fluorescence, scanning electron microscope (SEM) technique, etc. In general, it is reported that the addition of CKD to highly expansive clay with high plasticity converts it to medium plasticity clay, thus enhancing swelling and mechanical strength making these clays stiffer with more brittle behavior and consequently higher bearing capacity strength [40].

Also, there are further studies on enhancement of geotechnical properties by addition of CKD and other stabilizing agents, for stabilization of expansive clays, such as CKD and lime [35,7]; CKD and RBI grade stabilizer composed of lime, silica and fibers [55,56]; CKD and fly ash [25]; for silts and clays by CKD and fly ash [27]; CKD and ground granulated blast slag [6]; CKD and natural pozzolans such as volcanic ash [33], etc.

The quantification of the reduction of the swelling potential is performed by different authors under different tests, either by measuring indirectly plasticity parameters or directly measuring swelling. Cui et al. [24] applied CKD content in the range of 2–18 % to expansive clayey soil to analyze the reduction of the swelling pressure. By the application of the maximum amount of CKD the swelling pressure is reduced to magnitude in order of 39 % of the untreated sample. Additionally, direct shear test and UCS test were performed. All tests presented a reduction in swelling pressure and an increase in resistance parameters; this effect being reduced with the application of the critical amount of CKD defined at 10 %. The free swelling potential of the expansive soil treated with CKD and CKD in combination with lime was studied, first determining its optimum content by pH test [16] resulting in 16 % of CKD and 14 % CKD + 3 % lime, and by the application of these amounts, the reduction of free swelling from 80 % to 0 % is confirmed on treated samples cured at 7 and 28 days [35]. CBR tests over treated soil by addition of CKD at dosages from 5 % to 30 % were performed, thus increasing the CBR from 20 up to 40 % and reducing swelling down to 0.5–1 % [44]. The reduction in swelling by free swell index test (ASTM D5890), expansion index test (ASTM D4829) and CBR test (ASTM D1883) on samples with range of dosages of CKD from 4 % to 14 %, reducing the initial high swelling potential, reaching negligible swelling at critical dosage of 10 % CKD was analyzed in [45].

In this work a natural clayey soil from the region of Murcia (South-East of Spain) is studied, which has a high expansive potential and low deformational and shear strength behavior. This clayey soil is usually discarded as inadequate for its further reuse for different geotechnical structures according to the classification given in [47], being defined the importance for its stabilization as a ground improvement method for the mitigation of risks for infrastructure construction in the region of Murcia [29]. It is considered that its characteristics under remolded state should be compared to the obtained ones by the addition of two types of cement kiln dust (CKD) with different dosages. Two different types of cement kiln dust (CKD) used in this study are obtained as a by-product of the cement industry, being considered as an economical and environmental alternative to the traditionally applied ones, i.e. lime and Portland cement. Also, the inadequate soil material, i.e. expansive clayey soil, that is usually not applicable for construction of different geotechnical structures being deposited on landfills, is considered for its reuse in this case study. The identification criteria for expansive nature are characterized indirectly by physical and mineralogical properties, as well as directly by the measurement of free swelling by oedometer tests. Different criteria available in literature are used for the classification of the degree of swelling potential, such as given in [32,57,21,30] etc.

The objective of this study is to provide an investigation for the application of two different CKDs for the soil stabilization of problematic expansive clay soils, by studying the modification of its mineralogical and physical properties, compaction conditions, swelling and deformational properties, etc. In this way the effectiveness of CKDs is investigated by comparison of treated and untreated clay samples to interpret the stabilization mechanism. This study could provide a solution for cost saving necessity for landfill deposition of the expansive soil material and CKD produced, through its valorization as a construction material. The stabilization of this clayey expansive soil by traditionally used lime and cement, and its comparison to the application of volcanic ash as binder is previously performed [39], concluding the application of 3–5 % of cement and lime for the reduction of swelling potential and improvement of geotechnical properties under short term conditions regarding compressibility and resistance characterization.

2. Materials and methods

The soil used in this research is the clay of the region of Murcia (South-East of Spain) obtained from an excavation of the tunnel for its application for the road construction (denominated T100 at Fig. 1). This material was oven dried and pulverized by an agate mortar for its further identification to establish its physical, chemical and geotechnical characteristics. The following tests are performed to define the natural material: sieve and laser analysis for gradation curve, plasticity parameters, specific gravity weight, Proctor test for compaction analysis and consolidation test. The performed tests over studied materials are summarized in Table 1, as well as the applied standard for each test.

Laser analysis to determine the grain size distribution curve of raw materials are performed according to [14] (see Fig. 7). According to the Unified Soil Classification System [11], natural soil is classified as

Fig. 1. Location of collected raw material.

Table 1
Identification, mineralogical and geotechnical tests performed on raw materials and soil mixtures [13,17].

Tests	Standard	Natural soil	Soil mixtures	CKDs
X-ray difraction	ASTM D4452–14	X	X	X
Oriented Aggregates		X		
X-ray fluorescence	ASTM D8064–16	X		X
pH	ASTM D4972–19 ASTM D6276–19	X	X	X
LOI	ASTM D7348–21	X		X
Laser granulometry analysis	ASTM D4464–15	X		X
Specific gravity	ASTM D854–14	X	X	X
Atterberg limits	ASTM D4318–17e1	X	X	
Compaction	ASTM D1557–09	X	X	
Oedometer test	ASTM D2435–11	X	X	

medium plasticity clay (CL). The plasticity parameters, i.e. liquid limit (LL), plastic limit (PL) and plasticity index (PI), determined by [12], correspond to 37 %, 15 % and 21, respectively (see Fig. 8). The natural clayey soil is classified as inadequate for its further reuse in construction engineering according to the Spanish Standard PG-3 [47] classification, due to its following characteristics: free swelling at 4.1 %; approximately 95 % of the material is silt/clay size; the liquid limit (LL) and the plasticity index (PI) are > 50 % and > 30, respectively. For that reason, stabilization is necessary for improvement of its geotechnical characteristics for its possible reuse, in this case by the application of two different cement kiln dusts (CKDs) as an alternative to traditionally used lime and cement. These two CKDs, proceeding from two cement factories, located in different Spanish regions, one of them in a coast region, an area more proximate (< 100 km away) to the extraction area of the studied soil for its improvement (Fig. 1), thus proceeding from different raw materials, and having different chemical and mineralogical composition.

Table 2 presents the nomenclature of the samples used in the laboratory tests, that will further be used throughout the text for its simplicity, being T100 the initial symbol for soil, CKD for cement kiln dust in general, CKDC for cement kiln dust proceeding from factory in Carboneras (Almería) and CKDVS for cement kiln dust proceeding from factory in Villaluenga de Sagra (Toledo) (see Fig. 1 for location of collected raw materials). The percentages of CKDs indicated correspond to the dry weight of the soil sample, thus soil mixtures being denominated as T95CKDVS5, T90CKDVS10, T95CKDC5, T90CKDC10, and T85CKDC15.

The chemical and mineralogical composition of natural soil and two

Table 2
Definition of abbreviation of samples of remolded soil mixtures used through the study.

Denomination	Natural clay (%)	Additive (%)	
		CKDVS	CKDC
T100	100 %	-	-
T95CKDVS5	95 %	5	-
T90CKDVS10	90 %	10	-
T95CKDC5	95 %	-	5
T90CKDC10	90 %	-	10
T85CKDC15	85 %	-	15
CKDVS	-	100	-
CKDC	-	-	100

different CKDs are performed through X-ray diffraction (XRD) and X-ray fluorescence (XRF) test by the methods further described. The results of XRD and XRF are summarized in Table 3 and Table 5. In the natural remolded clay sample (T100), due to the high content of clay minerals in the majority crystalline phase (see Table 3), the identification of these by oriented aggregates (AO) was necessary. The AO diffractograms are represented in Fig. 5 and the quantification of clay minerals in Table 4.

For mineralogical identification, XRD by polycrystalline powder method is applied. Diffraction patterns have been obtained in a BRUKER D8 Advance diffractometer using CuKα radiation, in an angular range of 2θ from 10 to 60º, with a step size of 0.02º and a time per step of 1 s. They have been identified with the EVA DIFFRACplus 13.0 program by comparison with the PDF2 (Powder Diffraction File) database of the ICDD (International Center for Diffraction Data). The relative proportions of each crystalline phase were determined by following the [22] and software EVA of Bruker. The experimental error of this method is + /- 5 %.

The chemical analysis has been determined by XRF in a BRUKER S2 Ranger for major and minor elements in pellet. The chemical analysis is expressed as % by weight (wt%) of oxides. The "Loss On Ignition" (LOI), has been previously determined in all cases for the fitting of the chemical analysis.

The pH is measured with a pH-Meter Crison Basic 20, according to [15], being the evaluation of the application of different CKDs for the soil stabilization performed according to [16].

For specimen preparation of soil mixtures, dry materials were mixed thoroughly manually until uniform color was observed, prior to addition of water for further mixing for 10 min, after which leaving soil mixture during 45 min of rest time within a plastic bag before the molding for the performance of plasticity, compaction and oedometer tests [36].

The compaction tests are performed under modified energy [9] to determine conditions of compaction regarding optimum moisture content and dry specific unit weight of naturally remolded clay and different mixtures of natural remolded clay with CKDs. For this test, a soil sample with specific moisture content is compacted in five layers in the mold by modified energy weight, this procedure being repeated for different moisture content for each sample, both remolded clay and remolded soil mixtures with different dosages of CKDs, to determine correlation between unit specific dry weight and optimum moisture content.

The oedometer tests are performed according to [10] on specimens of both remolded natural clay material and remolded soil mixtures in circular mold with 70 mm of internal diameter and 20 mm height. All specimens for the oedometer analysis were compacted in the consolidometer ring under the same compaction energy as the obtained one by compaction test on the natural remolded clay soil to have the comparable value of the moisture content and specific dry weight for all samples. The specimens were placed between porous stones to permit drainage at both sides of the specimen, and after its preparation, were inundated by distilled water. At the beginning, the free swelling of all specimens is determined, being observed the stabilization of swelling after 3 days of the test. After this stage, the conventional oedometer test is performed under gradual loading and unloading stages (eight loading

Table 3
Quantification of mineral phases by XRD of the natural clay sample, two CKDs used and different soil mixtures.

Powder Diffraction File (PDF-ICDD)	Crystalline phases	Formula	T100	CKDC	CKDVS	T95CKDC5	T90CKDC10	T85CKDC15	T95CKDVS5	T90CKDVS10
00–046–1045	Quartz	SiO_2	28	-	6	21	27	24	27	20
01–076–0926	Plagioclase	$(NaCa)Al_2Si_2O_8$	5	-	-	6	3	5	5	6
01–082–0576	Clay minerals	$KAl_2(AlSi_3O_{10})(OH)_2$	26	-	10	33	30	25	28	26
01–086–0402	Hatrurite/Alite	Ca_3SiO_5 / C_3S	-	5	6	-	-	-	-	-
01–083–0461	Larnite/Belite	$Ca_2(SiO_4)$ / C_2S	-	6	4	-	-	-	-	-
00–030–0311	Brownmillerite/ Ferrite	$Ca_2(Al,Fe)2O_5$ / C_4AF	-	2	4	-	-	-	-	-
01–072–0916	Anhydrite	$CaSO_4$	-	6	-	-	-	-	-	-
00–048–1882	Mayenite	$Ca_{12}Al_{14}O_{33}$	-	8	-	-	-	-	-	-
00–037–1497	Lime	CaO	-	2	-	-	-	-	-	-
01–072–1214	Calcite	$CaCO_3$	35	-	54	38	38	46	39	47
00–036–0426	Dolomite	$CaMg(CO_3)_2$	6	-	-	2	2	-	1	1
01–074–1742	Aphtitalite	$(K,Na)_3Na(SO_4)_2$	-	8	-	-	-	-	-	-
00–005–0628	Halite	NaCl	-	15	-	-	-	-	-	-
01–073–0380	Silvite	KCl	-	48	16	-	-	-	-	-

Table 4
Quantification of clay minerals from sample T100.

Clay minerals	Chemical formula	Sample T100 (%)
Mica-Illite (Mica-Ilt)	$K(Mg,Fe)_2(Si_3Al)O_{10}(OH,F)_2$	61.6
Smectite (Sm)	$(Na,Ca)Al_4(Si,Al)_8O_{20}(OH)_4\cdot H_2O$	36.1
Chlorite (Chl)	$(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8$	2.3

stages under vertical compressive load 20, 40, 80, 150, 300, 600, 1000 and 1500 kPa, and three unloading steps at 600, 80 and 10kPa). All stages were maintained for 24 h, except the last unloading stage for 48 h. The free swelling, sample deformation and deformational modulus are determined to compare the influence of two different CKDs on the properties of the natural remolded clay.

The sample preparation for XRD analysis of soil mixtures is performed on the material extracted from oedometer specimens, once splitted in four parts in two orthogonal directions over the specimen height of the central point by that way extracting approximately 1 g of the material over the fractured surface.

For the preparation of oriented aggregates (OA) from natural soil, an additional fraction of the original sample (0.1–0.5 g) was taken and dispersed in distilled water. Subsequently, the fraction smaller than 0.5 μm is separated and extracted according to Stokes' law and pipetting onto three glass slides to prepare them in three different ways: (1) oriented aggregates without any further treatment (air-drying, AD), (2) oriented aggregates treated with ethylene glycol for 24 h (EG) and (3) oriented aggregates heated at 550 °C for 90 min (heat treatment, TT). This allowed more definitive identification of the expandable lattice clay minerals present. In addition, powdered randomly oriented clay separates were prepared and studied with a 0.01° 2θ step size, a count time of 120 s per step size, and a count time of 3 s per step between 57 and 64° 2θ to measure 060 reflections following [43].

Throughout the study performed, the results of the laboratory tests that corroborate the information cited above are presented and it shows the improvement of different geotechnical properties by the addition of two cement kiln dust (CKD) in different proportions as stabilizers for the reduction of swelling potential and compressibility of the natural clay material. Following Fig. 2 shows the aspect of the raw materials used in this study.

3. Results and discussion

The results are presented following the order of different tests summarized in Table 1.

3.1. Chemical and mineralogical characterization

Fig. 3 show the diffraction patterns of all raw materials, i.e., natural clay sample identified as T100, and two cement kiln dusts (CKDVS and CKDC) used in this study, while Fig. 4 summarizes the comparison of diffraction patterns obtained for different soil mixtures (T95CKDVS5, T90CKDVS10, T85CKDVS15, T95CKDC5, T90CKDC10) to the natural soil (T100). Table 3 summarizes the quantification of crystalline phases of raw materials and soil mixtures.

The main crystalline phases identified and presented in raw materials (Fig. 3) are: quartz (1), calcite (2), dolomite (3), sylvite (4), halite (5), aphthitalite (6), brownmillerite/ferrite (7), hatrurite/alite (8), larnite/belite (9), clay minerals (10), plagioclase (11), and anhydrite (12).

Main crystalline phases identified in soil mixtures are (Fig. 4) are quartz (1), calcite (2), dolomite (3), clay minerals (10), and plagioclase (11).

According to Table 3 in the natural remolded clay sample (T100), a major part of crystalline phases are clay minerals, quartz and calcite, corresponding to 26, 28 and 35 %, respectively. Due to the high content of clay minerals, the identification of these is performed using oriented aggregates method (AO). Fig. 5 shows the diffractograms of untreated (a), ethylene glycol solved (b) and 550 °C heated (c) oriented aggregates. The quantification of clay minerals in natural soil is given in Table 4 being the most abundant phases of the clay fraction in the T100

Fig. 2. Raw materials applied in this study: (a) natural expansive soil, (b) cement kiln dust from the factory in Carboneras (CKDC), (c) cement kiln dust from the factory in Villaluenga de Sagra (CKDVS).

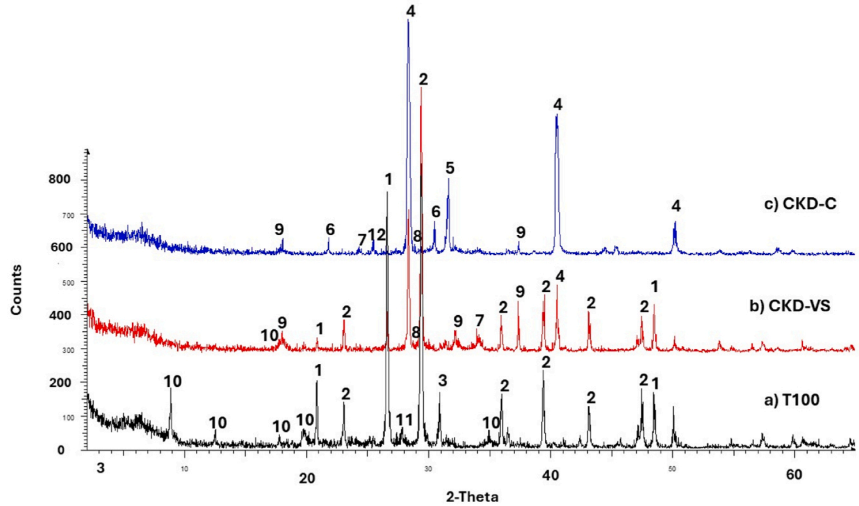

Fig. 3. Identified diffraction pattern of raw materials: (a) T100, (b) CKDVS, (c) CKDC.

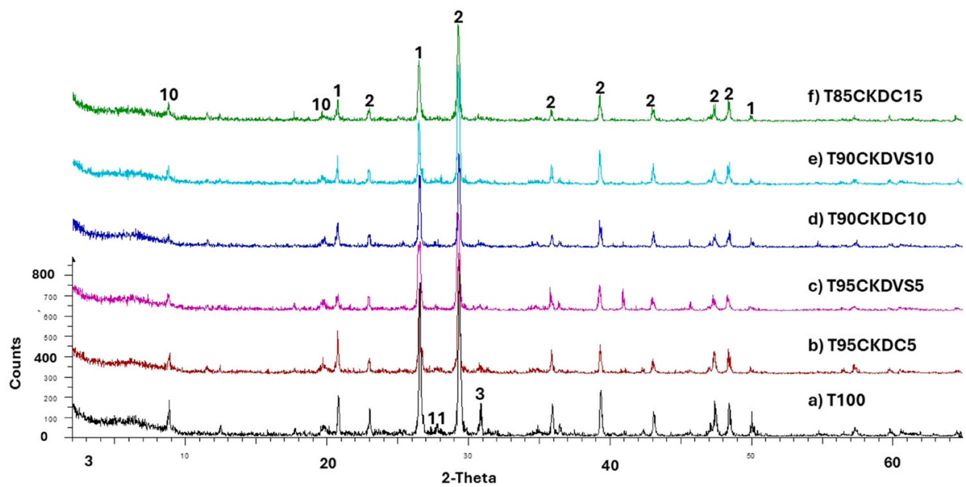

Fig. 4. Identified diffraction pattern of soil and soil mixtures: (a) T100, (b) T95CKDC5, (c) T95CKDVS5, (d) T90CKDC10, (e) T90CKDVS10, (f) T85CKDC15.

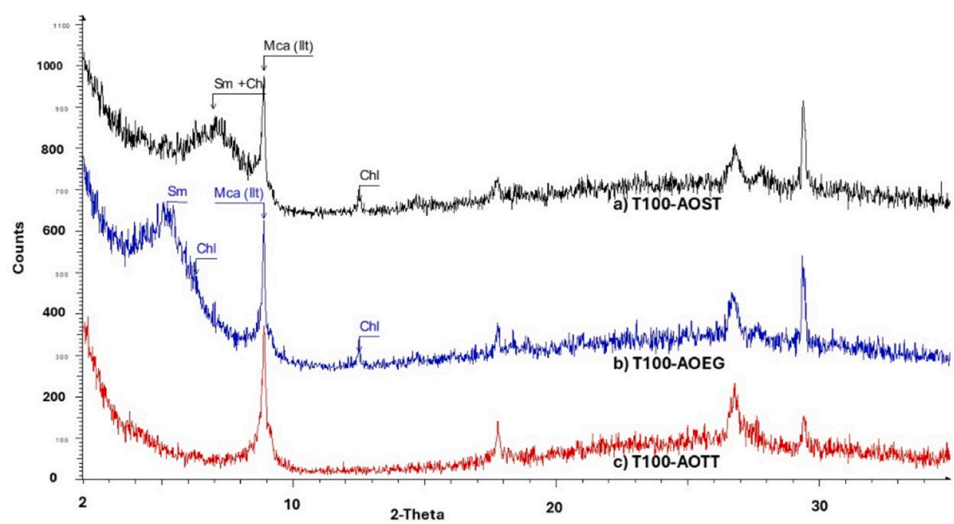

Fig. 5. Diffractograms of oriented aggregates of the sample T100. a) AOST Untreated; b) AOEG Glycolated; c) AOTT Heat treatment.

sample Mica-Illite and Smectite.

The XRF chemical analysis of the raw materials (soil and two CKDs) is shown in Table 5.

The major chemical elements present in the natural soil are silicon, calcium, aluminum, iron, magnesium, potassium, sulfur and sodium, while calcium, chlorine, potassium, sodium, sulfur and iron are found in CKDs in different concentrations in each CKD, depending on its origin and mineralogical composition.

The CKDVS contains 54 % $CaCO_3$, which is less effective compared to CaO still releasing Ca^{2+} that reduces the expansion. The CKDC used is characterized by containing 48 % KCl, which would cause: the K+ (potassium ion) in KCl displaces cations such as Na^+ (sodium) or Ca^{2+} (calcium) at the clay exchange sites; the reduction of the diffuse double layer, and by increasing the concentration of electrolytes (K^+ and Cl^-) in the pore water, the diffuse double layer surrounding the clay particles is compressed, therefore decreasing expansion and reduction of LL and PI due to the reduction in the capacity of the clay to absorb water, decreasing plasticity.

The definition of hydration modulus as the ratio of the CaO amount to the total sum of SiO_2, Al_2O_3 and Fe_2O_3 is introduced in studies defining a minimum value of 1.7 necessary for the effective stabilization reaction (Carlson, 2011). In this case, for the CKDC and CKDVS, the estimated value of hydrated modulus is 4.8 and 3.6, respectively, being these values greater than reported range of values from 1.7 to 3.3 for a great number of studied CKDs [20,41,53].

3.2. pH

The pH of natural remolded sample, different CKDs and different soil mixes are measured according to [15]. The results of pH determination test and its evaluation for soil stabilization are performed according to [16] to obtain the indication of the interaction of soil and CKD for different mix proportions for possible increase in strength characteristics of the soil [35,41,54]. The summary is given in Fig. 6, being values of pH for CKDVS estimated at 12.54 and for CKDC at 12.45, and the value of pH of the natural soil estimated at 9.16, classified as alkaline soil. In general, considering that CKD is highly alkaline by-product, that can successfully be used for soil stabilization, small quantity is required to provide pH value of 12.4 necessary for soil stabilization according to [16], the value of pH is elevated significantly for the pozzolanic reaction to occur (Fig. 6). It is considered that 10 % of both CKDs when mixed with this soil is enough to reach the value of 12.4, by that way characterized as highly alkaline pH indicating effectiveness of both types of CKD for the stabilization of this swelling clayey soil.

Table 5
XRF chemical analysis of raw materials: the natural clay sample and two CKDs.

Formula	T100 Conc. (%)	CKDC Conc. (%)	CKDVS Conc. (%)
Na_2O	1.09	1.84	< 0.01
MgO	2.82	-	0.97
Al_2O_3	9.83	0.32	2.22
SiO_2	29.30	1.42	5.95
P_2O_5	< 0.01	0.83	0.32
SO_3	1.10	7.83	2.53
Cl	0.35	21.20	9.23
K_2O	1.87	16.40	7.85
CaO	27.00	7.87	33.00
TiO_2	0.40	-	0.08
V_2O_5	< 0.01	-	-
Cr_2O3	< 0.01	-	-
MnO	0.03	-	0.01
Fe_2O_3	3.22	0.27	1.05
NiO	< 0.01	-	-
CuO	< 0.01	0.12	< 0.01
ZnO	< 0.01	0.08	0.01
Ga_2O_3	< 0.01	-	< 0.01
As_2O3	< 0.01	0.06	-
Br	< 0.01	0.15	0.11
Rb_2O	< 0.01	0.09	0.06
SrO	0.06	< 0.01	0.04
Y_2O_3	< 0.01	-	-
ZrO_2	0.02	< 0.01	< 0.01
Nb_2O_5	< 0.01	-	-
MoO_3	-	< 0.01	-
Ag_2O	-	-	-
CdO	-	0.01	-
SnO_2	< 0.01	< 0.01	< 0.01
Cs_2O	-	-	0.02
PbO	< 0.01	0.58	0.02
LOI	22.90	40.96	36.50

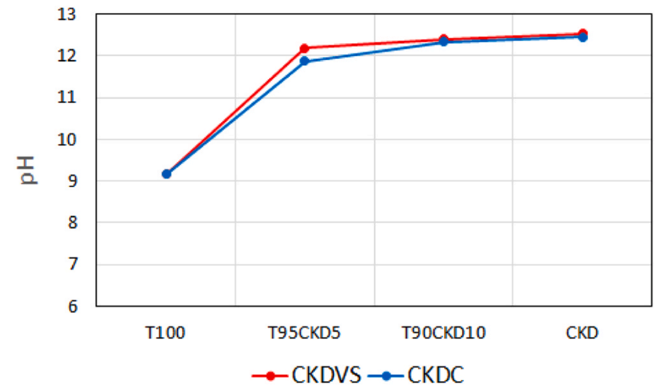

Fig. 6. pH summary for T100, T95CKD5, T90CKD10, CKDs.

3.3. Gradation curve

Fig. 7 summarizes gradation curves obtained for the natural clay soil and the two different cement kiln dust (CKDC and CKDVS) used in this study. The gradation distribution curve of the natural soil material analyzed, denominated T100, obtained by the preparation of sample by pulverization in electric device simulating agata mortar, consisting of 76 % of fines content (passing through sieve 0.063 mm). Also, there are two gradation curves for two analyzed and applied CKDs for soil stabilization, presenting 82 and 96 % of fines content and having mean particle size of about 30 and 10 μm, for CKDC and CKDVS, respectively, thus can be considered as fine-grained material of silty size grains according to its gradation curve.

3.4. Atterberg limits

Fig. 8 shows the plasticity chart and the summary of obtained values of liquid limit (LL), plastic limit (PL) and plasticity index (PI) obtained for different soil mixtures for its comparison to the remolded natural soil sample, carried out immediately after soil mixing. It can be observed, as expected, that the rapid improvement of soil physical properties under short-term conditions, i.e. that the reduction of LL and PI, and the increase of PL is higher with increasing addition of CKD, thus reducing expansion properties of the natural soil. This modification allows considering the enhancement of Atterberg limits, which provides an improvement in improving workability due to the reduction of absorbed water and decrease of PI. The decrease of LL is quantified in the range of 2.5–20 %, the increase of PL varies from 33 % to 50 %, and the reduction in PI results in 30–78 % in comparison to the natural soil. A greater reduction of plastic characteristics is obtained for CKDC. Considering the decrease in PI, the enhancement of conditions of the workability of soils during construction can be concluded. This plasticity index properties decrease is due to chemical reaction of calcium hydroxide with the soil, causing clay soil grains to flocculate into granular material thus reducing soil plasticity and consequently reducing swelling potential of the expansive clay material [20,4,40,45,5,54]. Additionally, according to activity index (AI) defined as relation between plasticity index (PI)

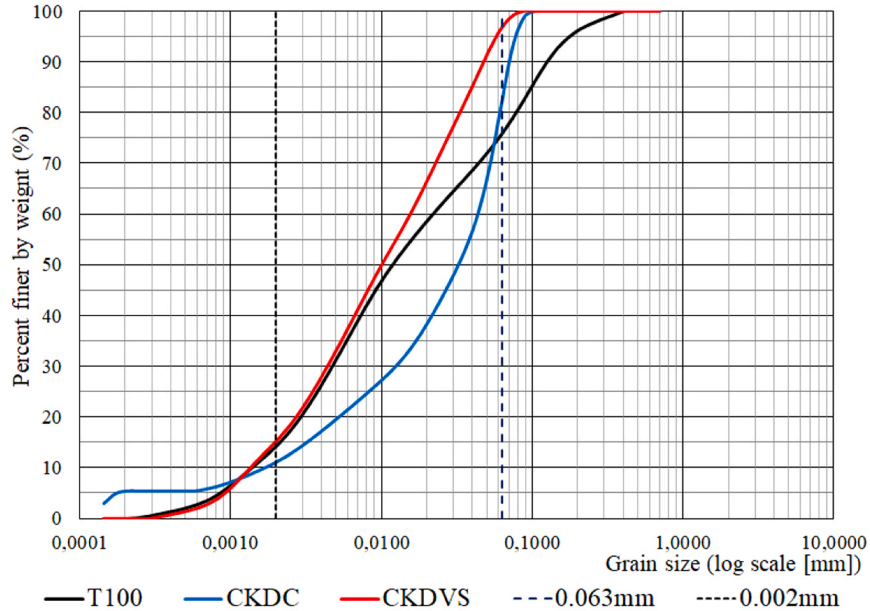

Fig. 7. Grain size distribution curve of raw materials (T100, CKDC, CKDVS).

and % of clay content [52], corresponding to 1.65, it is also defined as active clay being AI> 1.25 representing a clay with high volume potential change.

According to the indirect classification of swelling potential according to values of LL and PI (see Table 6), the natural soil is defined as with medium swelling potential, while the soil mixtures, having PI lower than 15 %, are defined as with low swelling potential [32,21,30]. Nevertheless, the reduction in LL and PI as an indirect measure of the swelling potential in this case is confirmed by the direct measurement of the swelling potential in oedometer test performed and further presented in Section 3.7.

3.5. Specific gravity weight

Fig. 9 summarizes values of specific weight obtained by the pycnometer bottle water method [8] for natural soil, two types of cement kiln dust and different soil mixtures. The Gs value of the two CKDs are the following: CKDVS similar to the one of natural soil and that of CKDC (2.98) like that of Portland cement, thus soil mixtures show little variation due to the low dosages of CKD introduced in the soil mixtures.

3.6. Compaction tests

The optimum water content and maximum dry density of the soil and soil mixtures are performed through the modified Proctor test [9] for the natural remolded soil as well as for all remolded soil mixtures. Fig. 10 summarizes the compaction test curves. It also summarizes zero void, full saturation curve based on results of specific gravity for the untreated clay material. Considering that there are not great variations in the value of G_s for treated samples, the saturation curves are not presented for soil mixtures, the difference among them considered negligible.

In general, the values of the maximum dry specific weight and optimum moisture content of the natural remolded soil without additives do not have great differences in comparison to the same material stabilized by the addition of Portland cement. In soils stabilized with Portland cement, the flocculating effect of cement reduces the optimum moisture content and reduces maximum specific weight, while on the other hand, considering that the specific weight of cement is greater, tends to increase its density, and depending on the nature of the soil one of these two effects will predominate. For clayey soil types, in general, the variation should be negligible both in the value of maximum specific dry weight as well as in optimum moisture content [34].

In this case, considering differences in chemical composition of both CKDs in comparison to the ordinary Portland cement, there are differences in the variation of the compaction curve. For the addition of CKDVS, that has approximately the same specific gravity value as of natural soil, it is observed that the maximum dry density is slightly lower than the original remolded soil maintaining approximately the same optimum moisture content. On the other hand, the addition of CKDC, that has high specific gravity value as is the case of ordinary cement, the compaction curve is slightly displaced to the left with respect to the original soil, maintaining approximately the same maximum specific dry weight and slightly reducing the optimum moisture content.

Different studies of the application of CKD for compaction tests show different results regarding workability evaluated by compaction curves, that depend greatly on the chemical composition of CKD, its specific weight, etc. Similar results to ones in this study are observed in [41,54,20] etc.

3.7. Oedometer tests

The principal objective of this study is the evaluation of the reduction of the expansive potential of soil by adding different CKDs (see Fig. 11), so the free swelling potential is directly measured in the oedometer test. All specimens of different mixtures are prepared under the same compaction conditions as defined for the natural remolded soil (T100) regarding its optimum moisture content (see Fig. 10). The summary of the analysis of the swelling potential under different criteria for the classification of swelling potential according to different authors is presented in Table 6, observing the reduction from high plasticity clay to low plasticity clay that would be acceptable for the application under different standards. T100 presents high expansive potential according to different classifications, being reduced to medium or low degrees depending on the amount of different CKD applied. The greater reduction of the swelling potential is observed with the increase of applied CKDs indicating its appropriate use.

It can be concluded that the greater reduction of expansive potential is obtained with the gradual increase of the CKD applied (see Fig. 11), being greater the decrease for the application of CKDC. The swelling potential of T100 estimated at 4.1 % is reduced to 2.5 and 0.5 % for the addition of 5 and 10 % of CKDVS respectively, while for the addition of CKDC the swelling potential is estimated at 1, 0.25 and 0.1 % for the

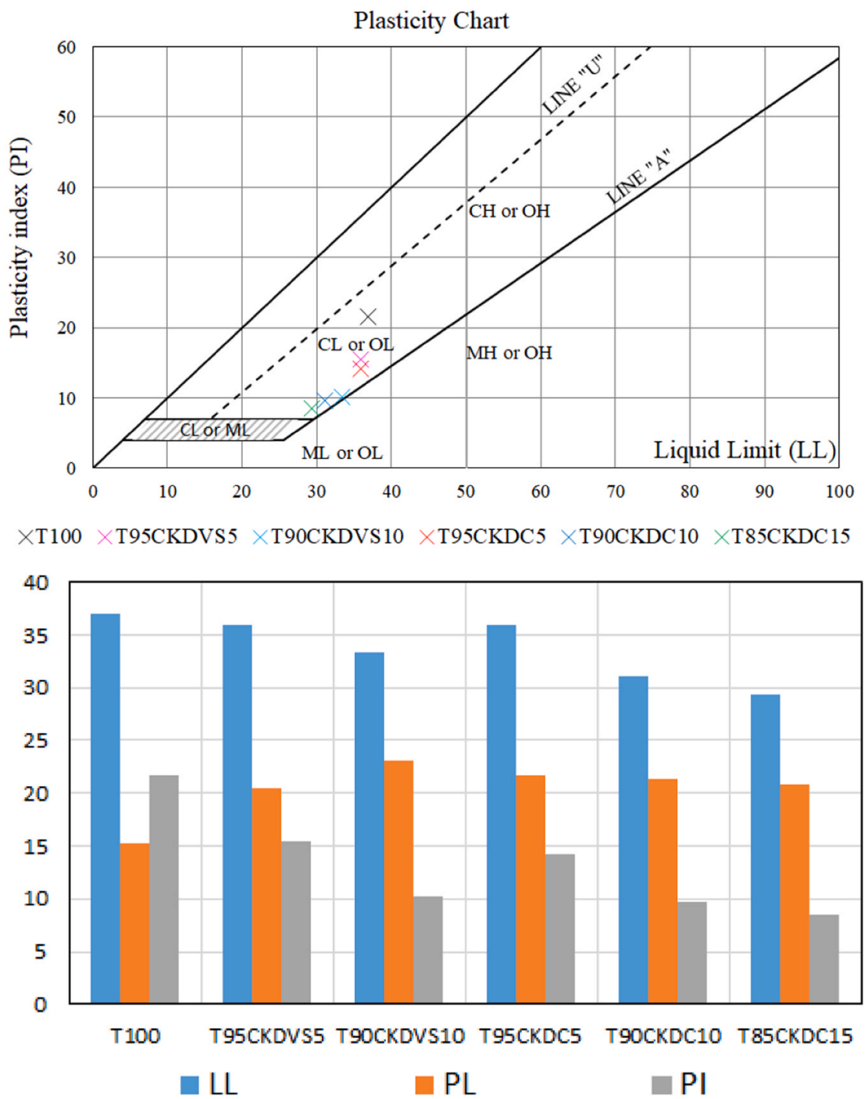

Fig. 8. (a) Plasticity chart for different samples, (b) summary of LL, PL, PI.

Table 6
Classification of swelling potential by direct measurement in oedometer test.

Denomination	Classification of swelling potential		
	Vijayvergiya and Ghazzaly [57]	Cuellar [23]	Chen [21]
T100	H	M	H
T95CKDVS5	M	M	M
T90CKDVS10	L	L	L
T95CKDC5	M	L	M
T90CKDC10	L	L	L
T85CKDC15	L	L	L

* H=high; M=medium; L=low.

addition of 5, 10 and 15 % of CKDC respectively. Similar results regarding reduction of free swelling potential are observed in [35,45] etc.

Fig. 12 presents the relation between specimen vertical deformation with time by the comparison of different consolidation stages for the range of studied soil mixtures, representing the loading and unloading stages after resetting the free swelling stage. It can be observed that the gradual decrease of specimen deformations, the reduction in the total sample deformation and increase in deformation modulus with the increase of the CKD amount. The greater reduction in specimen deformation is obtained for the application of CKDC having greater specific weight. The unloading stage for soil mixture samples shows a lower range of recovery of the deformation for CKDC.

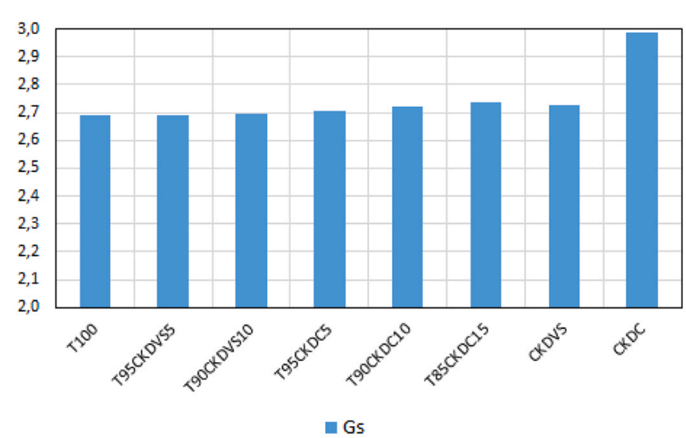

Fig. 9. Specific weight for raw materials and the soil mixtures.

Fig. 13 presents results of oedometer tests by the relation of sample deformation and applied load, being observed the reduction of the

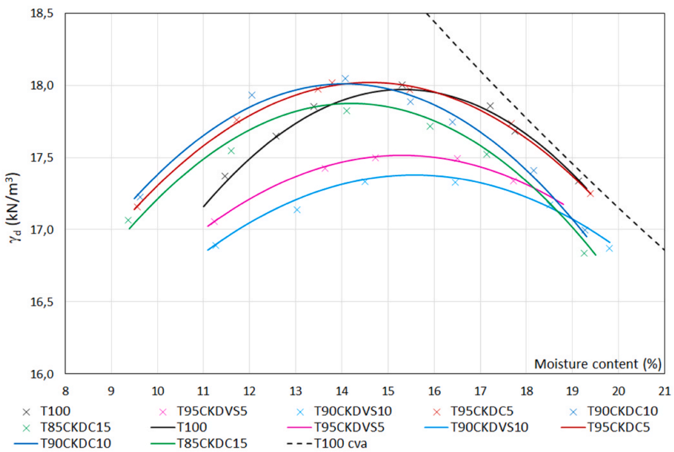

Fig. 10. Compaction tests for different soil mixtures.

sample deformation with the addition of CKDs. The greater the dosage of each CKD, the greater the settlement reduction of the specimen. The greater reduction of the settlement is observed for the CKDC that has greater G_s value.

Fig. 14 shows the variation of the deformation modulus under loading stages of the oedometer tests for the remolded soil specimen and different soil mixtures, as well as the summary of deformation modulus under final loading stage and unloading modules. It can be observed that the increase in deformation modulus both under loading and unloading is achieved with the increase of the amount of the applied CKD, being greater increase observed for CKDC having greater G_s. It also summarizes the compression (Cc) and swelling (Cs) index being observed the decrease of parameters with the increase of the applied amount of stabilizer.

4. Conclusions

Based on the present study, regarding the effect of the application of two different cement kiln dust (CKD) on geotechnical properties of the stabilized expansive clay, the following conclusions can be summarized:

- The mineralogical composition of the natural clayey soil of this study from the region of Murcia is 35 % calcite, 28 % quartz, 16 % mica-illite, 9.5 % smectite, 6 % dolomite, 5 % plagioclase, and 0.5 % chlorite. The geotechnical characterization of this soil defines it as an inadequate soil for its further reuse in construction engineering according to the Spanish Standard PG-3 (2019) classification. The recovery of this swelling soil is proposed.
- In general, the use of CKDs for soil improvement is possible provided that a mineralogical and chemical characterization of the soil and CKD is carried out or that this information is included in the marketing of CKDs besides necessary geotechnical characterization of the application to soil stabilization. The solution for the recovery and reutilization of CKDs is provided to reduce their deposition in landfills.
- The use of CKDs is favorable compared to the use of cement because of their lower cost and for their recovery being a by-product of the cement industry. In general, there is no average type of CKD, depending on its chemical and physical composition on the availability of different raw materials for clinker production close to the location of the cement factory, being necessary to study each CKD source for its application.
- In this case, the stabilized soil presents lower content of fines in comparison to the natural one, due to particle flocculation considering high content of CaO causing a modification in clay mineral thus producing more sandy material, and by that way resulting in lower liquid limit and plasticity index of the soil mix, as well as lower swelling potential and compressibility necessary for better conditions regarding support capacity.

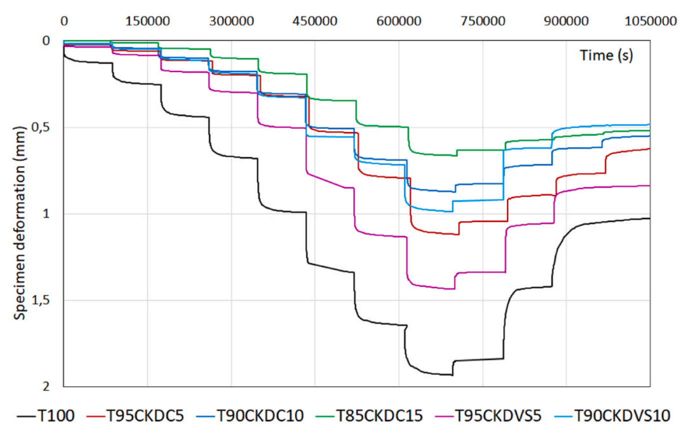

Fig. 12. Specimen deformation vs time for different soil mixtures.

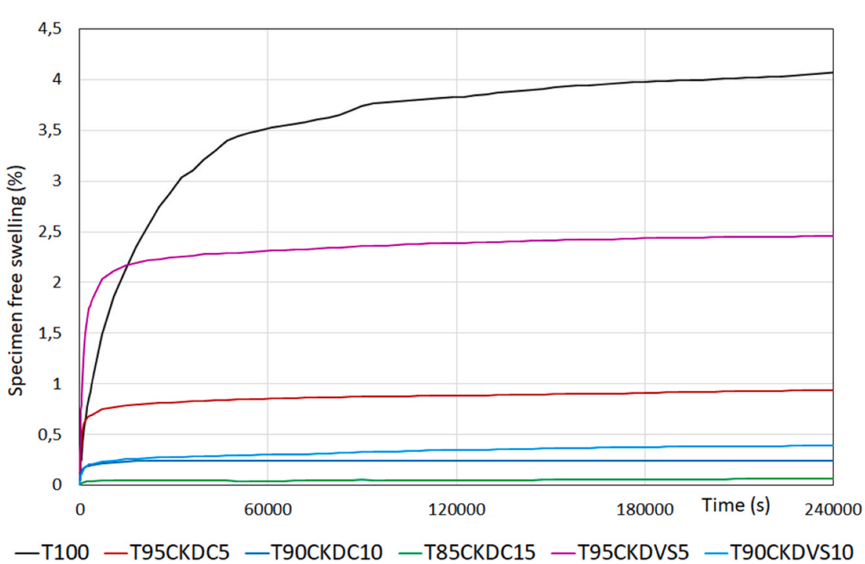

Fig. 11. Evolution of free swelling for different soil mixtures.

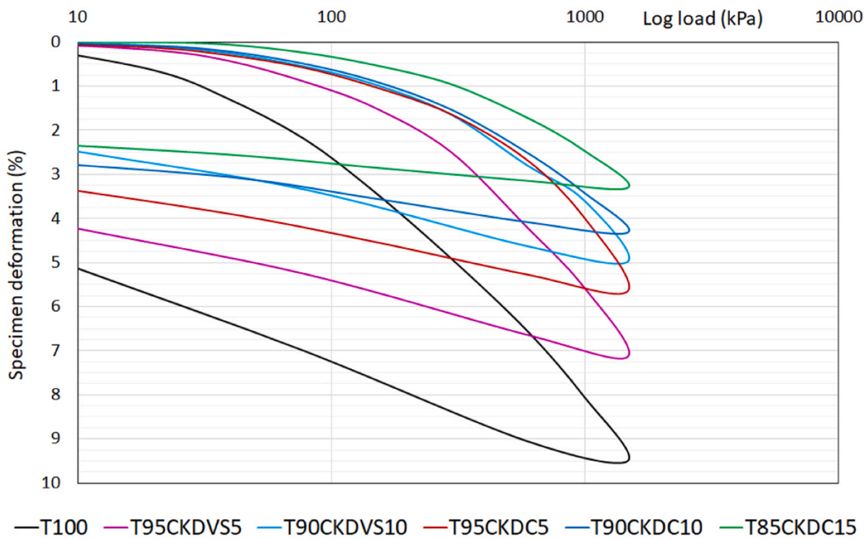

Fig. 13. Specimen deformation (%) vs applied load for different samples.

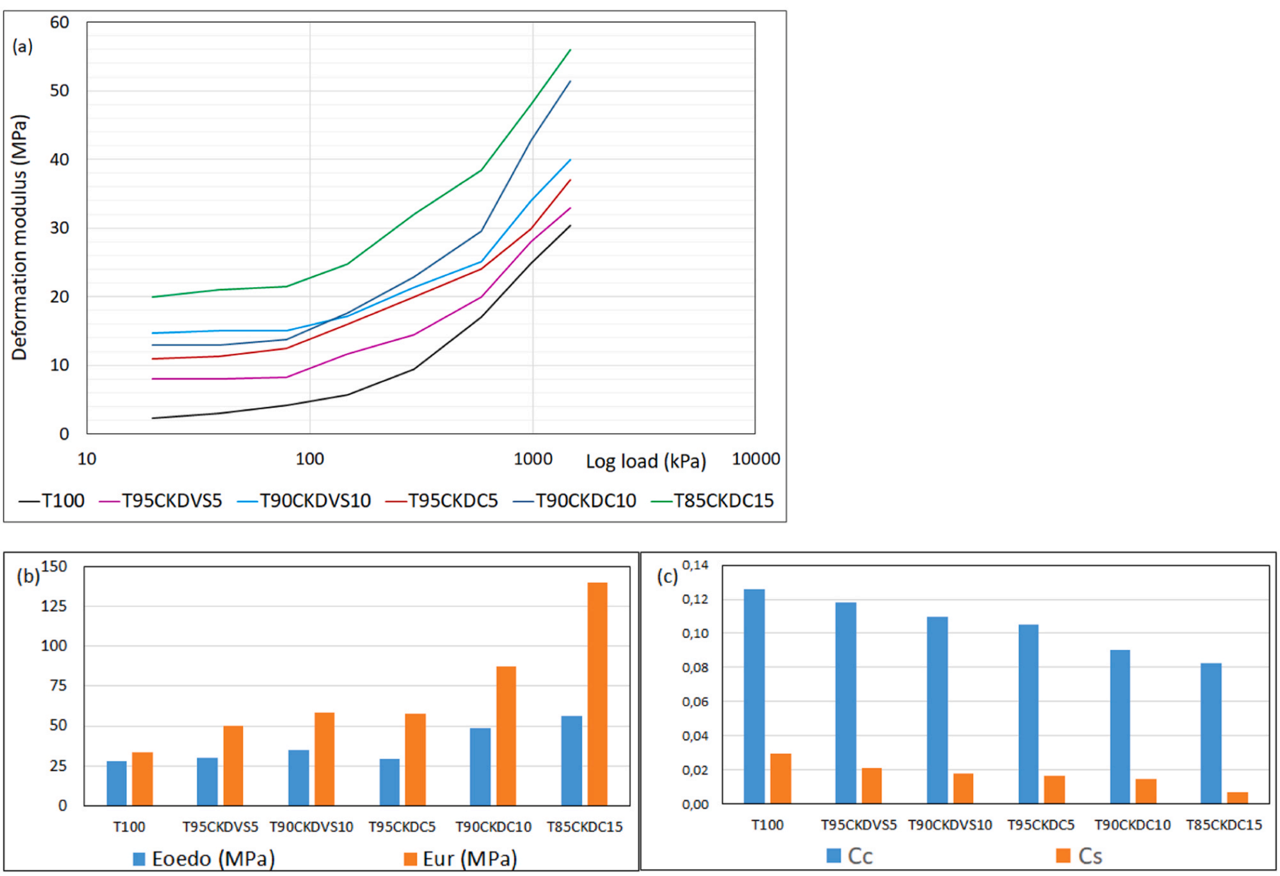

Fig. 14. Soil mixtures with different CKDs: (a) deformation modulus vs applied load during loading stages, (b) deformation modulus under maximum applied loading stage and unloading in oedometer test, (c) compression and swelling index under maximum applied load stage and unloading in oedometer test for different soil mixtures.

- By the analysis of pH for different soil mixtures, it is concluded that by the addition of 10 % of each type of CKD for the same soil, the pozzolanic reaction is possible to occur indicating the effectiveness of the application of different CKDs.
- The performance of Atterberg limit tests indicates that the addition of different CKDs reduces liquid limit, increases plasticity limit and reduces plasticity index, by that way indirectly measuring the low swelling potential when 10 % of different CKDs are added as stabilizers to the natural remolded soil.
- The compaction curves do not provide great differences between the original and the stabilized soils, as expected for clayey materials, being specific dry weight and optimum water content of the approximately same range as of the natural soil. For the addition of CKDVS that has approximately the same G_s as the clayey material,

the compaction curve maintains the same optimum moisture content while the maximum specific dry weight is slightly lower. On the other hand, the addition of CKDC that has the value of G_s of the same order as ordinary Portland cement, the compaction curve maintains approximately the same maximum specific unit dry weight with slightly lower optimum moisture content.

- The reduction of swelling potential, indirectly determined by plasticity index properties, is confirmed by oedometer tests directly measuring free swelling potential of the specimen. It is confirmed that the reduction of free swelling by the addition of both types of CKD passes from high to low free swelling value.
- The reduction of compressibility is observed by comparison of sample deformation vs time curves for different specimens of soil mixtures, observing a decrease in compression and swelling index.
- By the performance of oedometer tests, the increase in deformation modulus under loading as well as increase in unloading modulus is confirmed by that way reducing the compressibility of the natural clayey remolded material thus reducing settlements under different construction loading.
- As an overall conclusion, the application of CKD for the stabilization of expansive clay soils could be beneficial from the economic and environmental perspective, being possible to generate an eco-friendly material without the necessity to discard both the expansive soil and the industrial by-product material thus reducing necessity for their deposition to landfills.

CRediT authorship contribution statement

Svetlana Melentijevic: Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Adilson Cameia:** Formal analysis, Data curation, Visualization. **Fernando García Bañó:** Formal analysis, Data curation, Visualization. **Roberto Ponce:** Formal analysis, Data curation, Validation, Supervision. **Sol Lopez-Andres:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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