

## COMPRESSIVE STRENGTH OF SELECTED FINE GRAINED SOILS TREATED WITH CEMENT KILN DUST AND CALCAREOUS FLY ASH

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### Abstract

**This paper presents the results of unconfined compressive strength tests carried out on samples of two different fine grained soils mixed with anthropogenic materials produced in Poland, showing binding properties – cement kiln dust and fly ash obtained from combustion of brown coal in a pulverized boiler. The tests were performed on cylindrical samples in a testing machine for compression tests after various curing time ranging from 1 to 8 weeks. The conducted work constitutes the first stage of research devoted to the recognition of the effects of calcareous fly ash and cement kiln dust addition into the fine grained soils.**

**Keywords:** Cement kiln dust; Fly ash; Fine grained soil; Soil improvement; Compressive strength.

## 1. INTRODUCTION

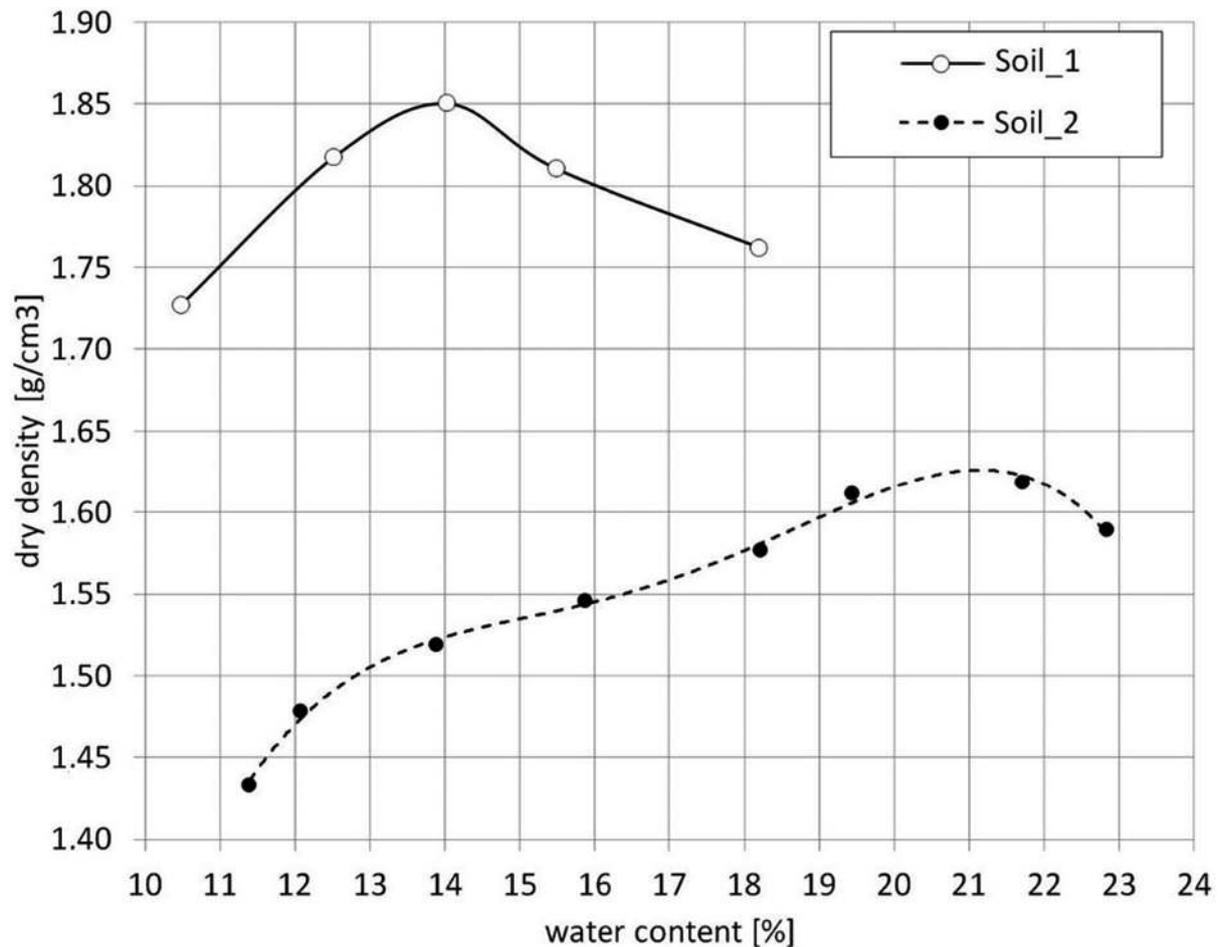
Materials arising as a result of the production process, whose formation is not the primary goal, as in the case of fly ash from power plants, blast furnace slags from steelworks, cement kiln dust from cement plants in accordance with current policy should be managed instead of storing in landfills. Frequently, these materials show valuable properties and have the potential to be used in various areas of civil engineering, including geotechnical works. The assessment of improvement effect of a soft fine grained soil with the use of fly ash or cement kiln dust based on unconfined compressive strength has been discussed widely in literature (i.a. [1–9]) and is still a subject of scientific interest. Unconfined compressive strength tests commonly used in the field of building materials enable the assessment of strength gain due to chemical reactions ongoing in the presence of binders. From geotechnical point of view this type of test does not reflect the real

stress state prevailing in the loaded subsoil, but it is used to assess the suitability of binders such as cement or fly ash for soil stabilization.

The usual amount of cement kiln dust added to the soil that results in soil improvement vary from 8 to 20%, as reported in literature. Authors [2] tested the influence of cement kiln dust addition in quantity up to 10% on the behaviour of collapsible soils and the results of unconfined compressive strength in the curing time from 7 to 28 days. They noticed, that unconfined compressive strength rapidly increases during first week. After that time the improvement goes on although it slows down. Laboratory investigation presented in [4] evidence the effectiveness of stabilization with the use of cement kiln dust applied for low and high plasticity soils. The observed improvement was more significant for soils with low plasticity index. The paper [6] describes treatment with the use of cement kiln dust different materials – the sandy and clayey soils and wastes in the form of sludge. As reported by

**Table 1.**  
**Properties of tested soils**

Parameter	Standard	Soil_1	Soil_2
Plastic limit [%]	PN-88/B-04481	19	29 [11]
Liquid limit [%]	PN-88/B-04481	28	66 [11]
Plasticity index [%]	PN-88/B-04481	9	37 [11]
Optimum water content [%]	PN-EN 13286-2 Proctor test method A	14 [10]	21 [11]
Maximum bulk density [g/cm <sup>3</sup> ]	PN-EN 13286-2 Proctor test method A	1.85 [10]	1.63 [11]
Loss on ignition [%]	PN-88 B-04481:1988	1.9 [10]	4.8 [11]
Specific density [g/cm <sup>3</sup> ]	PN-88 B-04481:1988	2.6 [10]	2.7 [11]
pH	ASTM-D 4972-01 1998	6.2	7.5

**Figure 1.**  
Proctor compaction curves obtained for the Soil\_1 and Soil\_2 (based on [10, 11])

authors the improvement of clayey soils results from direct cementation, promotion of cation exchange and pozzolanic reaction, thus the process of clay stabilization is more complex in comparison to coarse grain soils. The paper [7] contains the results of cement kiln dust addition in quantity up to 10% into the fine grained soils – selected silt and clay, both of

low plasticity. After 28 days the maximum value of unconfined compressive strength obtained for silt was 10.6 kg/cm<sup>3</sup> and for tested clay 10.16 kg/m<sup>3</sup>. It was noticed that the rate of improvement is high up to first two weeks of curing time and after that time proceed with lower speed. The most efficient was addition of cement kiln dust in amount of 5 to 10%.

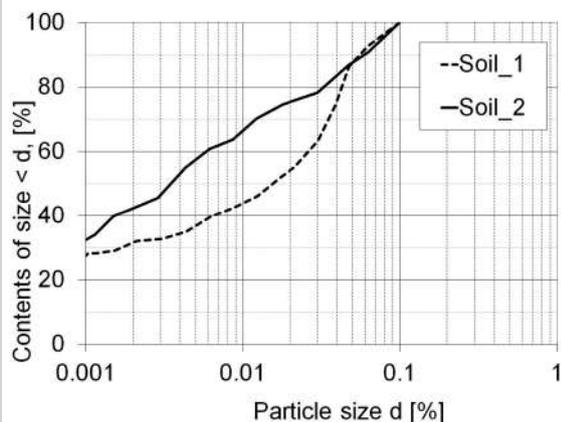


Figure 2.  
Grain size distribution of the soils used in the study according to PN-EN ISO 17892-4:2017-01E

Authors [8] investigated the effectiveness of three different cement kiln samples – one taken from the landfill and two obtained directly from the manufacturer's outlet. The material was mixed with three low plasticity clays. The limited improvement was observed for the soil defined as loess, while the effect was much stronger in soil for which the addition of cement kiln dust in quantity up to 15% did not influence strongly the moisture-density relationship. According to the literature [1] the use of fly ash for soil stabilization can be cost effective due to the fact, that this material improves characteristic of both granular and cohesive soils. As reported in [5] addition of 7–10% of fly ash results in higher unconfined compressive strength after 7 and 28 days. Literature [3] describes the laboratory investigation in which the soil was treated with a mix of activated fly ash (80–90%) and cement (10–20%). The mix was added into the various types of soils in quantity up to 10%. The results show that the strength of treated soils is gradually improved with the curing time.

The goal of this paper was to give the preliminary view on the effect of a small amount (6–8%) of cement kiln dust and selected type of fly ash addition for the purpose of fine grained soil treatment. The waste material for which a better strength development with the curing time was obtained was chosen for further testing in terms of application for soil strengthening.

## 2. MATERIALS

The common worldwide problem of roads construction over the soft fine grained soil and the difficulties related to the demand for huge amounts of earth material during road construction was mentioned i.a. in [1, 5]. Taking into account these aspects the unconfined compressive strength tests discussed in this paper were performed for the mixes of two types of locally available fine grained soils, named in this paper „Soil\_1” and „Soil\_2” and two types of waste materials generated in large amounts in Poland – fly ash and cement kiln dust. Soil\_1 was a natural soil taken from the top layer of the subsoil during road construction. The main goal of performed preliminary tests presented in this paper was to verify the effect of the fly ash addition on the mechanical properties of this soil. Soil\_2 was an artificial soil obtained as a product of fine fractions washout from a sand. This soil was used in the laboratory investigation in order to observe the possible changes of mechanical properties ongoing with the time as a result of cement kiln dust addition. Such a mix could be used to build layers of road embankment.

The main properties of both soils are presented in the Tab. 1. and their grain size distribution tested according to PN-EN ISO 17892-4:2017-01E is shown in the Figure 2.

In presented work two types of waste materials were used as an additive: fly ash and cement kiln dust. The fly ash was obtained from Bełchatów power plant. This world's largest energy unit based on brown coal combustion in pulverized boiler every year generates enormous amounts of materials, which are created during production of electrical energy. The phase composition and the properties of fly ash can vary because it depends on the combustion parameters and the properties of coal burned in furnace, however, it is known that this material contains high amount of calcium compounds, including a few percent of free calcium oxide [12–14]. The main crystalline components are anhydrite, tricalcium aluminate, tetracalcium sulfo aluminate, gehlenite, anorthite and quartz and quick lime [12]. In a short term the fly ash can provide cations ( $\text{Ca}_2^+$ ,  $\text{Al}_3^+$ ,  $\text{Fe}_3^+$ ) and promote flocculation of dispersed clay [1]. In longer term the processes of hydration and hardening of calcareous fly ashes include reactions between calcium oxide and active silica components as well as the reactions of the anhydrite and the active components of glassy phase [12]. Inside the sample of hardened fly ash can be detected ettringite, calcium silicate



Figure 3.  
Mold used for samples preparation [10]



Figure 4.  
Formed samples of fine grained soil mixed with cement kiln dust [10]

Table 2.  
Oxide composition of fly ash from Belchatów power plant tested with XRF according to ISO 29851-2:2010

Component	The content after conversion into the initial state [% mass (% m/m)]	
	fly ash	cement kiln dust
SiO <sub>2</sub>	42.56	18.29
Al <sub>2</sub> O <sub>3</sub>	18.81	4.57
Fe <sub>2</sub> O <sub>3</sub>	4.51	2.16
CaO	24.14	64.19
including free CaO	2.06	21.39
MgO	1.40	1.32
Na <sub>2</sub> O	0.22	0.48
K <sub>2</sub> O	0.21	0.99
SO <sub>3</sub>	2.74	3.03
TiO <sub>2</sub>	1.32	0.23
P <sub>2</sub> O <sub>5</sub>	0.13	0.12
ZnO	0.02	0.23
residue	0.27	4.16

hydrates and calcium aluminate hydrates, while the surface layers of hardened sample contain calcium carbonate, created as a result of carbonation [12]. The improvement effect as a result of hydrates formation can be observed for a long time and it depends on the properties of fly ash, initial conditions of the samples and curing conditions. The chemical composition of the fly ash used in the study is presented in the Tab. 2.



Figure 5.  
Strength press used for the tests [10]

Cement kiln dust used in the experimental work is obtained as a waste product during production of a Portland cement clinker. This fine grained material is collected from the stacks of high-temperature rotary kilns. The chemical and physical characteristic depends on the feed raw materials, type of operation and dust collection facility. Typically it contains mainly calcium oxide (around 50%), silica (around 17%) and alumina compounds (around 5%) [15]. Mixing of soil with 5–30% of cement kiln dust results in reduction of maximum dry density, liquid limit, plasticity and compressibility and increase in plastic limit, optimum water content and compressive strength and those trends are stable with increasing amount of cement kiln dust [15]. As mentioned in [16] the unconfined compressive strength of soil treated with cement kiln dust depends on the content of free lime and alkali ( $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ ). The high amount of alkali contributes to deterioration of strength, while the increased content of free lime causes soil strengthening. The chemical composition of the cement kiln dust sample used in the study is presented in the Tab. 2.

Free calcium oxide contained in both materials used in this study plays a relevant role in the processes of fine grained soils improvement. In short term addition of  $\text{CaO}$  to the soil increases the pH of pore fluid. Calcium ions attracted to the clay surface can change the particles arrangement as a result of flocculation and aggregation, which influences the mechanical behaviour of the soil [17]. Improvement ongoing with the time can be observed for the soils showing pozzolanic activity [18].

### 3. METHODS

The unconfined compressive strength tests were carried out on samples with composition as below:

- Soil\_1 with addition of 4, 6, and 8% of cement kiln dust, with respect to the mass of dry soil,
- Soil\_2 with addition of 4, 6, and 8% fly ash, with respect to the mass of dry soil.

The research presented in this paper was focused on the use of cost-effective waste materials, which in the first place, in accordance with the waste management policy, should be managed instead of being located on a landfill. Thus, no comparative studies have been carried out with the use of soils mixed with standard binders, such as cement or lime. Literature [8] reports that cement kiln dust with high content of free lime can provide 7-day compressive strengths comparable to those obtained for cement-soil mixes and even higher for the mixes of soil and hydrated lime.

In order to perform unconfined compressive strength tests each investigated material was compacted in cylindrical molds with diameter 80 mm and height 80 mm (Figure 3) at optimum water content of the base soils used in the mix (Figure 1 and Tab. 1) according to PN-EN 13286-2:2010/AC:2014-07 Annex A with specific energy of compaction equal to  $0.6 \text{ MJ/m}^3$ .

The samples were then taken out from the mold, signed (Figure 4), covered to prevent drying and stored in room temperature for 7, 14, 28, 42 and 56 days.

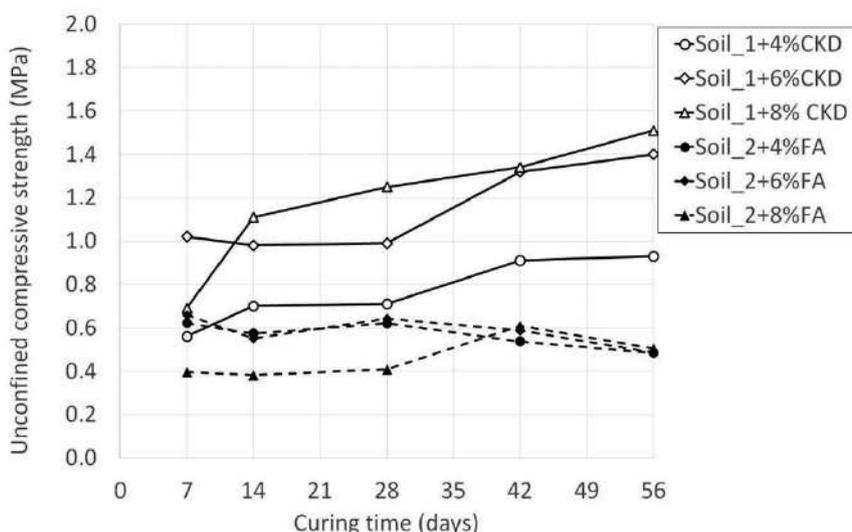


Figure 6. Unconfined compressive strength obtained for the mix of soils and additives with curing time (based on [10, 11])

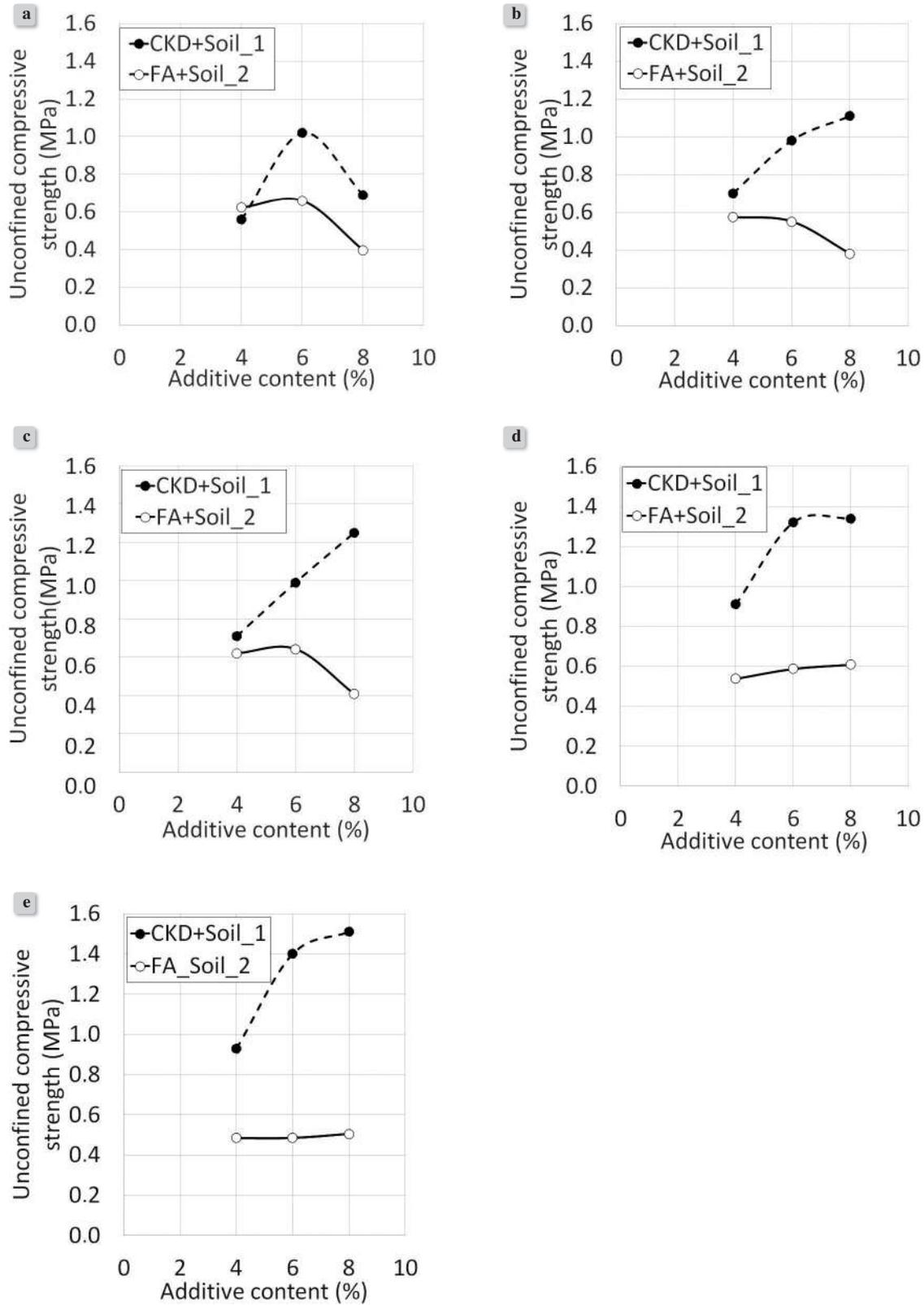


Figure 7. Unconfined compressive strength obtained for the mix of soil and additive after: a) 7 days; b) 14 days; c) 28 days; d) 42 days e) 56 days (based on [10, 11])

After specified curing time samples were pressed in a strength press WALTER&BAI K18329 (Figure 5), accuracy class 2 (expanded uncertainty 0.66 for 1 kN, 0.43 for 2 kN, 0.34 for 3 kN, 0.29 for 6 kN, 0.39 for 9 kN). The samples were compressed at setting for a given speed of strength increase 0.25 MN/m<sup>2</sup>s.

For each mix tested in specific day three samples were prepared. The total number of tested samples was equal to 90. The strength of a soil and the mixes just after preparation was too low to obtain a reliable results of unconfined compressive strength.

#### 4. RESULTS AND DISCUSSION

Figure 6 presents the values of unconfined compressive strength obtained for tested soils mixed with additives at different curing time. It can be observed that with curing time all of the mixes of soil\_1 and cement kiln dust gain strength. This behaviour is consistent with the study presented in [15]. As in the case of the CBR results presented and discussed in [16] this effect can be explained by chemical bond created in a reaction between cement kiln dust and components of a soil. Moreover, the increased content of cement kiln dust contributed to the higher strengths in the specific curing time, as it can be observed in the Figure 7. The exception is the results obtained at the 7<sup>th</sup> day of curing time (Figure 7a), where a lower value of unconfined compressive strength was observed for the mix containing 8% of cement kiln dust in relation to the mix with 6% of this additive.

Observing the characteristics shown in the Figure 6 obtained for the Soil\_2 mixed with fly ash the unconfined compressive strength remain at a similar level throughout the whole curing time of the samples, regardless of the amount of fly ash added to a soil. It can be assumed that the free lime contained in fly ash used in the study in a quantity of 2% most likely was not sufficient to observe any effects of pozzolanic reaction between portlandite and the soil, neither other components of fly ash. The increased content of fly ash from 4% to 8% did not influence unconfined compressive strength or even in some cases contributed to deterioration of strengths (Figure 7a, 7c). This effect may be related to the irregular shape of grains and high surface area of used fly ash, which is typical for fly ash obtained from brown coal combustion in pulverized boiler. Higher fly ash content usually results in increased optimum water content of the mix, as presented in [5]. For the tests presented in this paper the water content of compacted mixes was constant and equal to optimum water content of the soil.

#### 5. CONCLUSIONS

The results presented in this paper indicate the fact that addition of 6–8% of calcareous fly ash used in the tests does not provide improvement of fine grained soil, as no increase in unconfined compressive strength was noticed, most likely due to the low content of free CaO in fly ash. This effect can be remedied by using larger quantity of fly ash or addition of few percent of quicklime. The use of cement kiln dust containing around 21% of free CaO in the same amount of 6–8% allowed to observe a gradual increase in compressive strength. In [8] the authors drew attention to the fact, that the cement kiln dust originating from a given source has its unique properties due to the proportions of raw materials used during production process and used technology. This also applies to fly ash, as its properties depend strictly on the material feed to the boiler and combustion parameters. Due to the fact, that the tests presented in this paper proved the effect of soil strengthening with the use of selected cement kiln dust it is therefore advisable to study more thoroughly the effects of using the material obtained from the same source for the purpose of fine grained soil improvement on a larger number of natural soil types in terms of other properties, i.a. shear strength and compressibility. Outcomes of this study will be used for further research on fine grained soils stabilization with the use of waste materials for designing road pavements or foundations beds.

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