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Discussion on selected results obtained for fine grained soil treated with fly ash

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ABSTRACT

The paper presents part of the results obtained during research carried out in order to complement the knowledge about phenomena occurring in a mix of fine grained soil and fly ash from fluidized bed combustion. Mentioned phenomena include chemical reactions ongoing in fly ash and modified behaviour of fine grained soil treated with fly ash. Changes in physical properties, physical-chemical properties and mechanical behaviour are presented in this paper based on the example of soil–fly ash mix prepared with the addition of 40% of fly ash.

Keywords: Fly ash, Speswhite kaolin, Mechanical behaviour, Physical behaviour

1. INTRODUCTION

Various areas of human activity are accompanied by generation of wastes. Effective wastes management helps to reduce the scale of landfills and creates an opportunity to reduce costs of investments. Complete recognition of materials properties allows for their safe and optimal use in economy. One of the wastes showing great potential in the construction sector is fly ash, created as a by-product during production of electric energy in power plants working based on coal combustion. Poland is one of the countries in which fly ash is produced annually in large quantities and is commonly used, for example as a component of cement or concrete, in roads construction and geoengineering. However, it should be highlighted that properties of fly ash are not permanent as they are a resultant of boiler type, combustion parameters and the characteristic of burned materials. Based on the literature review the approximated characteristics of the fly ash produced in conventional pulverized boilers or boilers using fluidal bed combustion can be determined, which enable materials pre-selection for a specific application.

Technology of Fluidized Bed Combustion (FBC) gained popularity as it gives an opportunity for efficient combustion of fuels with low calorific value. Properties of FBC fly ash were described by many authors, among others by Sulovský (2002), Giergiczny (2006), Brandt et al. (2010) and Zapotoczna-Sytek et al. (2013). Coal combustion in fluidized bed takes place in relatively low temperature

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(around 850°C), which affects the form of constituents forming fly ash. Clay minerals contained in carbon rock undergo the partial or complete dehydroxylation, which makes that the material gains pozzolanic properties. Moreover, ground sorbent (limestone or dolomite) is added into the bed in order to bind sulphur compounds, which results in the presence of anhydrite $CaSO_4$ and calcium compounds in fly ash. Part of calcium can be found in the form of free calcium oxide influencing binding properties of this waste material. FBC fly ash comes up against difficulties in application as a component of concrete or cement, but its valuable binding properties can be used in the field of geotechnical engineering. Paper presents selected results of a study carried out in order to investigate the properties of fine grained soil treated with FBC fly ash, entirely presented in the PhD dissertation of the author of this work (Knapik 2016).

2. METHODS AND PROCEDURES

Depending on the test, mixes of soil and fly ash were stored for 0 day (not longer than 21 hours), 7 days or 28 days in closed containers, oedometer rings or molds. Attention was paid in order to reduce the contact of mix with atmospheric air and to limit the variations of ambient temperatures.

In order to test grain size distribution of a mix, samples were stored for specified curing time. Then, they were mixed with solution of hexametaphosphate in mechanical mixer for 20 minutes and sieved. Equivalent grains diameter was calculated according to Formula (1), provided by Dołżyk and Szypcio (2014).

$$d = 0{,}05462\sqrt{\frac{\eta H_r}{(\rho_s - 1)t}} \qquad (1)$$

where:

η – dynamic viscosity of solution (mm)

H_r – hydrometer effective depth (mm)

ρ_s – specific density (Mg/m^3)

t – time (s)

The pH value of mixes cured in closed containers was tested according to the standard ASTM–D 4972–01 1998 with the use of handheld pH meter Hanna Instruments HI−991001.

For the purpose of sedimentation tests, prepared samples were stored for 16 hours in small closed containers. Then, they were mixed with the use of laboratory mixer for 10 minutes with additional distillate water, poured into the measuring cylinder and hand-mixed by rotations. During the whole procedure a special attention was put in order to avoid any material loss. Height of suspension was measured in time intervals selected to obtained well defined sedimentation curve.

In order to characterize materials in terms of mechanical behaviour samples were tested in oedometer according to ASTM-D2435-96 and in direct shear strength apparatus according to PKN-CEN ISO/TS 17892-10:2004. Oedometer rings were filled just after preparation of a mix and material was cured in this way for specified time. Samples tested in direct shear strength apparatus were prepared in rectangle metal molds, protected with plastic foil and greased.

Swelling was measured in oedometer. Samples were prepared in saturated state in oedometer ring and the test was started immediately. During the test samples were constantly soaked (oedometer cell was filled with distillate water within measuring time). Upper surface of samples was loaded with pressure 0.4 kPa, generated by loading cup.

3. MATERIALS

Two types of materials were used in experimental work presented in this paper: Speswhite kaolin and selected FBC fly ash.

Speswhite is a highly refined kaolin obtained from deposits in Cornwall, distributed by Imerys Materials. The research based on well-known soil allowed to reduce the scale of investigation and to avoid the risk of variability, typical for natural soils.

This fine grained soil is characterized by grain size distribution presented in the Figure 1.

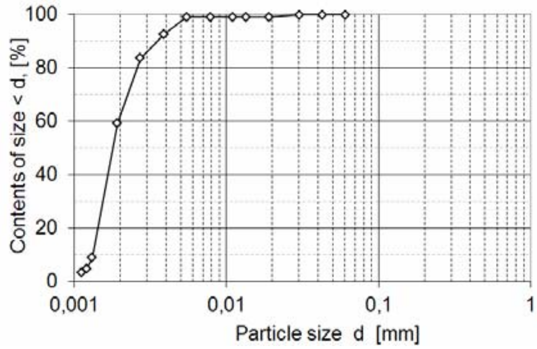

Figure 1. Grain size distribution of Speswhite kaolin

The pH value of tested sample was 4.2. X-Ray analysis showed that crystalline phases present in Speswhite kaolin are kaolinite, muscovite and quartz (Vitale et al. 2015). Kaolinite clay belongs to the group of 1:1 clay minerals in which silica sheet and alumina sheet are held by hydrogen bonding between them. Soil particle can be formed by many platelets. As described by Mitchell and Soga (2005) bonding between successive layers is sufficiently strong that there is no interlayer swelling in the presence of water. Depending on water chemistry (the pH value, ions type, valence and concentration) kaolinite layers can deflocculate or flocculate, which influence soil properties.

Speswhite kaolin was investigated by Vitale et al. (2015) in terms of pozzolanic activity. Very low rate of hydrates formation was confirmed for first four weeks of curing time, as presented in the Figure 2.

Fly ash used in experimental study was obtained in power plant placed in Silesia region of Poland. Combustion of coal and coal slime took place in fluidized bed boiler. The amount of main components of fly ash are listed below:

- SiO_2 40÷42%
- Al_2O_3 20%
- Fe_2O_3 6÷8%
- CaO 17÷19% (in which CaO_{free} 5%)
- SO_3 4÷6%

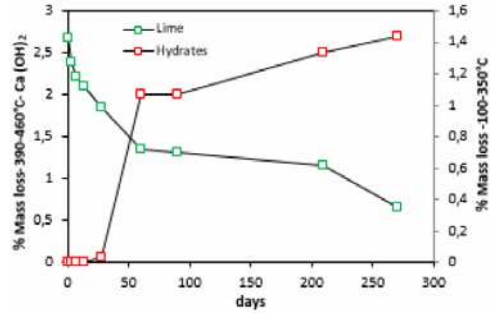

Figure 2. Results of thermal analysis obtained for Speswhite kaolin treated with lime (Vitale et al. 2015)

Loss on ignition measured for fly ash was 2% and the pH value was equal to 12.6. Grain size distribution is presented in the Figure 3.

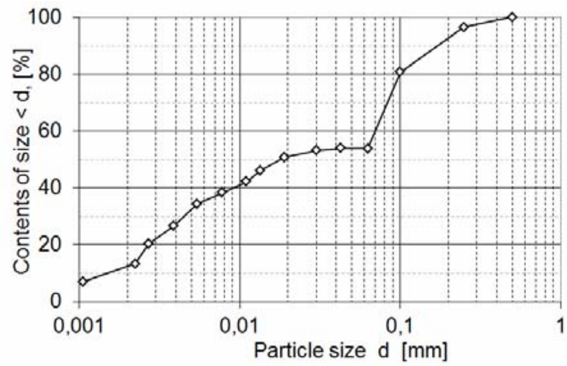

Figure 3. Grain size distribution of fly ash

Mass of fly ash in the mix FA40 was calculated with respect to mass of kaolin – 40 g of fly ash for 100g of soil. Samples were prepared at two different initial water content, namely 50% and 100%. Initial water content of mix, as well as the samples prepared from pure Speswhite kaolin was equal to 50% (samples signed with symbol “w50”) or 100% (samples signed with symbol “w100”).

4. RESULTS

Samples of the mix was tested in order to investigate the changes in the pH value over the curing time. The results are presented in the Figure 4. It can be noticed, that initially highly alkaline environment is changing. A rapid drop in the pH value within first week of curing time is followed by progressive but more gentle decrease within the next days.

Characteristic of the pH value over the time is not significantly different for the both tested mixes.

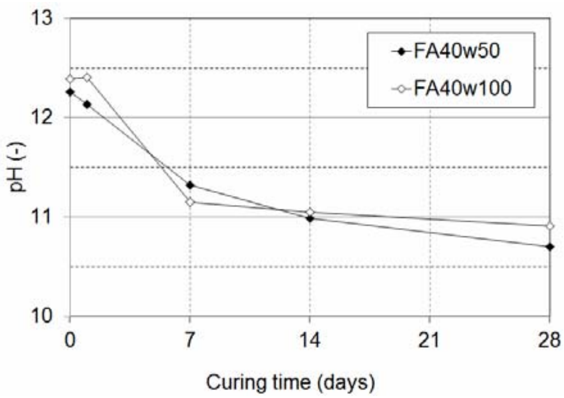

Figure 4. The pH values measured in curing time for the mixes FA40w50 and FA40w100

Sedimentation curves obtained for the mix FA40 and for the sample of kaolin are shown in the Figure 5. The curves are characterized by two different trends. It can be observed, that in case of the mix FA40w100 the time before settlement starts is shorter and the rate of sedimentation is higher in comparison with the sample of kaolin. Additionally, the trend of the curve obtained for the mix FA40w100 in the time range of 10÷1000 min is divided for two parts. Initially high slope is lower in second stage. It can be assumed that this shape is a result of following stages: sedimentation and self-weight consolidation. In case of the sample of kaolin the slope of the curve is approximately stable.

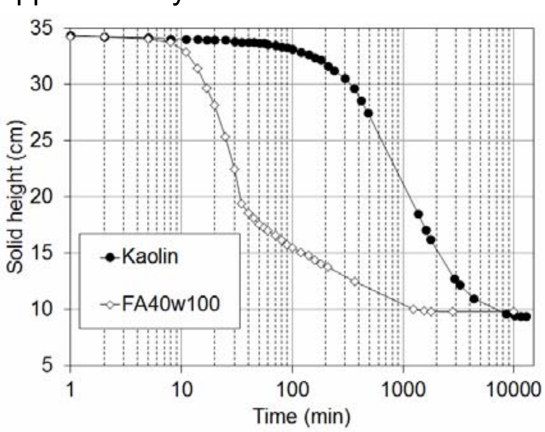

Figure 5. Sedimentation curves obtained for the sample of kaolin and the mix FA40w100

The grain size distribution of the mix FA40 was tested in three different curing times – 0, 7 and 28 days. The results are presented in the Figure 6. The changes in grain size distribution are most evident within the first week of curing time.

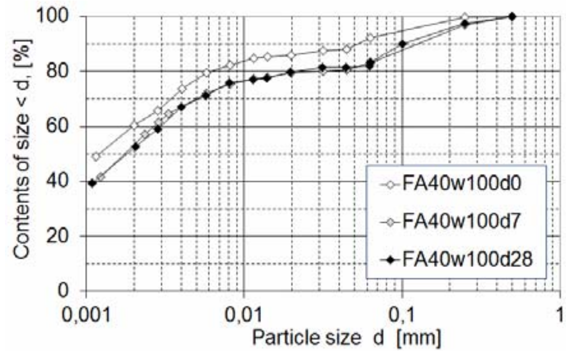

Figure 6. Grain size distribution obtained for the mix FA40w100 tested after 0, 7 and 28 days of curing time

The oedometer tests were performed for the samples with 50% and 100% of initial water content. The results are summarized in the Figures 7÷9.

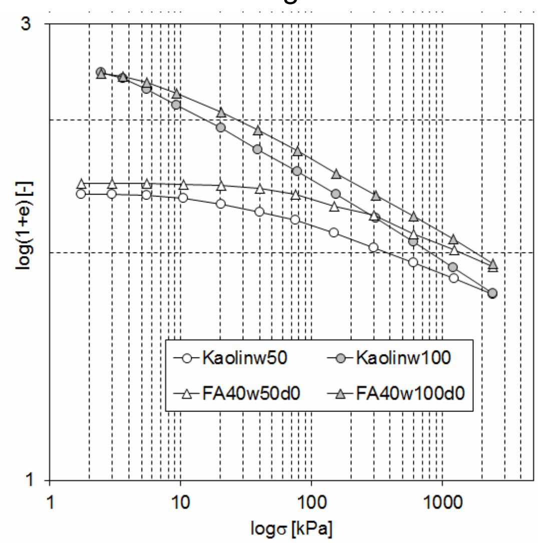

Figure 7. Consolidation curves obtained for kaolin and the mix FA40 prepared at initial water content 50% and 100%, tested at 0 day of curing time

In the Figure 7 it can be observed, that the consolidation curves obtained for samples tested at 0 day of curing time, presented as a plot of log(1+e) to logσ, converge at high vertical stress level (2450 kPa). Oedometer tests performed after 7 days (Figure 8) evidenced, that the vertical stress used during the test was not sufficient to obtain the crossing point. In the Figure 9 it can be observed, that at vertical stress equal to 2450 kPa, the void ratio of both samples reached almost the same value.

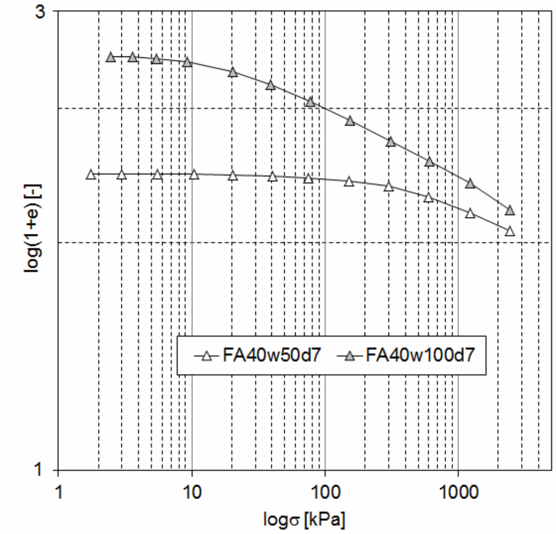

Figure 8. Consolidation curves obtained for the mix FA40 prepared at initial water content 50% and 100%, tested after 7 days of curing time

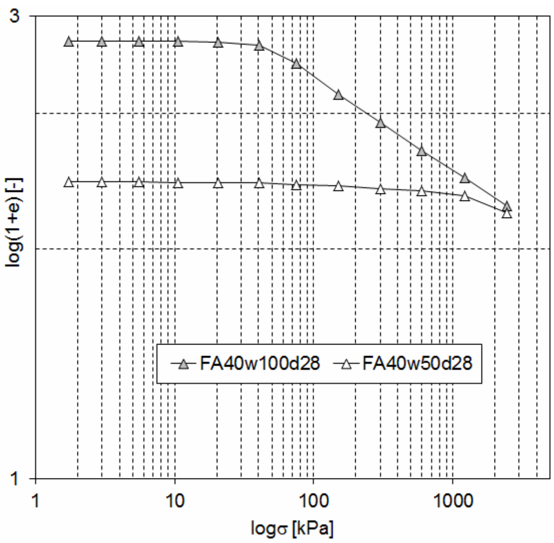

Figure 9. Consolidation curves obtained for the mix FA40 prepared at initial water content 50% and 100%, tested after 28 days of curing time

In order to facilitate observations of changes in compressibility ongoing in curing time, the results are compiled in a different way in the Figures 10 and 11. The curves are grouped with respect to initial water content. The volume change at the highest vertical stress is decreasing with curing time for the mix prepared at initial water content 50%. In case of mix prepared at 100% of water content, the volume change at the highest vertical stress is higher for the sample tested after 7 days, however, it is also somewhat higher than volume change obtained for the sample tested after 28 days. The last observation could be connected with the differences in the value of void ratio (2.6 for the sample tested after 7 days and 2.7 for the sample tested after 28 days).

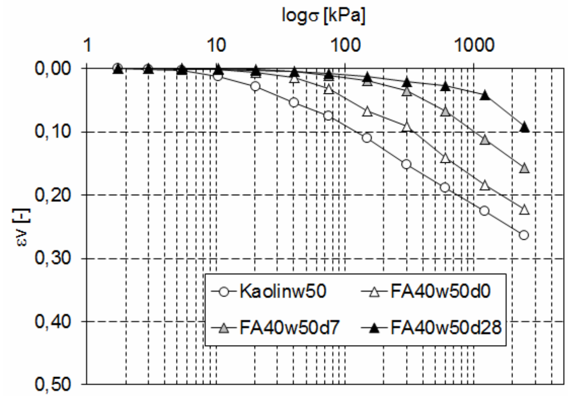

Figure 10. Volume changes under vertical load obtained for kaolin and the mix FA40 prepared at initial water content 50% tested at 0, 7 and 28 days of curing time

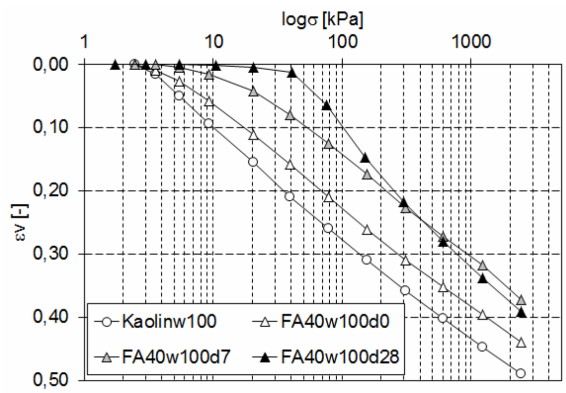

Figure 11. Volume changes under vertical load obtained for kaolin and the mix FA40 prepared at initial water content 100% tested at 0, 7 and 28 days of curing time

For both mixes, prepared at initial water content 50% and 100%, an successive increase of the yield stress in curing time can be observed, as presented in the Figure 12.

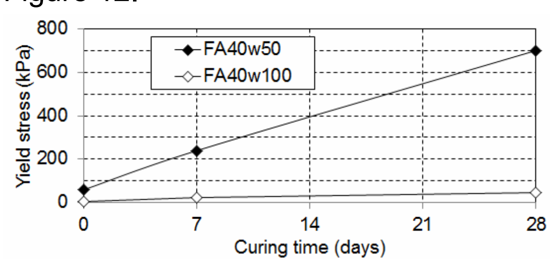

Figure 12. Calculated yield stress

Direct shear strength tests were performed for kaolin and the mix FA40 prepared at initial water content 50%. The results are presented in the Figures 13÷15. The mix of kaolin and fly ash is characterized by somewhat higher shear strength at 0 day of curing time in comparison to the sample of not treated soil. After 28 days of curing time, the strength of the mix is increasing mainly due to high value of cohesion.

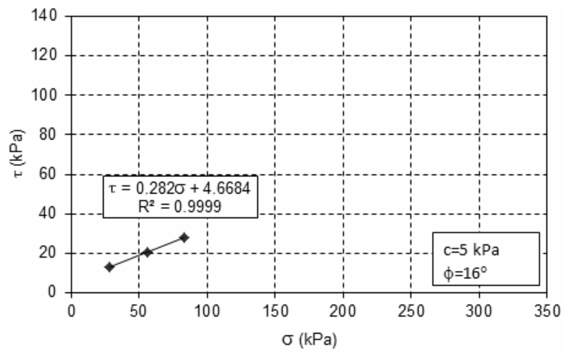

Figure 13. Determination of strength parameters for kaolin

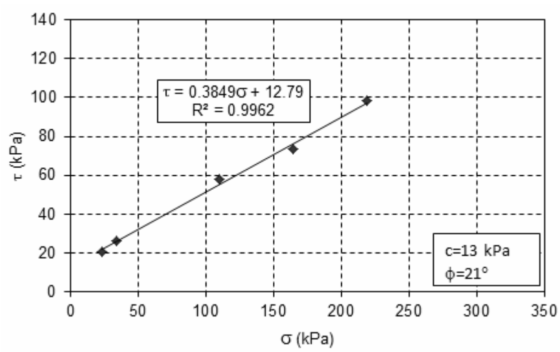

Figure 14. Determination of strength parameters for the mix FA40 tested at 0 day of curing time

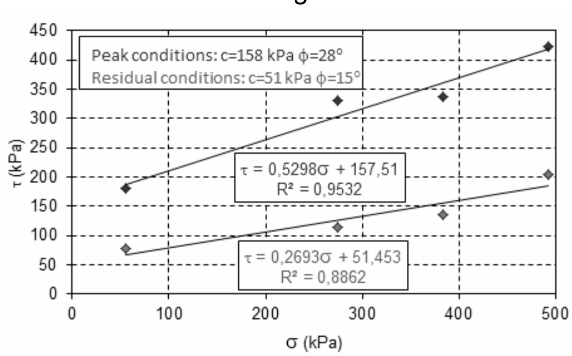

Figure 15. Determination of strength parameters for the mix FA40 tested after 28 days of curing time – peak and residual conditions

The measurements of volume changes during curing in contact with water are plotted in the Figure 16.

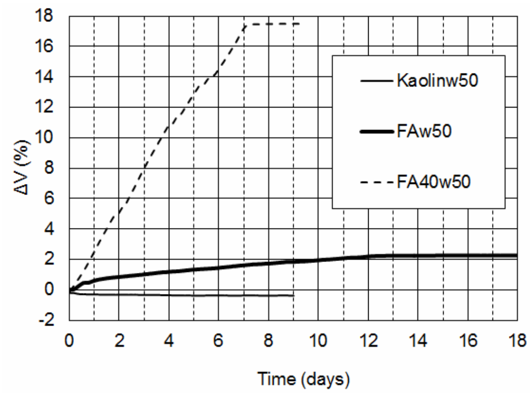

Figure 16. Volume changes measured for kaolin, fly ash and the mix FA40

It was observed, that the sample of kaolin settled under pressure 0.4 kPa. Sample of fly ash shown swelling behaviour. The volume changes lasting 12 days ended with the final volume change of the sample equal to 2.25%. Volume changes measured for the mix FA40 significantly exceeded the values measured for pure components of the mix. The void ratio increased from the initial value equal to 1.32 up to the value of 1.71 and the water content increased up to the value 71%.

5. DISCUSSION

Presented results evidence, that addition of fly ash into the fine grained soil, represented by Speswhite kaolin, causes changes in physical properties, physical-chemical properties and mechanical behaviour. Observed effects are time-dependent.

Highly alkaline environment is necessary to provide dissolution of silica and alumina (Keller 1964). Fly ash, used in quantity 40%, changes the pH value of pore water from acid to highly alkaline, which is favourable in terms of formation of hydrates such as calcium silicate hydrates, calcium aluminate hydrates and ettringite. Decrease in the pH value of the mix FA40 observed during the first week of curing time is a result of ongoing chemical reactions – formation of hydrates and possibly some carbonation (the contact with atmospheric air was limited but some air was trapped in container together with the sample).

Sedimentation tests evidenced, that the presence of fly ash changes the behaviour of fine grained soil. The parameters of sedimentation curve (Figure 17) were discussed in the paper of Palomino et al. (2008).

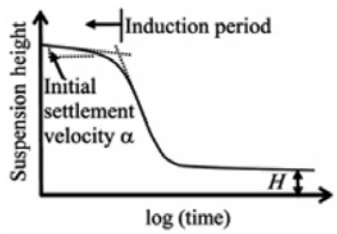

Figure 17. Characteristic parameters of sedimentation curve (Palomino et al. 2008)

In the mix FA40 the time needed to obtain clear water above the sediment is shorter. Due to the fact that the length of induction period specifies the degree of particles association, it can be assumed that fine grained particles present in the mix formed bigger and heavier flocks in comparison to pure kaolin. This phenomena is connected with changed pore water chemistry.

The initial grain size distribution of the mix results from the grain size distribution of the components – Speswhite kaolin and fly ash. It was observed, that the grain size distribution of the mix is changing mainly during first week of curing time. Due to the fact that the test was performed with the use of dispersant, observed changes in grain size distribution should be connected with the formation of new products, which bind solid particles together in a permanent way.

Addition of fly ash causes immediate changes in mechanical behaviour of a soil, which is a summarized result of changes in pore water chemistry and introduction into the soil coarser fractions. Shearing strength of the mix is increasing during curing time mainly due to higher values of cohesion. Changed pore water chemistry can influence the compressibility behaviour in short term. Formation of new products results in changed compressibility behaviour with curing time, causing decreased values of volume changes upon loading and increased values of yielding stress. Compressibility behaviour observed for Speswhite kaolin and for the mix FA40 tested at 0 day of curing time is consistent with the observations of Lopes et al. (2015). Authors noticed that the compressibility curves obtained for the samples prepared at two different water content tend to converge at higher stress level as a result of gradual changes in soil structure (Figure 18).

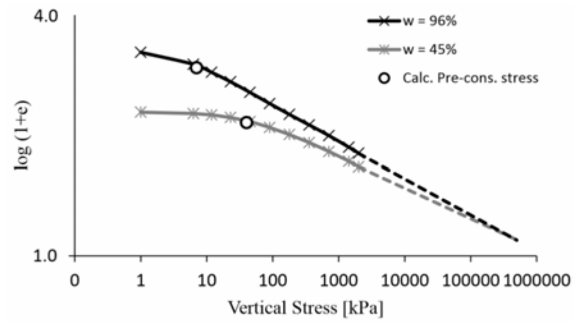

Figure 18. Consolidation curves, log(1+e)-logσ'_v plot, dashed lines indicate the projection of the curves for greater loads (Lopes et al. 2015)

Tests performed by the author of this paper evidenced that the value of vertical stress for which the compressibility curves reach the same point is not stable in curing time in case of soil treated with fly ash. This aspect can be explained with the fact, the initial water content can influence the rate of new products formation.

Measurements of volume changes evidenced, that the mix FA40 shows substantially higher swelling than the sample of fly ash. It can be assumed, that hydration and formation of new products is not the only mechanism causing volume changes. Having regard to the influence of initial conditions of the sample on the swelling it should be highlighted that the samples were in saturated state from the beginning of the test. Observed phenomena is the subject of the future study planned by author of this paper.

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