

COMPRESSIBILITY OF FLY ASH AND FLY ASH-BENTONITE MIXTURES

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Abstract. Environmental protection, one of the most important issues nowadays, forces civil engineers to look for alternative solutions to the known ones. The use of substitute materials as an embankment fill or a ground material under the embankment instead of natural soil follows these trends. A great amount of fly ash is disposed of in landfills. It is a cost-effective material that can be used in construction instead of natural soil. The geotechnical properties of fly ash as a construction material in place of soil need to be examined. It includes laboratory tests to determine the chemical composition and geotechnical characteristics. In the present work, one-dimensional consolidation tests have been conducted to examine the compressibility behaviour of compacted fly ash and fly ash-bentonite mixtures used in the earth structures like road embankments. The analysis of the consolidation phenomenon is useful for predicting the magnitude and rate of settlement of the structure. Materials compacted at OMC to their MDD, according to Standard Proctor, were tested in Rowe-Barden type consolidometer on saturated and non-saturated samples. Coefficients of consolidation have been compared between values derived from log-time and square-root-of-time methods and direct hydraulic conductivity tests. Bentonite amount in fly ash-bentonite mixtures influences the vertical deformation of the sample.

Keywords: bentonite, compressibility, compaction, consolidation, fly ash, road embankment materials.

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Introduction

According to the hierarchy of Directive 2008/98/EC, preventing waste production is the most important activity. The second in a line is preparing for re-use, then recycling, recovery and the last resort is disposal – sending waste to landfill. Fly ash is a by-product of burning coal in power plants. Based on Eurostat (Eurostat Database, 2021), in 2020, Poland accounted for 43% of the total EU hard coal consumption and 19% of the total EU brown coal consumption. According to the Statistical Yearbook of the Republic of Poland (2020), at the end of 2019, there were 1.9 million tons of fly ash produced. The majority of this amount (83.1%) was recovered. However, the problem of disposing material is still present – about 25 million tons of fly ash were stored in a landfill at the end of 2019 in Poland. This indicates a high need for waste management. Storage of coal combustion products requires large areas that result in costs with regard to energy and heat production. Waste or by-products can provide the source of profitable and low-cost construction materials. The combustion waste might be used as a substitute for natural soil.

Two classes of fly ash are defined according to ASTM C618 (ASTM International, 2019): class F – fly ash with pozzolanic properties derived from anthracite and bituminous coal combustion, and class C – fly ash with high content of calcium from burning of sub-bituminous and lignite coals, which has cementitious properties. As the literature presents (Kim et al., 2005; Zabielska-Adamska, 2006a), fly ash ranges in size from silt, sandy silt to sand. Application of fly ash to engineering purposes is possible when geotechnical properties are evaluated and characterised. The geotechnical utilization of fly ash can take several ways. Many studies show that it can be used as fill material (Indraratna et al., 1991; Trivedi & Sud, 2007). To improve the properties of fly ash, additives such as lime, cement, bentonite, and others are added (Ghosh & Subbarao, 2007; Zabielska-Adamska & Wasil, 2017). A number of researchers reported the application of fly ash with additives, or soil, stabilized with fly ash for embankment (Kaniraj & Gayathri, 2004; Kim et al., 2005) and hydraulic barrier construction (Mollamahmutoğlu & Yilmaz, 2001; Zabielska-Adamska, 2006b; Wasil, 2017).

The compressibility of fly ash depends on its maximum dry density, degree of water saturation, pozzolanic properties, and hardening ability with time. Laboratory tests have shown that partially saturated fly ash is less compressible than fully saturated (Gray & Lin, 1972; Zabielska-Adamska, 2018). This is due to the disappearance of the capillary forces in a fully saturated sample causing its higher compressibility. The settlement of structures placed on fly ash embankments can be estimated based on consolidation test results.

The primary consolidation of fly ash does not take longer than one minute (Porbaha et al., 2000), which suggests its similarity to non-plastic silts or granular soils. No additional settlement was observed over time as the hardening process took place. Additionally, the improvement of consolidation characteristics is a reflection of pozzolanic reactivity (Sear, 2001; Sivapullaiah & Moghal, 2011).

Gray & Lin (1972) claim that properly compacted and stabilized fly ash has strength and durability comparable to compacted soil. The advantage is the use of fly ash as an earth-fill that does not require special equipment. It is a material easy to handle by conventional compaction plants. The settlement of the ground beneath the embankment made of fly ash was less than under the granular fill embankment – field study showed. It is due to its lower bulk density than the natural material.

Leonards & Bailey (1982) analysed the properties of compacted fly ash as structural fill to support precipitators' foundation. During the construction, the compaction and settlement were checked. Researchers stated that estimation of settlement based on the penetration tests was not applicable to compacted fly ash. The cause was that the material had low unit weight and a tendency to crushing. The plate load test was found to be reliable for settlement determination.

Laboratory tests and construction observations were taken by Martin et al. (1990) for fly ash used as fill under construction and highway embankment. Based on conducted tests and the literature, the conclusion that the geotechnical properties of fly ash can be quantified using common methods has been made. The researchers pointed an advantage on fly ash over fine-grained soils – less sensitivity to moisture content during the compaction process.

The results of laboratory tests (Kim et al., 2005) carried out on the fly ash-bottom ash mixtures with different amounts of fly ash (50%, 75% and 100%) showed that the mixtures with a lower amount of fly ash were more compressible. It is related to the higher crushability of bottom ash. In addition, the compressibility of compacted fly ash-bottom ash mixtures was similar to typically compacted sand in terms of material for highway embankments.

Based on their research, Kim & Prezzi (2008) concluded that fly ash was slightly more compressible than sand – both compacted the same. It was observed that water content during compaction influenced the fly ash compressibility. At low to moderate stress levels, the samples compacted dry of optimum were slightly stiffer than compacted wet of optimum. At the high-stress level, deformations of the samples compacted at the dry- or wet-side were comparable.

Zabielska-Adamska (2018) tested fly ash compacted at different moisture contents, using Modified and Standard Proctor compaction method. The compressibility of the tested materials was dependant on moisture content during compaction. In addition, the unsaturated samples were less compressible than samples saturated with the back pressure method.

In the paper, laboratory tests of fly ash from Bialystok Thermal and Power Station are presented. The tests of one-dimensional consolidation were performed in Rowe-Barden type consolidometer. The effect of bentonite amount in the fly ash-bentonite mixture on the compressibility was investigated. Based on the results of the tests, parameters describing the settlement of tested materials were derived. The compression index, coefficient of consolidation, and coefficient of volume change were determined. The coefficients of consolidation calculated using the log-time (Casagrande's) and square-root-of-time (Taylor's) methods were presented. The objective of this study was to determine the compressibility of fly ash and fly ash-bentonite mixtures as substitute materials for natural soils in earth structure application.

1. Soil consolidation

Soil compressibility is the capability of decrease in volume due to applied load. It is one of the factors which causes the settlement of the soil. The decrease in volume of the specimen subjected to the stress is caused by three factors (Taylor, 1948): compression of the solid particles, compression of air or water present in voids, and an escape of water or air from the voids. Additionally, solid particles move relative to each other, and some of them might be crushed. Taylor (1948) stated that the compressibility of soil depended on the soil skeleton rigidity. The rigidity depends on the structural arrangement of particles and the degree of bonds between the particles (in fine-grained soils). Compressibility of the soil increases as the clay fraction increases – soil composed mostly of flat grains is more compressible than soil with a predominance of spherical grains. Head & Epps (2011) stated that in inorganic soils, the compressibility of water was negligible, and the compression of the soil grains was vastly small. It indicates that the theory of consolidation is based on the escape of water from the voids present in the soil. It shows, in turn, for soils with high permeability, like sand, that the escape of water can be quick. It is different in cohesive soils with low or very low permeability, where settlement can take a very long time.

The loading causes compression. On shallow depths, it is three-dimensional but in deeper layers is basically one-dimensional. Terzaghi's

theory of one-dimensional consolidation has a few assumptions. The first one is that the soil is homogeneous and fully saturated. The water present in pores and soil particles is incompressible. The flow of water in soil takes place following Darcy's law. The compression and flow of water are vertical. The coefficient of permeability and the coefficient of volume compressibility remain constant throughout the process, and the consolidation time is dependent on soil permeability (Terzaghi et al., 1996).

In the fully saturated soil with a low value of hydraulic conductivity, after increasing the load ($\Delta\sigma$), all the increase is taken over by pore water pressure (Δu) as excess pore water pressure. Due to water diffusion from the soil pores, the effective stress value in soil particles increases ($\Delta\sigma'$) to take up the pressure change ($\Delta\sigma' = \Delta\sigma$). The pore water pressure reaches the value equal to the atmospheric pressure, present before the load increase ($\Delta u = 0$). The process of soil consolidation is presented as the consolidation curve.

From the consolidation test, the parameters describing the compressibility of soil can be derived: coefficient of consolidation c_v , coefficient of volume compressibility m_v , and compression index C_c . In general, applied to overconsolidated clays is the coefficient of volume compressibility m_v , and C_c to normally consolidated clays (Head & Epps, 2011). The vertical settlement of soil subjected to a vertical stress increase at the surface is described by the equation:

$$\Delta h = \frac{\Delta e}{1 + e_0} h, \quad (1)$$

where h is the initial thickness of the sample, e_0 is the initial void ratio, Δe is the decrease in void ratio when stress increase from σ'_{v0} to σ'_{v1} . The relevant, in terms of consolidation test, is a void ratio (Head & Epps, 2011):

$$e = \left(\frac{\rho_s}{\rho_d} \right) - 1, \quad (2)$$

where ρ_s is specific density, and ρ_d is the dry density of soil.

Change in the void ratio (for one log cycle of pressure change) is written in terms of compression index C_c , which is used to determine the magnitude of settlement, and is calculated by the equation (Head & Epps, 2011):

$$C_c = \frac{-\delta e}{\delta(\log_{10} \sigma')} \quad (3)$$

or the coefficient of compressibility and change in effective stress:

$$a_v = \frac{\Delta e_i}{\Delta \sigma'_{vi}}, \quad (4)$$

where $\Delta \sigma'_{vi}$ is effective stress change, and Δe_i is void ratio of soil change.

The parameter which indicates the compressibility per unit thickness of the soil is the coefficient of volume compressibility also known as modulus of the volume change (Head & Epps, 2011):

$$m_v = \frac{a_v}{1 + e_1}, \quad (5)$$

where e_1 is the void ratio at the start of the load increment.

According to Terzaghi's theory, the coefficient of consolidation, which is used to calculate the rate of settlement, is described by the equation (Lancellotta, 1995):

$$c_v = \frac{k}{\gamma_w m_v} = \frac{k(1 + e_0)}{\gamma_w a_v}, \quad (6)$$

where k is the hydraulic conductivity and γ_w is the unit weight of water.

The coefficient of consolidation might be calculated based on tested hydraulic conductivity, as Equation (6) presents, or evaluated according to the consolidation results from the laboratory tests. Two procedures are well known: the log-time method suggested by Casagrande and the square-root-time method developed by Taylor. The compression of clays subjected to load can be divided into three phases (Head & Epps, 2011): initial compression, primary consolidation, and secondary compression. As the literature suggests, in many applications, the primary consolidation phase is taken into account to estimate the settlements (Lancellotta, 1995). The equation to evaluate the coefficient of consolidation on the basis of consolidation curves by the log-time method is as follows:

$$c_v = \frac{0.196H^2}{t_{50}}, \quad (7)$$

and by the square-root-time method:

$$c_v = \frac{0.848H^2}{t_{90}}, \quad (8)$$

where H is half the thickness of the sample, t_{50} is the time corresponding to 50% of consolidation, and t_{90} is the time corresponding to 90% of consolidation.

2. Materials and test procedures

2.1. Fly ash and bentonite

Laboratory tests of the compressibility were conducted on fly ash from Bialystok Thermal and Power Station. The coal combustion residue was collected from the dry disposal site. Tested fly ash was a by-product

of the combustion of bituminous coal. Fly ash was tested alone and as mixtures with variable amounts of bentonite. The bentonite powder used in the presented study is a commercially available material. Bentonite was added to improve the properties of fly ash, like hydraulic conductivity (Wasil, 2020), which is important in the case of compacted material beneath embankment, where the high water table is present. The percentage of addition represents the dry mass of bentonite per dry mass of fly ash in a tested sample. The tested samples were as follows: fly ash with 0% of bentonite, fly ash with 5% of bentonite, fly ash with 10% of bentonite, and fly ash with 15% bentonite. The symbols of tested materials used in the text are respectively: FA, FA+5%B, FA+10%B and FA+15%B.

The grain size distributions of tested materials were obtained from the results of sieve and hydrometer analysis conducted before the compaction. Figure 1 presents grain size distribution curves.

Tested materials ranged in size from sandy silt (saSi) – FA and FA+5%B, clayey silt with sand (sacSi) – FA+10%B, to silty clay with sand

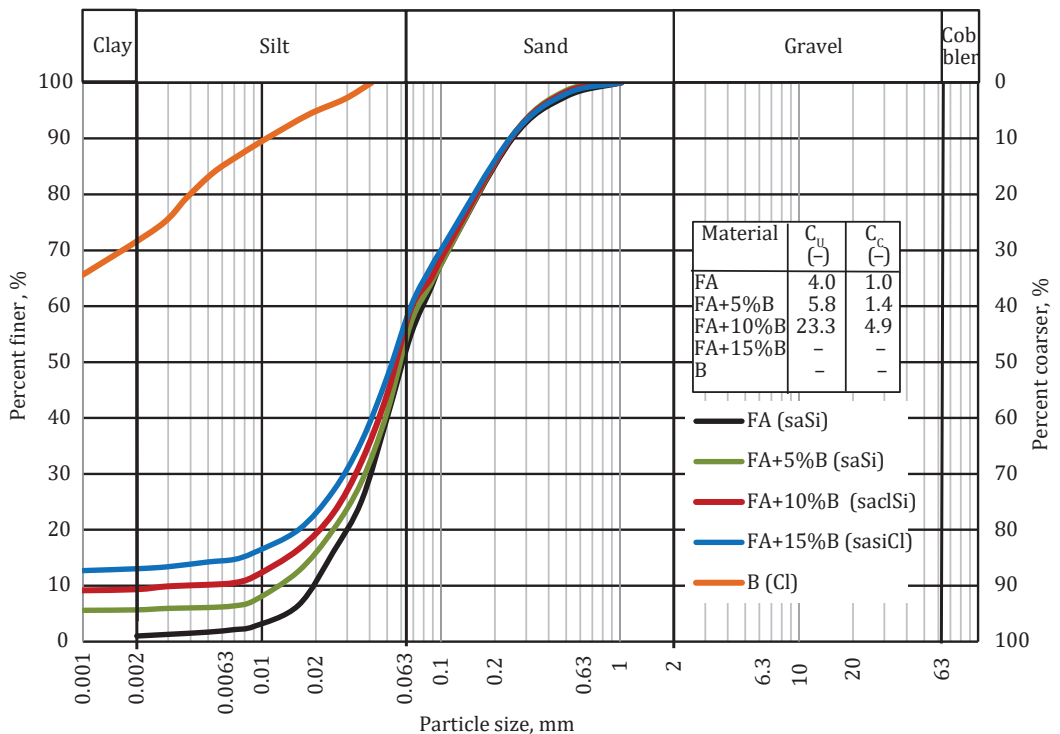


Figure 1. Grain size distribution curves of tested materials before compaction

(sasiCl) – FA+15%B according to ISO 14688-2 standard (2017). Bentonite grading corresponds to clay (Cl). Tested mixtures had a certain amount of finer particles, which was caused by the bentonite addition. Based on the grain size distribution curves, the coefficient of uniformity, C_u , and the coefficient of curvature, C_c , of tested materials were calculated. It was impossible to get effective sizes for the bentonite, which was caused by the character of the grain distribution curve. According to ISO 14688-2:2017, only fly ash can be assessed as uniformly graded. The chemical composition and loss on ignition (LOI) value of tested fly ash (FA) and bentonite (B) are given in Table 1.

According to ASTM C 618 (ASTM International, 2019) classification, tested combustion by-products can be classified as class F (except for LOI) fly ash. This type of fly ash contains at least 70% pozzolanic compounds (silica oxide SiO_2 , alumina oxide Al_2O_3 , and iron oxide Fe_2O_3). In the case of the fly ash from Białystok Thermal Power Station, the sum of these compounds according to Table 2 is equal to 76.91%.

Maximum dry density (MDD) and optimum moisture content (OMC) of fly ash and fly ash-bentonite mixtures were established according to Standard Proctor compaction tests following European Standard (EN 13286-2:2010). In the case of fly ash and its mixtures, the compaction parameters can be obtained for the material compacted only once (Zabielska-Adamska, 2008). It is caused by the crushing of spherical grains filled with smaller grains during re-compaction. Tested materials get then different physical properties – MDD value increases with the decrease in OMC compared to once compacted material.

Table 1. Chemical composition of materials used in laboratory tests

Chemical Compound	Percentage, %	
	Fly ash	Bentonite
SiO_2	43.28	71.62
Al_2O_3	31.81	18.37
Fe_2O_3	1.82	–
CaO	1.10	3.09
MgO	2.16	2.58
Na_2O	–	4.34
K_2O	3.42	–
TiO_2	0.63	–
LOI	12.45	–

Compaction parameters and specific gravity values of materials tested in this study are presented in Table 2.

According to Table 2, with the increase in bentonite amount in the mixture, the MDD values increase, and the OMC values decrease. Bentonite has the highest value of specific density and, in the case of mixtures the addition of bentonite causes an increase in specific density.

In Poland, the requirement for granular material, which can be used as an embankment fill, is the relative compaction:

$$I_s = \frac{\rho_d}{\rho_{dmax}}, \quad (9)$$

where ρ_d is the field density of soil, and ρ_{dmax} is maximum dry density (MDD) determined by standard compaction. The minimum value of I_s is dependent on the road type. The relative compaction value assumes that for a given road type, the load will not cause the excessive settlement of the embankment. On the construction site, to check the compaction of the soil in the embankment, a static plate load test (VSS) or dynamic load plate test is used. The VSS test gives values of primary (E_1) and secondary modulus of elasticity (E_2) and effective strain (I_0). The dynamic load plate test allows obtaining dynamic deformation modulus (E_{vd}), based on which, using empirical formulas, I_s can be calculated. To estimate the settlement of the embankment, the consolidation tests for the compacted material are conducted, and in the field, the monitoring of the settlement is often checked. The structural conditions for the material which will be built in the embankment are to get maximum density, which is possible by the compaction of the material at its optimum moisture content (OMC) and is dependent on the compaction energy. Properly compacted material should have sufficient bearing capacity to avoid excessive settlement.

Table 2. Geotechnical properties of tested materials

Material		Specific density $\rho_s, \text{g/cm}^3$	Maximum dry density MDD, g/cm^3	Optimum moisture content OMC, %
Bentonite	B	2.45	–	–
Fly ash	FA	2.18	1.073	40.0
Fly ash + 5% of bentonite	FA+5%B	2.18	1.100	39.0
Fly ash + 10% of bentonite	FA+10%B	2.22	1.118	36.3
Fly ash + 15% of bentonite	FA+15%B	2.24	1.134	33.0

2.2. Methods

Laboratory tests of the compressibility and one-dimensional consolidation of fly ash-bentonite mixes and fly ash were conducted using the Rowe and Barden type consolidation cell. In this type of consolidometer, the sample under conditions of no lateral strain is hydraulically loaded. The compression of the specimen under pressure is measured by means of vertical deformation. Settlement due to one-dimensional compression results from a decrease in the volume of the voids and can be analysed in terms of effective vertical stress.

Tests were carried out on compacted samples of fly ash and fly ash with variable percentages of bentonite additions. The material was dried, and then, to the fly ash an appropriate amount of water was added. To prevent drying and provide uniform moisture content, the prepared materials were stored in an airtight container for 24 h. Bentonite was added to the fly ash and thoroughly mixed right before the sample preparation. Bentonite amounts were 5, 10 and 15% by the dry mass of the sample. The amount of water needed to get the optimum moisture content of the materials was calculated, considering the fact that in the case of mixtures, the bentonite will be added. The prepared material was compacted in three layers in the mould, in which the consolidation ring from the Rowe and Barden cell was placed. The disc sample had the following dimensions: diameter $D = 70$ mm and height $H = 25$ mm. The mass of the FA and that of FA+B mixes were adequate

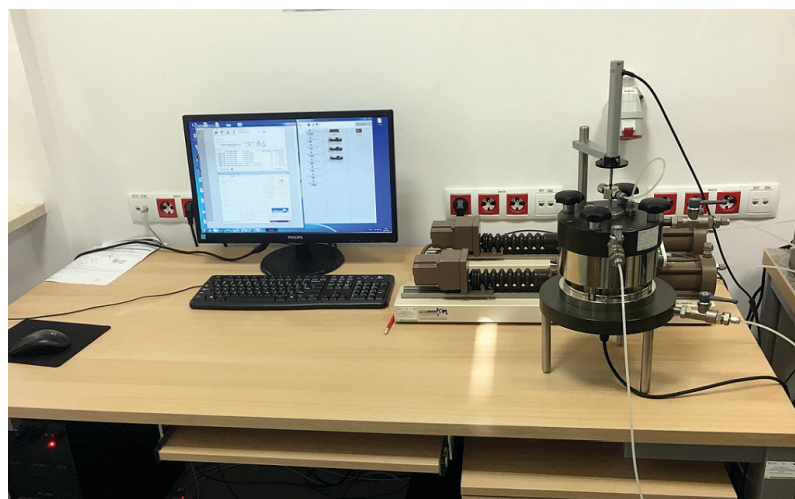


Figure 2. Consolidation cell assembly during the test

to get their maximum dry density (MDD) correspond to the one derived from the Standard Proctor method (see Table 2) at their optimum moisture content (OMC). To avoid clogging porous stones placed on the bottom and the top of the sample, filter paper was used. After sample preparation, the assembly of the consolidation cell was performed. The results during the tests were saved by a computer program. The saturation of the sample and applying stress was possible thanks to pressure controllers. The assembly of the apparatus is presented in Figure 2.

The literature (Zabielska-Adamska, 2018) indicates that the conditions of full and partial saturation are important in determining compression and settlement characteristics of the compacted fly ash. According to British Standard (1377-6:1990), seating pressure of 5 kPa was applied to the sample. The first step of the test was the sample saturation with water. The saturation was performed by using the back pressure method (Head & Epps, 2014). The level of saturation was checked by the B parameter (Skempton, 1954):

$$B = \frac{\Delta u}{\Delta \sigma'}, \quad (10)$$

where Δu is the pore water pressure corresponding to an increase in total vertical stress $\Delta \sigma'$.

Tests of compressibility were conducted on quasi-saturated samples (Shahu et al., 1999; Zabielska-Adamska, 2020) – state of the soil, where some of the air voids are closed, and water voids are continuous. In the paper, quasi-saturated samples are called saturated samples. From the relation of the B parameter to the degree of saturation S_r , minimum value of B can be determined. It is related to the fact that for some soil types (Lipiński & Wdowska, 2010) and fly ash (Zabielska-Adamska, 2020), when B is lower than 1.0, full saturation might be assumed. In the presented paper, the B parameter had values from 0.75 to 0.89 for tested samples. It corresponded to the S_r values from 0.98 to 0.99.

Consolidation tests (lasting 24 hours) for saturated samples were performed after parameter B reached the required value. The loading steps for fly ash specimens were as follows: 25, 50, 100, 200 and 400 kPa. In the case of mixtures of fly ash with bentonite, the steps were as follows: 50, 100, 200 and 400 kPa, which were caused by a higher value of effective stress during the saturation process. Additionally, to establish the impact of partial saturation on the compressibility characteristics of the materials, not fully saturated samples were tested directly after placing them in the consolidation cell.

3. Results and discussion

In Figure 3, the test results of the compressibility test of fly ash and mixtures of fly ash with bentonite compacted at OMC are presented as a relation between the vertical strain ε_v and effective stress σ_v' and the relation between the void ratio e and vertical stress σ_v' .

As shown in Figure 3, bentonite addition has an impact on the compressibility of fly ash samples. Fly ash-bentonite mixtures display smaller values of compressibility than fly ash samples. Compressibility decreases along with bentonite addition – the smallest values of deformation were obtained by FA+15%B sample. The compression index, C_c , is the slope of the compression curve in the loading stage presented in Figure 3, as the relation of void ratio e versus log pressure σ_v' . It indicates the amount of compression of the soil and has been calculated according to Equation (3). The values of C_c of tested materials are presented in Table 3.

The bentonite addition in an amount higher than 5% reduced the compressibility of the mixtures. The obtained values are consistent with the one presented in the literature.

Kaniraj & Gayathri (2004) for class F fly ash tested in the triaxial cell on fully saturated samples presented a value of C_c equal to 0.041 for the effective stress less than 300 kPa and 0.084 for effective stress from 300 kPa to 800 kPa. They divided the curve because of the different slopes. Sankar & Niranjana (2015) tested class F fly ash with the addition of cement. For pure fly ash compacted at OMC to MDD, the compression

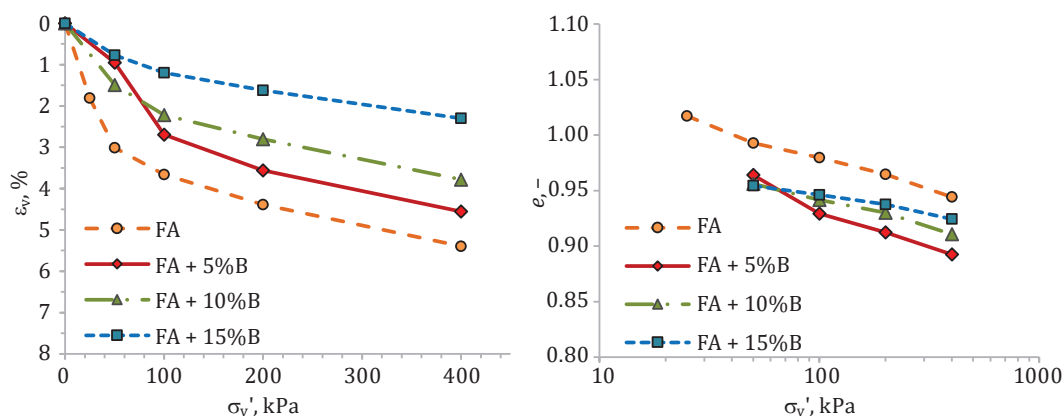


Figure 3. Vertical strain ε_v versus pressure σ_v' , and void ratio e versus log pressure σ_v' plots of tested materials compacted at OMC

index had a value of 0.044. However, the saturation of the sample was not controlled – the tested sample was immersed in water for 24 hours before the loading increment. Tu et al. (2009) tested class F fly ash using a control rate of strain test (CRS) in the consolidation chamber where the saturation of the sample could be controlled, and the values of C_c varied from 0.039 to 0.064.

Class F fly ash, tested in the conditions of controlled saturation of the sample, with bentonite addition in the amount of 10%, 20% and 50% (Mollamahmutoğlu & Yilmaz, 2001), had lower values of the compression indices – from 0.009 to 0.019. The C_c values were increased among the increasing bentonite content. However, the values were lower than obtained in the presented studies. It was caused by the fact, that fly ash and fly-ash bentonite mixtures had lower values of initial void ratios e_0 – from about 0.47 to 0.38. In other studies (Porbaha et al., 2000), where e_0 was equal to 1.02 and 0.85 for fly ash without additives, the C_c values were 0.078 and 0.036, respectively.

According to the literature (Head, 1986), the full saturation of the sample is the principle for the proper test procedure, although is sometimes neglected. Providing settlement characteristics of fly ash, tested in the condition of partial saturation, should be connected with the determination of saturation degree or B parameter. It is caused by the differences that may result from the settlement of fully and not fully saturated samples. Therefore, to present the test results, the laboratory test condition should be emphasized. To present the effect of partial saturation on the settlement of the fly ash and fly ash-bentonite mixtures, tests were conducted on the saturated samples and the samples before the saturation process. The results are presented in Figs. 4–7.

Table 3. The compression index values of tested materials

Material	C_c, (–)
FA	0.057
FA+5%B	0.061
FA+10%B	0.050
FA+15%B	0.033

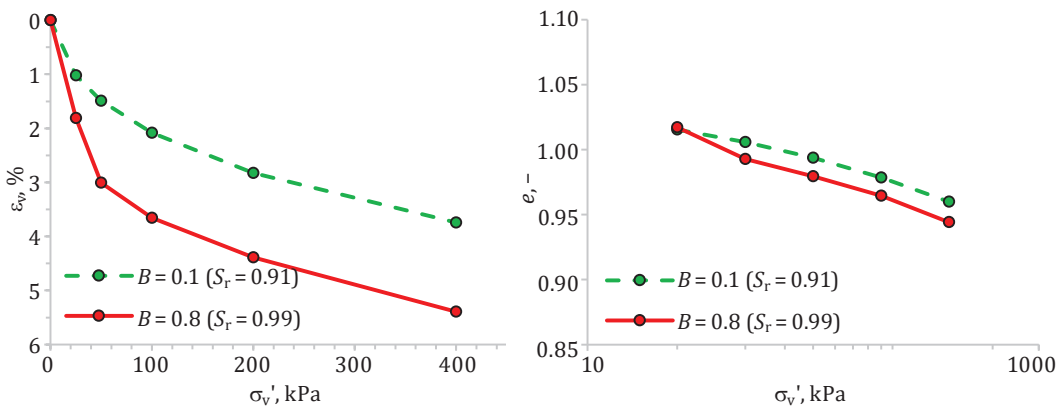


Figure 4. Vertical compression ε_v , % versus pressure σ_v' , and void ratio e versus log pressure σ_v' plots of saturated and non-saturated fly ash sample

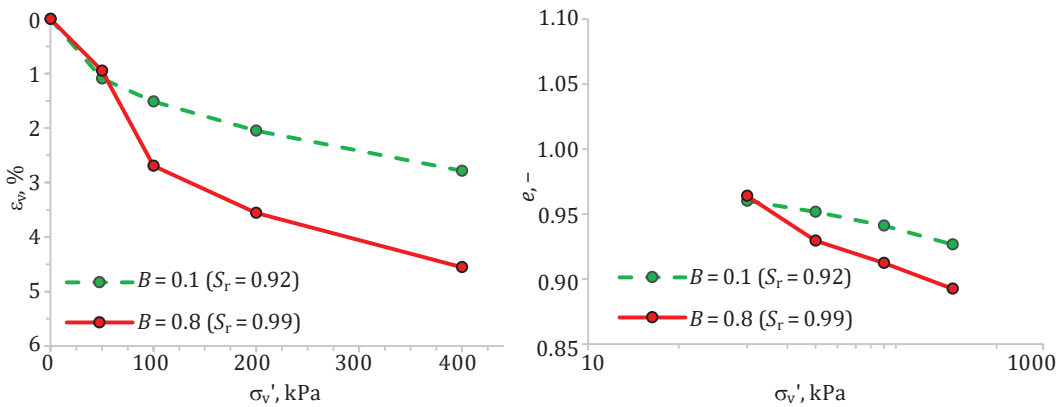


Figure 5. Vertical compression ε_v , % versus pressure σ_v' , and void ratio e versus log pressure σ_v' plots of saturated and non-saturated fly ash with 5% of bentonite sample

As it can be observed in Figs. 4–7, the settlement process of fully and partially saturated samples differs. During the test of partially saturated samples, after the load was applied, water initially was draining from the sample. After some time, the water was flowing into the sample, which was caused by suction. The differences in the strain values of saturated and partially saturated samples decreased according to an increase in bentonite amount in the mixture. In the case of FA+15%B, not fully saturated samples had higher values of a vertical strain – 4.4% at $\sigma_v' = 400$ kPa – than fully saturated samples ($\epsilon_v = 2.3\%$), which was caused by swelling of the saturated sample. The presented results are consistent with the research of fly ash in the literature (Zabielska-Adamska, 2018).

According to Announcement of the Minister of Infrastructure and Construction (2016), the maximum value of operational settlement of the surface of the embankment body and the ground should not exceed 10 cm. In the case of fly ash and its mixtures with bentonite, the vertical deformation at a vertical stress of 400 kPa was as follows: FA – 5.4%, FA+5%B – 4.6%, FA+10%B – 3.8%, and FA+15%B – 2.3% (see Figure 3). According to the Eurocode 1 (EN 1991-1-1) traffic load on the road pavement, for Load Model 1, at Lane no. 1 for the Tandem system is calculated as equal to 90.91 kN/m^2 and the UDL system – 9 kN/m^2 . Through the pavement, there is a dispersion of concentrated loads, so on the compacted soil (embankment fill), the smaller values of loads are applied. The load from pavement (dependant on its materials and layer thickness) should be taken into consideration either. It can be seen in Figure 3 that if the applied load is smaller, the vertical deformation

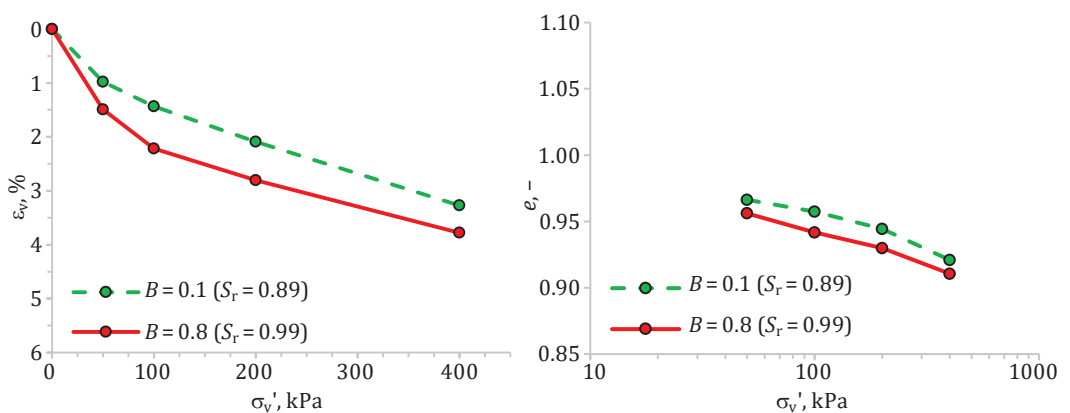


Figure 6. Vertical compression ϵ_v , % versus pressure σ_v' , and void ratio e versus log pressure σ_v' plots of saturated and non-saturated fly ash with 10% of bentonite sample

is lower. Tests were performed on the saturated samples. In the field, partial saturation mostly occurs. As the results show (see Figs. 4–6), for partially saturated samples, the vertical deformation was lower than for saturated, except FA+15% (see Figure 7).

In Figure 8, the results of the consolidation test of the FA+5%B sample are shown. As observed, the consolidation process is relatively fast after the load is subjected. The main settlement (from 72 to 90% of the entire height of a given settlement stage) took place after load application in a short period of time – within one minute. As can be observed for the FA+5%B, the further settling is smaller (accounts for 18 to 10% of the settlement height at each step of loading). The same tendency was observed for the samples of FA, FA+10%B, and FA+15%B. In the literature (Kaniraj & Gayathri, 2004), a similar trend was observed. It was suggested then that calculation of the hydraulic conductivity based on the consolidation curves gave divergent results in comparison with results obtained from direct laboratory tests. However, in the case of tested materials, after immediate settling, the additional settlement occurred. In studies by Porbaha et al. (2000), the settlement took place in the first minute of test duration, and there was no additional settling. It might occur because the saturation of the sample was not controlled, so there was uncertainty whether the sample was fully saturated.

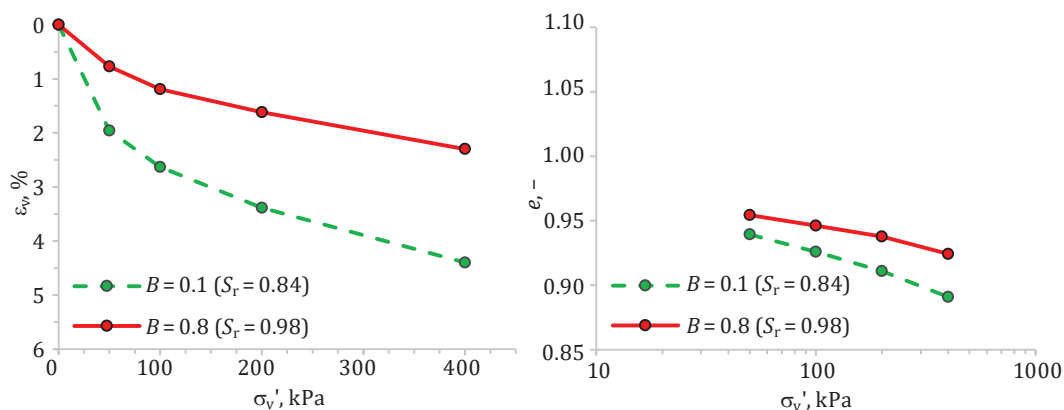


Figure 7. Vertical compression ε_v versus pressure σ_v' , and void ratio e versus log pressure σ_v' plots of saturated and non-saturated fly ash with 15% of bentonite sample

The coefficient of consolidation, c_v , which governs the rate of consolidation, was determined for each load increment. Two curve-fitting methods were used, log-time and square-root-of-time, to calculate c_v from the consolidation test results, using Eqs. (7) and (8). These methods can be used when the primary consolidation takes a long time, and as it can be observed, it is a rather quick process in fly ashes (within one minute). However, researchers use these methods. Additionally, c_v based on the results from the direct test of hydraulic conductivity (Wasil, 2020) was calculated using Equation (6). The obtained values are presented in Table 4.

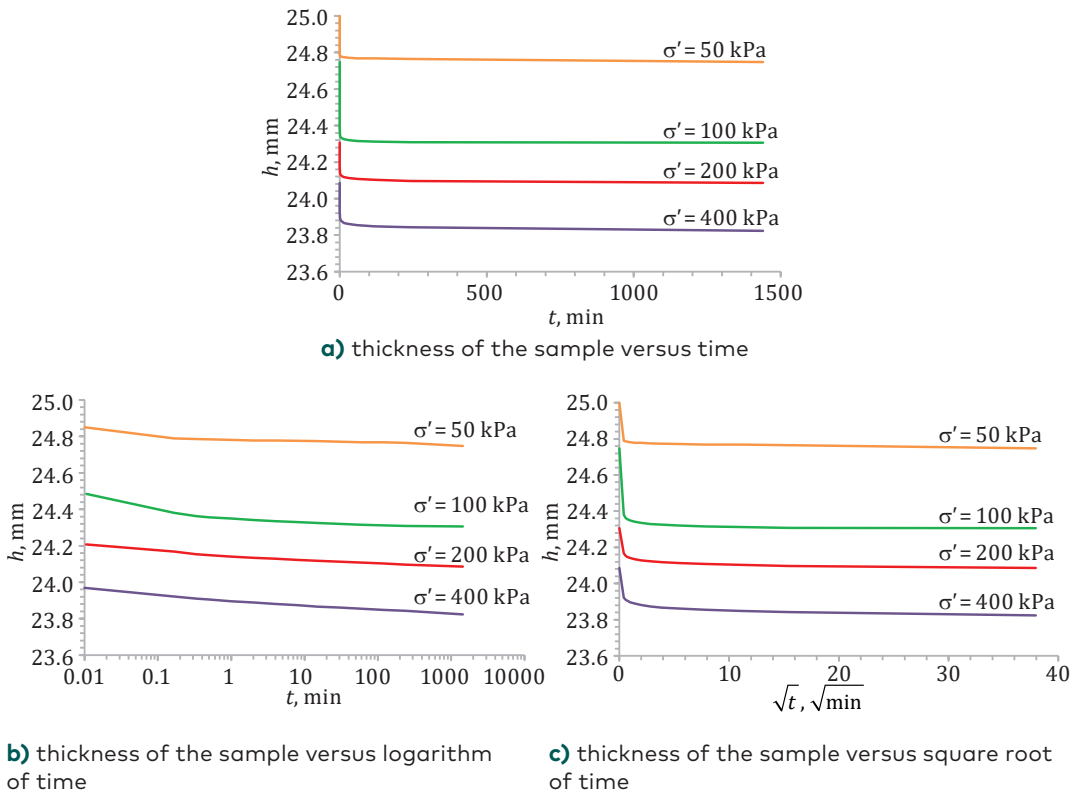


Figure 8. Consolidation test results of FA+5%B sample

As can be observed in Table 4, values from the direct test vary from values obtained based on fit-curve methods. The highest difference – to three orders of magnitude – can be observed in the case of FA samples, where c_v calculated from direct hydraulic conductivity tests has the lowest values. In other cases, values do not vary by more than one order of magnitude. In general, the log-time method results in the lowest

Table 4. Values of coefficient of consolidation c_v of tested materials derived from different approaches

Consolidation pressure, kPa			25	50	100	200	400
Coefficient of consolidation c_v , m ² /s	FA	sqrt-time	$8.6 \cdot 10^{-7}$	$7.5 \cdot 10^{-7}$	$5.9 \cdot 10^{-7}$	$3.3 \cdot 10^{-7}$	$1.3 \cdot 10^{-7}$
		log-time	$1.3 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$	$7.0 \cdot 10^{-7}$	$6.0 \cdot 10^{-7}$	$5.2 \cdot 10^{-7}$
		direct test	$1.4 \cdot 10^{-9}$	$1.7 \cdot 10^{-9}$	$1.8 \cdot 10^{-9}$	$2.4 \cdot 10^{-9}$	$8.0 \cdot 10^{-9}$
	FA+5%B	sqrt-time	–	$6.1 \cdot 10^{-7}$	$2.6 \cdot 10^{-6}$	$1.7 \cdot 10^{-6}$	$1.7 \cdot 10^{-6}$
		log-time	–	$1.7 \cdot 10^{-6}$	$4.5 \cdot 10^{-7}$	$3.4 \cdot 10^{-7}$	$1.2 \cdot 10^{-7}$
		direct test	–	$3.8 \cdot 10^{-7}$	$6.6 \cdot 10^{-7}$	$2.5 \cdot 10^{-6}$	$3.4 \cdot 10^{-6}$
	FA+10%B	sqrt-time	–	$2.2 \cdot 10^{-6}$	$4.4 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$	$1.2 \cdot 10^{-6}$
		log-time	–	$1.0 \cdot 10^{-6}$	$2.8 \cdot 10^{-7}$	$1.9 \cdot 10^{-7}$	$1.9 \cdot 10^{-7}$
		direct test	–	$4.4 \cdot 10^{-7}$	$1.4 \cdot 10^{-6}$	$3.5 \cdot 10^{-6}$	$3.3 \cdot 10^{-6}$
	FA+15%B	sqrt-time	–	$3.4 \cdot 10^{-6}$	$2.7 \cdot 10^{-6}$	$1.8 \cdot 10^{-6}$	$7.4 \cdot 10^{-7}$
		log-time	–	$7.6 \cdot 10^{-7}$	$3.4 \cdot 10^{-7}$	$1.9 \cdot 10^{-7}$	$1.1 \cdot 10^{-7}$
		direct test	–	$6.8 \cdot 10^{-7}$	$1.3 \cdot 10^{-6}$	$2.4 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$

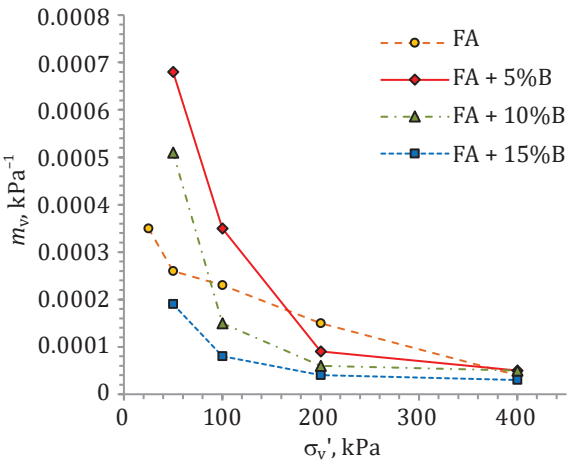


Figure 9. Variation of coefficient of volume change m_v versus effective stress σ'_v for fly ash and fly ash-bentonite mixtures

values of c_v , except fly ash sample, where lower values were obtained by the sqrt-time method. The values obtained on the basis of direct tests increase with an increase in consolidation pressure (one exception is for the FA+10%B, where c_v at consolidation pressure of 400 kPa is slightly lower than at consolidation pressure of 200 kPa). In general, values of coefficient of consolidation derived from the consolidation tests decrease with an increase in consolidation pressure. A similar tendency was observed by Pandian & Balasubramonian (1999). However, values they obtained from the log-time method were higher than from the sqrt-time method. In the case of fly ash in the present study trend is the same. In the case of fly ash-bentonite mixtures, higher values of c_v were obtained by the sqrt-time method.

The coefficient of consolidation of Indian fly ash (Kaniraj & Gayathri, 2004) had values from $8 \cdot 10^{-6}$ to $2 \cdot 10^{-4}$ m²/s and agreed with c_v values for silts. Kaniraj & Gayathri (2004) recommended that the hydraulic conductivity of fly ashes should not be based on the c_v from the consolidation test, but should be tested directly and then the coefficient of consolidation should be calculated using Equation (6).

Figure 9 presents the variation of coefficient of volume change m_v versus effective stress σ_v' for fly ash and its mixtures with variable bentonite addition.

As it can be observed (see Figure 9), fly ash with 15% of bentonite addition had the lowest compressibility among the tested materials. The m_v values decreased with increasing effective pressure. In the case of fly ash-bentonite mixtures, the higher amount of bentonite results in lower values of m_v at a given effective stress level. Results for fly ash are consistent with the literature (Kaniraj & Gayathri, 2004). Fly ash without additives has a different distribution of m_v values than mixtures with bentonite.

Conclusions

The present study has investigated the bentonite content and laboratory tests conditions on compressibility behaviour and consolidation characteristics of the alternative material useful for the earth structures, such as road embankments and ground beneath the embankment. Fly ash from the Bialystok Thermal and Power Station and its mixtures with bentonite have been tested. The following conclusions can be derived from the study:

1. The consolidation process in fly ash and fly ash with 5, 10, and 15% of bentonite is rather quick – the main settlement takes place in a short time after subjecting the load, and further settling is small. It confirms the similarity of tested materials to non-plastic

silts, as earlier literature suggests. It is advantageous in terms of embankment settlement under road construction.

2. Bentonite addition reduces the vertical deformation of fully saturated fly ash-bentonite mixtures. The lowest value was obtained for FA+15%B samples. It was confirmed by the coefficients of volume change m_v , which for fly ash with 15% of bentonite addition sample obtained the lowest values.
3. Compressibility of compacted fly ash and fly ash-bentonite mixtures decreases along with bentonite addition – the smallest deformation values were obtained by FA+15%B sample. The compression index values of tested materials vary from 0.061 to 0.033. Small values of C_c indicate that properly compacted fly ash and fly ash-bentonite mixture earth structures will not be subjected to large settlements. In addition, the main deformation of tested materials occurs in a short period of time after the load is subjected. It is advantageous for the material used in earth structures, such as embankments and fills, because no large deformation will occur further.
4. The coefficient of consolidation derived from the direct hydraulic conductivity tests had different values than those derived from fit-curve methods. The lowest values were obtained for fly ash in the direct test, where the order of magnitude was equal to 10^{-9} . For the same material, values obtained from fit-curve methods were two or three orders of magnitude higher. Values obtained for fly-ash bentonite mixtures from direct and indirect methods had values in the same order, or one order in magnitude different, and the range of the c_v was about 10^{-6} and 10^{-7} m²/s.
5. The conditions of laboratory tests in terms of saturation of the sample with water are important. Saturation of the sample affects the compressibility characteristics of fly ash, fly ash with 5, 10, and 15% of bentonite addition. In general, for partially saturated samples, the deformation was lower than for fully saturated samples, except for the FA+15%B sample.
6. The compressibility laboratory tests confirmed that fly ash and fly ash-bentonite mixtures, where the bentonite addition is 5, 10, and 15%, could substitute natural soils used in earth structures.

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