Available online at www.sciencedirect.com

ScienceDirect

Journal of Hazardous Materials 151 (2008) 481–489

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

# Laboratory compaction of fly ash and fly ash with cement additions

Katarzyna Zabielska-Adamska*

*Bialystok Technical University, Faculty of Civil and Environmental Engineering, Wiejska Street 45E, 15-351 Bialystok, Poland*

Received 24 November 2006; received in revised form 4 June 2007; accepted 6 June 2007
Available online 8 June 2007

## Abstract

The use of power-industry wastes as a material for earthen structures depends on its compactibility. It has been confirmed that a fly ash/bottom ash mix compacted several times in Proctor's moulds are not representative. The relationship between dry density of solid particles and water content for re-used waste samples was determined. The re-compaction effect on grain-size distribution, density of solid particles, specific surface and sand equivalent of wastes was investigated. Tests were conducted on fly ash samples compacted by the Standard and Modified Proctor methods. Another aim of the paper was to investigate the influence of cement additions on the compactibility of a fly ash/bottom ash mix. Waste samples in the natural state and with different percentages of cement additions (2, 5 and 10%) were compacted by both impact compaction methods to obtain compactibility curves $\rho_d(w)$. It was found that cement addition resulted in an increased $\rho_{d\,max}$ value, while $w_{opt}$ decreased. Linear regression relationships for changes in compaction parameters after cement stabilisation are also given.

*Keywords:* Fly ash; Compaction; Compaction parameters; Stabilized fly ash; Cement addition

## 1. Introduction

Soil compactibility is the ability to obtain maximum possible dry density of solid particles $\rho_d$, and is dependent on compaction energy, the way it is used, as well as the type of soil and its moisture content. An increase in dry density, $\rho_d$, at constant soil moisture is a compaction effect, which differs from the soil consolidation process, where the $\rho_d$ increase is caused by water drainage from porous soils. During non-cohesive soil compaction, the moisture increase from dry state initially causes an increase in capillary forces, which create difficulties in soil grain displacement. A further moisture increase causes a decrease in capillary forces—soil grain displacement is made easier and soil is compacted. After approaching the state where soil pores are completely saturated by water, water and compressed air in water intercept a load, which is suddenly applied. Soil grain displacement does not occur, but soil can fluidize itself or become loose [1].

Soil compactibility is measured by the degree of compaction $I_s$, which is determined by:

$$I_s = \frac{\rho_d}{\rho_{d\,max}} \tag{1}$$

where $\rho_d$ is the dry density of solid particles determined for soil compacted in an embankment and $\rho_{d\,max}$ is the maximum dry density of solid particles determined in the laboratory for the same material as $\rho_d$.

Laboratory soil compactibility tests involve compaction in standardized ways at various moisture contents and plotting the relationship between dry density of solid particles (or unit weight) and moisture content. The moisture content at which compacted soil reaches the maximum dry density of solid particles is called optimum water content $w_{opt}$. Compaction curves $\rho_d(w)$, tested at various values of compaction energy, run asymptotically to the line of maximum compaction, called the zero air voids line, calculated assuming that soil pores are completely filled with water, as well as the line of saturation degree $S_r = 1$, which determines the degree of saturation when the soil sample is completely saturated.

The most common methods, which are applied for determining compaction parameters of fine-grained soils, are dynamic

---

* Tel.: +48 85 746 96 09; fax: +48 85 746 95 59.
*E-mail address:* kadamska@pb.bialystok.pl.

0304-3894/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2007.06.011

### Nomenclature

| | |
|---|---|
| $C_C$ | coefficient of curvature |
| $C_U$ | coefficient of uniformity |
| $D$ | percentage cement addition (%) |
| $I_s$ | degree of compaction |
| MP | Modified Proctor method |
| $S_r$ | degree of saturation |
| SEM | scanning electron microscopy |
| SP | Standard Proctor method |
| $w$ | water content (%) |
| $w_{opt}$ | optimum water content (%) |

*Greek symbols*

| | |
|---|---|
| $\rho_d$ | dry density (Mg/m$^3$) |
| $\rho_{d\,max}$ | maximum dry density at optimum water content (Mg/m$^3$) |
| $\rho_s$ | solid particle density (Mg/m$^3$) |

methods. The values, $\rho_{d\,max}$ and $w_{opt}$, are obtained by Proctor's method (called the Standard Proctor test), with compaction energy corresponding to field compaction conditions by lightweight soil compactors, and the modified AASHTO method (also called the Modified Proctor test) with energy corresponding to field compaction by heavy compactors.

For many years, attempts have been made to correlate compaction parameters with physical properties of mineral soils. They can be divided on two categories. The first includes numerical correlation equations obtained for cohesive and non-cohesive soils, which relate the compaction parameters with soil classification descriptors, Atterberg's limits [2], density of solid particles and grain-size distribution [3]. The second, less popular, method includes studies involving only the modelling of the compactibility curve rather than only compaction characteristics, commonly using an artificial neural network modelling techniques for curve simulation [4].

The exact establishment of fly ash compaction parameters is justified by the relationship between the mechanical properties of fly ash and moisture content at compaction, as in the case of cohesive soils and, particularly, the considerable loss of bearing capacity of fly ash, based on the California Bearing Ratio for fly ash compacted wet of optimum [5]. The aim of the paper was to determine a compaction test procedure and its influence on fly ash compaction parameters for standard and modified compaction methods. An effort was made to establish an influence of re-compaction on fly ash physical properties. Since it is often necessary to improve fly ash as regards its high permeability, tests on fly ash mixed with various percentage cement additions (2, 5 and 10%) were also conducted. Another aim was to obtain compaction parameters from compactibility tests of stabilized fly ash as related to cement additions and establish statistical correlation relationships.

## 2. Laboratory tests of fly ash compaction

### 2.1. Literature review

For the sake of the macroscopic similarity of power-industry waste to fine-grained mineral soils, dynamic Standard and Modified Proctor methods are the most commonly used for determining fly ash and bottom ash compaction parameters, $\rho_{d\,max}$ and $w_{opt}$.

One of the first compactibility tests, on waste from a power-industry lagoon, was performed by Raymond and Smith [6], who mentioned that the test procedure could affect compaction parameters. They noticed, during compaction by the Standard Proctor method, a difference between fly ash compaction curves when samples, wetted during the test, were compacted many times, or when every point on the curve was obtained using "fresh" samples. It was later confirmed by Leonards and Bailey [7], who tested (via Modified Proctor) a fly ash and bottom ash mix from a dry disposal site. They explained the observed effect by grain degradation. Although the above phenomenon has been known for many years, many researchers still widely use re-compacted samples for determining fly ash compaction parameters. A number of authors mention difficulties in obtaining a good correlation between water content and dry density, which probably might be caused by repeated compaction. It is necessary to say that many national standards allow soil sample re-compaction, such as the Polish Standard, where the soil sample can be compacted five times [8].

Trivedi and Sud [9] conducted compactibility tests on pond ash with the aid of a vibration table or vibration plate in the field in comparison to the Standard Proctor method. They found that the density in the vibration test was lower than in the Proctor test at the dry side of optimum. Additionally, in the vibration test, a reduction in density, increasing with moisture content, was observed, which is similar to non-cohesive soils. Generally, the vibration tests lead to higher compaction parameters than the dynamic method. Kayabalı and Buluş [10] compacted bottom ash by the Standard Proctor method or with a vibratory hammer used in a Proctor's mould. A good correlation was not obtained between water content and dry density for both research methods.

An interesting study on a fly ash/bottom ash mix was carried out using different bottom ash quantities, ranging from 0 to 100%, during compaction by the Standard Proctor method [11,12]. Addition of bottom ash leads to an increasingly better-graded size distribution, which allows fly ash to obtain a $\rho_{d\,max}$ increase. The higher $w_{opt}$ associated with higher fly ash quantities follows from the need to release capillary tension from the greater surface area. Decreasing bottom ash content shows two distinct characteristic. When fly ash increases from 0 to 25%, an increase in $\rho_{d\,max}$ and a decrease in $w_{opt}$ are observed, as in the case of silt and sand mix, because the size-grain distribution is improved, but bottom ash grains are still in contact. A higher fly ash content separates the bottom ash grains and the $\rho_{d\,max}$ gradually decreases, while $w_{opt}$ increases. The greatest $\rho_{d\,max}$ and lowest $w_{opt}$ values are obtained when fly ash content in the mix is equal to 25% [12]. Lee et al. [12] also stated that compaction by means of vibration became increasingly more effective as the fly ash content decreased. Other researchers have pointed out the flat shape of the waste compaction curve [13].

### 2.2. Tested fly ash

Compactibility tests of power industry wastes were conducted on samples of six shipments of a fly ash and bottom ash mixture from hard-coal combustion at the Bialystok Thermal-Electric Power Plant and stored in an old dry-storage yard (finished storage), where slag is up to 10% of the stored wastes. Therefore, due to the low content of slag in the mixture, in the paper, the mix is referred to as fly ash.

Grain-size distribution of all the tested fly ash samples corresponds to sandy silt. In the laboratory, graining of mineral soil is estimated by uniformity and curvature coefficients. According to this criterion, tested fly ash qualified as a material responding poorly to compaction. Density of solid particles, $\rho_s$, of all the fly ash samples ranged from 2.25 to 2.32 Mg/m$^3$.

### 2.3. Laboratory compaction tests

Fly ash tests for optimum water content, $w_{opt}$, and maximum dry density of solid particles, $\rho_{d\,max}$, were initially conducted according to the classic Proctor method, allowing repeated ramming for the same soil specimen. Compaction curves obtained for one of the fly ash shipments by the Standard Proctor method are shown in Fig. 1. Values $w_{opt}$ and $\rho_{d\,max}$, obtained for the same fly ash shipment, are in following ranges: $w_{opt} = 36.0–37.5\%$, $\rho_{d\,max} = 1.144–1.164$ Mg/m$^3$. Due to the scatter of the obtained values and the completely different shapes of the compaction curves, it was confirmed that re-compacted specimens should not be taken into consideration.

Next, tests on six different fly ash shipments, compacted by the Standard and Modified Proctor methods, were performed. During the tests, fly ash specimens were compacted once only in a Proctor's mould—each point of the compaction curve ($\rho_d$, $w$) was determined for separately prepared specimens. Specimens were moisturized so as to produce an increase in moisture content of each subsequent specimen of about 2% and were then stored for 24 h in closed tins. Compactibility tests of virgin specimens were performed and then the same specimens were used several times to determine the influence of repeated ramming on fly ash compaction. Curves of $\rho_d(w)$ relationships, obtained by both compaction methods for two fly ash shipments, when the same fly ash specimen was rammed only once or several times, are shown in Figs. 2 and 3. It should be stated here that Figs. 1 and 2 present curves determined for the same fly ash shipment, but obtained when re-compaction was permitted or when only virgin samples were used. As can be observed in Fig. 2, the two independent compaction curves of the first single-compacted fly ash shipment, which were obtained by the standard method, are very close to each other. Compactibility curve shape, representing the relationship $\rho_d(w)$, clearly depends on compaction energy and the number of repeated rammings. Curves obtained for once-compacted fly ash are flat for both compaction methods and more so for the standard than modified method.

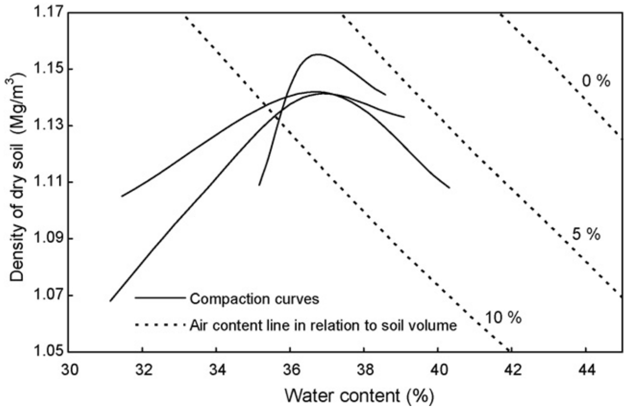


Fig. 1. Compaction curves obtained by the Standard Proctor method for the first fly ash shipment when every compaction curve was established based on one specimen.

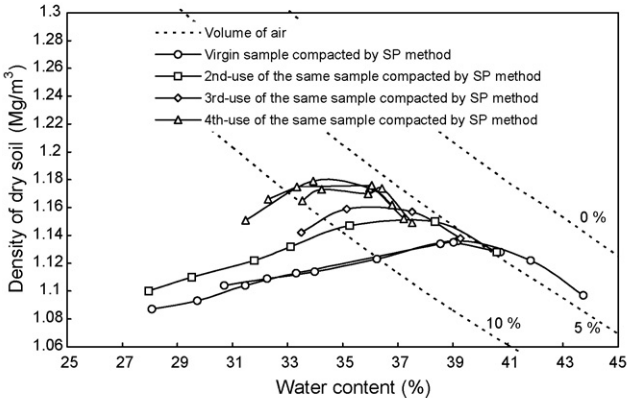


Fig. 2. Compaction curves obtained for the first fly ash shipment by the Standard Proctor method, when the same sample was compacted once or repeatedly.

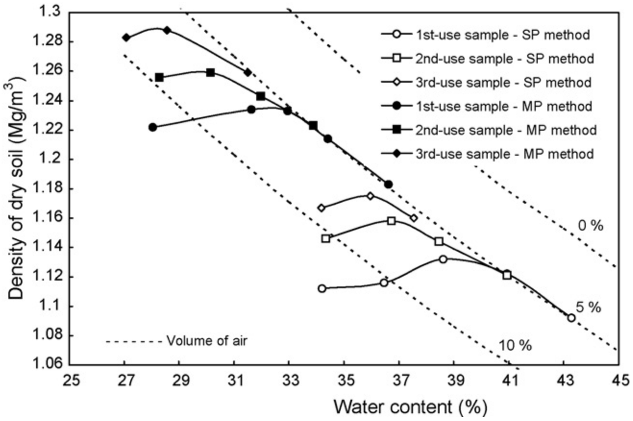


Fig. 3. Compaction curve for the second fly ash shipment, determined by the Standard (SP) and Modified Proctor (MP) methods when the same sample is compacted once or repeatedly.

### 2.4. *Report on test results*

It should be stated that fly ash specimens compacted many times could not be considered as representative. Values for maximum dry density of solid particles increased with number of repeated compaction at decreasing optimum water contents, in comparison with specimens compacted only once under the same conditions. It should be emphasized that laboratory determination of compaction parameters, $\rho_{\mathrm{d\,max}}$ and $w_{\mathrm{opt}}$, according to standards, which allow repeated sample compaction, leads to incorrect evaluation of the compactibility effect. Compaction parameters obtained for the same fly ash shipment could be completely different if re-use of the same sample was allowed or not (Figs. 1 and 2).

The phenomenon of obtaining greater dry densities after the second ramming of the same fly ash specimens is also known for mineral soils. A simple explanation of this effect is the apparent plastic volumetric-strain, which is caused by successive fly ash compactions. The differences between fly ash compactibility curves, when the same material was used for various graph points or when the same material was tested only once, were previously observed in fly ash classic works on fly ash [6,7]. In these studies the researchers stated that crumbling of the dynamically rammed fly ash grains contributed to better waste compaction, but this thesis had not been explained.

The obtained parameters $\rho_{\mathrm{d\,max}}$ and $w_{\mathrm{opt}}$, for six fly ash shipments tested by the standard and modified methods (compacted once and many times) are displayed in Fig. 4. The determined points lie along a line parallel to the saturation degree line $S_{\mathrm{r}}$. On the basis of all the test results, a linear regression relationship, of maximum dry density as a function of moisture content $\rho_{\mathrm{d\,max}} = f(w_{\mathrm{opt}})$, was established and is described as follows:

$$\frac{1}{\rho_{\mathrm{d\,max}}} = 0.458 + 0.011 w_{\mathrm{opt}} \qquad (2)$$

The correlation coefficient calculated for the relationship $\rho_{\mathrm{d\,max}} = f(w_{\mathrm{opt}})$ is equal to $R = 0.9783$, which indicates that the established regression equation explains over 95.6% of the variations in optimum water content.

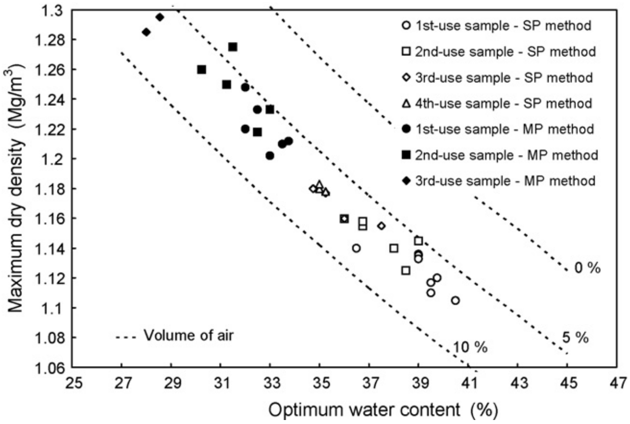


Fig. 4. Points ($\rho_{\mathrm{d\,max}}$, $w_{\mathrm{opt}}$) obtained for six fly ash shipments by both compaction methods when the same sample is compacted once or repeatedly.

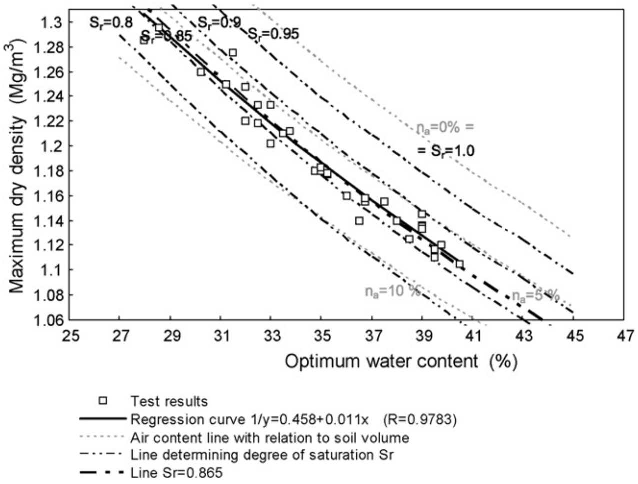


Fig. 5. Relationship $\rho_{\mathrm{d\,max}} = f(w_{\mathrm{opt}})$ for all fly ash test results in comparison to line of air content with relation to sample volume, and line determining degree of saturation $S_{\mathrm{r}}$.

The regression line $\rho_{\mathrm{d\,max}} = f(w_{\mathrm{opt}})$, in comparison to the lines of air volume and saturation degree $S_{\mathrm{r}}$, is presented in Fig. 5. It was found that the regression line $\rho_{\mathrm{d\,max}} = f(w_{\mathrm{opt}})$ determined for tested fly ash agreed approximately with $S_{\mathrm{r}} = 0.865$, describing the relationship:

$$\rho_{\mathrm{d\,max}} = \frac{86.5\rho_{\mathrm{s}}}{w_{\mathrm{opt}}\rho_{\mathrm{s}} + 86.5} \qquad (3)$$

where $\rho_{\mathrm{s}}$ is the solid particle density.

Fly ash from the old dry-storage yard of the Bialystok Thermal-Electric Power Plant is a material which can be easily compacted. Fly ash optimum water contents are included between the lines of air content in relation to sample volume 5–9% (most commonly 6–7%) with the Standard Proctor method and 5–8% with the Modified method. The porosity of fly ash compacted at optimum water content is in the range 0.501–0.516 (average value: 0.508) with the Standard Proctor method and 0.454–0.474 (average value: 0.466) with the Modified test. Thus, high values of minimum porosity are obtained in the densest state determined (fly ash dried to constant mass) by vibration. The range of porosity tested by means of a vibratory fork is from 0.524 to 0.548, which confirms worse compaction results for fly ash by vibration [12].

### 2.5. *Influence of compaction on selected physical fly ash properties*

To establish the influence of compaction on physical properties of fly ash, such as grain-size distribution, density of solid particles, sand equivalent and total specific surface, fly ash, in a natural state and after compaction, were tested. On the basis of grain-size distribution tests, which were performed for fly ash in a natural state and after several rammings in a Proctor's mould by standard energy, it can be concluded that graining changes insignificantly after compaction. The content of grains >0.071 mm is equal to:

- 45.86% in the natural state,
- 44.61% after the third ramming using the same sample,
- 37.05% after the fifth ramming using the same sample.

The compaction effect on solid particle density, $\rho_s$, was not established. Average values of $\rho_s$, determined for the same fly ash sample in the natural state and after five compactions using the Standard Proctor test, were similar. Experimental results show that greater maximum densities of solid particles, $\rho_{d\,max}$, obtained after multiple ramming of the same fly ash sample, was not caused by the increase in solid particle density, $\rho_s$, after liquidation of closed voids in fly ash grains.

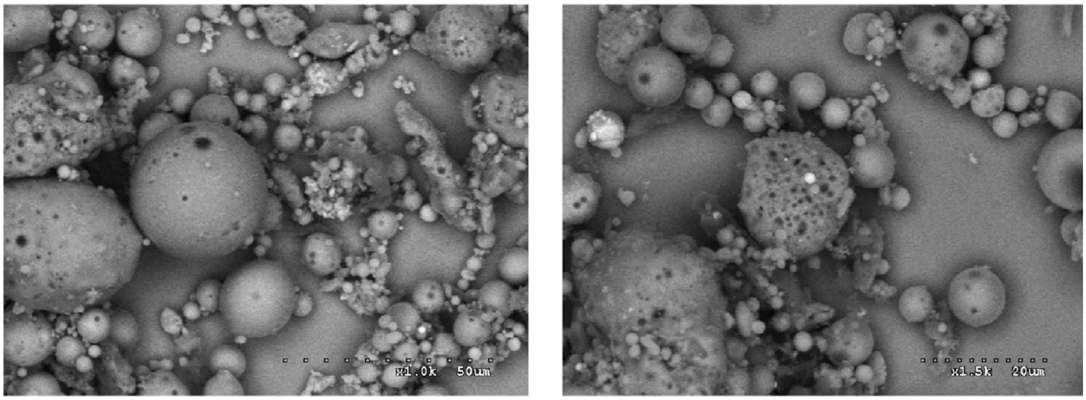
The influence of compaction on sand equivalent and total specific surface values was also observed. The percentage (in volume ratio) content of sand and gravel fractions, denoted as a sand equivalent, equals 35.1 in the natural state for one typical waste sample, but decreases to 17.8 after five rammings by the Standard Proctor method, and to 12.4 by the Modified method. The specific surface value, tested by method of methylene blue sorption (calculated on the basis of sorption capacity evaluation of aqueous fly ash suspension) increases from 2.60 $m^2/g$ (in the natural state) to 3.52 $m^2/g$ (after compaction), independently of used compaction energy.

The phenomenon of an increase in maximum dry density of solid particles, $\rho_{d\,max}$, at decreasing optimum water content, $w_{opt}$, for repeatedly compacted fly ash is accompanied by a reduction in fly ash grain size and growth of specific surface. It is completely opposite to the compaction process in mineral soils. For these materials, greater values for $\rho_{d\,max}$ and lower for $w_{opt}$ are obtained for coarse-grained material with lower specific surface. Dynamic ramming of fly ash causes partial crumbling of its unstable grain. It contributes to better fly ash compaction after graining improvement. To find an explanation of this phenomenon the scanning electron micrographs of fly ash, before and after compaction, were done (Fig. 6). It can be seen clearly, that crushed spherical ash grains were stuffed with smaller grains, which improved their packing. During compaction, smaller grains filled greater that had been crushed, so dry density and compactibility of fly ash sample was better, without a necessity to increase fly ash moisture. This effect is impossible for mineral soils.

The graining coefficients, $C_U$ and $C_C$, determined from grain size-distribution curves for fly ash in the natural state and after five compactions by the standard method, also show the possibility of better compaction of re-compacted fly ash. The uniformity coefficient, $C_U$, equals 5.33 for fly ash in the natural state, after repeated compaction it decreases to 4.33. However, the curvature coefficient, $C_C$, exceeds the threshold value and equals 1.12 (in the natural state: 0.91). Based on the compactibility curve shapes for mineral soils, which are well or poorly grained [14], it can state that compactibility curves, obtained for repeatedly compacted fly ash, are steeper than for fly ash compacted only

(a) Magnification factor 1,000

Magnification factor 1,500



(b) Magnification factor 1,500

Magnification factor 1,500

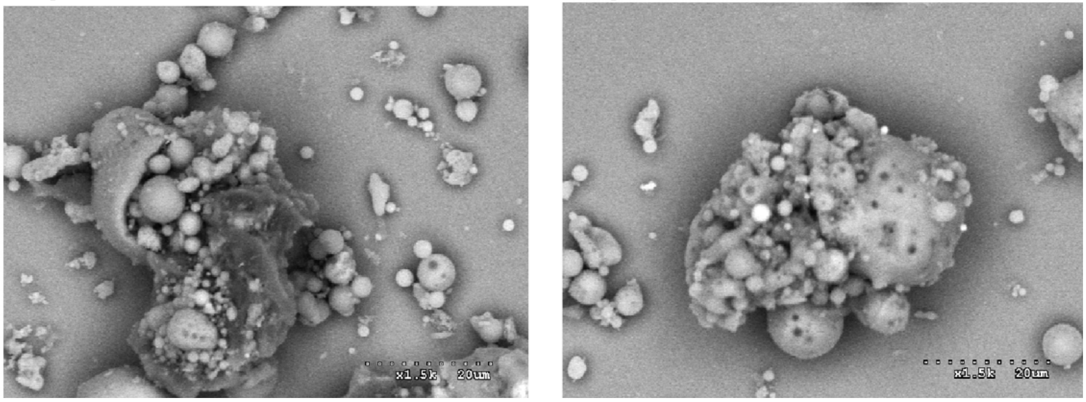


Fig. 6. SEM images of tested fly ash: (a) before compaction and (b) after compaction.

once. In addition, the greater values for $\rho_{\mathrm{d\,max}}$ and lower values for $w_{\mathrm{opt}}$ also confirm the improvement in graining of compacted fly ash.

## 3. The influence of cement addition on fly ash compactibility

### 3.1. Literature review

The use of a hydraulic binding agent necessitates compactibility tests on fly ash with various percentages of binder added and the determination of its influence on compaction parameters, $\rho_{\mathrm{d\,max}}$ and $w_{\mathrm{opt}}$, and even the compactibility curve shape, $\rho_{\mathrm{d}}(w)$, because the mechanical and filtration properties of power-industry wastes, built-in earthen construction, closely depend on compaction [5].

Fly ash can be improved by the addition of bentonite, lime, cement or silica. The compactibility of a fly ash/bentonite mixture increases with increasing amount of bentonite (5–30%) in the mix, with about the same value of optimum water content [15]. Bentonite addition increases the solid dry density of the mix, which influences maximum dry density. Kumar and Stewart [16] observed the opposite effect of bentonite addition on maximum dry densities of bottom ash and bentonite mix, while optimum water contents were nearly constant. It is difficult to discuss their results because the dry densities of solid particles of bottom ash and bentonite were not revealed. Poran and Ahtchi-Ali [17] tested solid waste incinerator fly ash, with physical properties quite similar to coal fly ash. The waste was compacted with 5 or 10% additions of lime and cement. In the case of lime stabilization, compaction parameters were nearly the same as for non-stabilized waste. For cement, only the 10% cement addition caused a maximum dry density and optimum water content increase. Kayabalı and Buluş [10] investigated the influence of bentonite or lime on bottom ash compaction with the aid of vibratory hammer. They did not report an unambiguous relationship between compaction parameters and agent addition. Additionally, the obtained compaction curves were very dissimilar in shape, even for the same agent.

### 3.2. Description of fly ash and test method

Compactibility tests of power-industry waste in a natural state and with cement addition at 2, 5 and 10% by weight of waste were conducted using both compaction methods: standard and modified. Tests were performed on samples of five fly ash/bottom ash mixtures from the new dry-storage yard at the Bialystok Thermal-Electric Power Plant. Every test-shipment was stored in the dry storage yard for at least 2 years. In this paper, the tested fly ash/bottom ash mix is referred to as fly ash, because there is only a vestige of bottom ash in the mix. These fly ash samples also correspond, in terms of the grain-size distribution, to sandy silt, as described in Section 2, but they are characterized by different solid particle density values, $\rho_{\mathrm{s}}$, which range from 2.08 to 2.20 Mg/m$^3$.

Fly ash samples were moisturized 24 h before testing (water content of particular sample increases about 2%) and stored in closed tins. Directly before compaction, the cement addition of 2, 5 or 10% was added to the fly ash. Specimens were accurately mixed and compacted. Fly ash without cement addition was compacted as control. Only a single-compaction of the same waste specimen was permitted for the study. Curves $\rho_{\mathrm{d}}(w)$, obtained by both compaction methods for two typical fly ash shipments, are presented in Fig. 7.

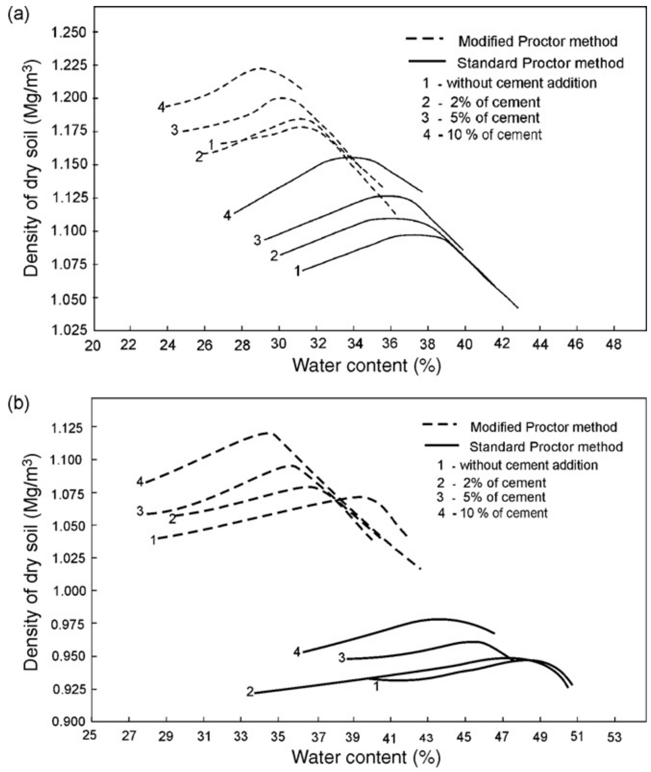


Fig. 7. Compactibility curves obtained for fly ash/cement mixes with various dry densities of solid particles: (a) sample I with $\rho_{\mathrm{s}} = 2.20$ Mg/m$^3$ and (b) sample IV with $\rho_{\mathrm{s}} = 2.12$ Mg/m$^3$.

To determine the influence of cement addition on increasing the density of solid particles, $\rho_{\mathrm{s}}$, solid particle density tests on fly ash in the natural state and with various cement additions were conducted. The changes in fly ash moisture content after cement addition were also determined.

### 3.3. Test result analysis

Cement addition to fly ash increases the maximum dry density of fly ash/cement mixes, with decreasing optimum water content values (Fig. 7). Points ($\rho_{\mathrm{d\,max}}$, $w_{\mathrm{opt}}$) lie approximately along a line with a similar slope for every tested fly ash sample. The line determining the degree of saturation $S_{\mathrm{r}} = 1$ (which is equal to volume of air of 0%) could not be drawn in Fig. 7 for the various solid particle density values, $\rho_{\mathrm{s}}$, for fly ash samples in the natural state and ash/cement mixes. The relationship $\rho_{\mathrm{s}} = f(D)$, where $D$ is the percentage cement addition, was established as a linear regression, as:

$$\rho_{\mathrm{s}} = 2.1134 + 0.0097D \tag{4}$$

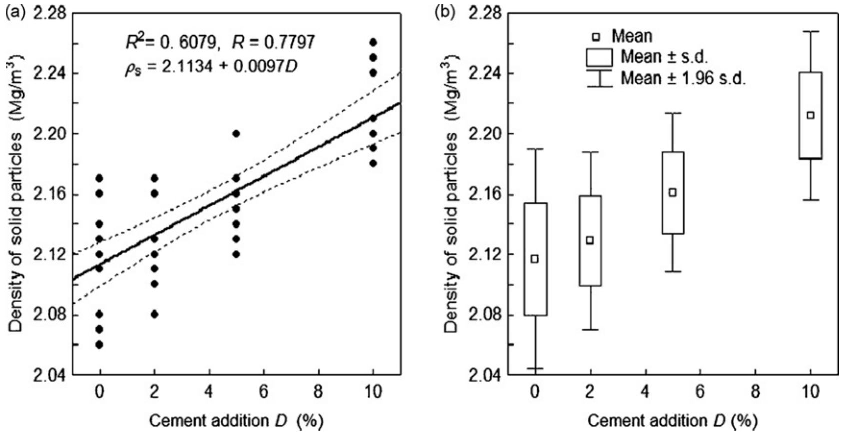


Fig. 8. Dependence the solid particle density of fly ash and cement mix on cement addition: (a) linear regression curve (confidence level 0.95) and (b) $\rho_s$ mean values at various cement additions $D$.

Eq. (4) was determined for three fly ash shipments with $\rho_s$ equal to 2.15 Mg/m$^3$ (shipment III), 2.12 Mg/m$^3$ (shipment IV) and 2.09 Mg/m$^3$ (shipment V). The equation explains 60.8% of $\rho_s$ changeability (Fig. 8); it should be useful only for relationship tendency evaluation.

Adding cement to fly ash results in a moisture decrease of about 5% at 10% addition of cement and a moisture decrease of 1–2% with 2% addition of cement.

The $\rho_{\mathrm{d\,max}} = f(w_{\mathrm{opt}})$ relationship, established from all obtained compactibility curves, is presented in Figs. 9–11. Points obtained by both compaction tests on five fly ash shipments with cement additions of 0, 2, 5 and 10% (Fig. 9) lie along one curve. The best modelling of this line is a regression in the form of a polynomial function (Fig. 10). The equation for this line is:

$$\rho_{\mathrm{d\,max}} = 1.8026 - 0.0246 w_{\mathrm{opt}} + 0.0001 w_{\mathrm{opt}}^2 \qquad (5)$$

The correlation coefficient of Eq. (5) is $R = 0.9978$, which shows that the established regression equation explains 99.6% changeability of maximum dry densities. A regression relationship in the form of a linear function is also correct statistically (Fig. 11),

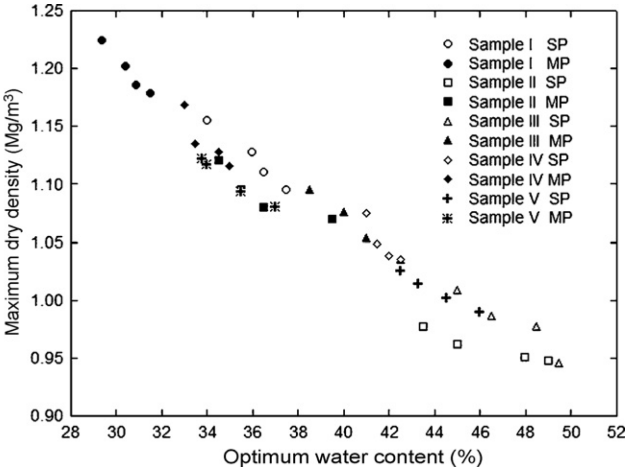


Fig. 9. Scatter diagram of $\rho_{\mathrm{d\,max}} = f(w_{\mathrm{opt}})$ determined for five fly ash shipments and two compaction methods: Standard Proctor (SP) and Modified Proctor (MP).

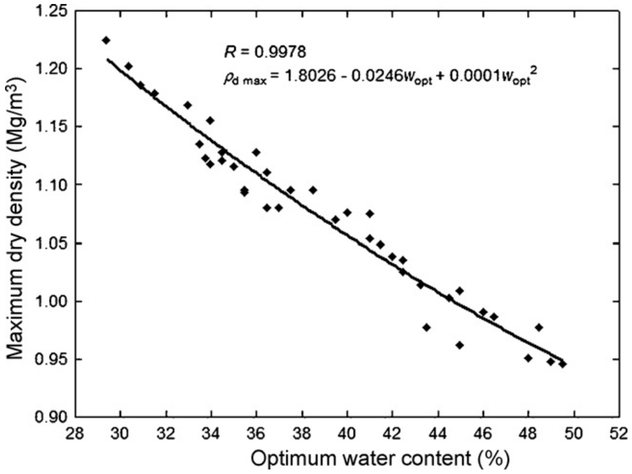


Fig. 10. Scatter diagram of $\rho_{\mathrm{d\,max}} = f(w_{\mathrm{opt}})$, determined on the basis of all fly ash shipments and compaction methods, with polynomial function fitting.

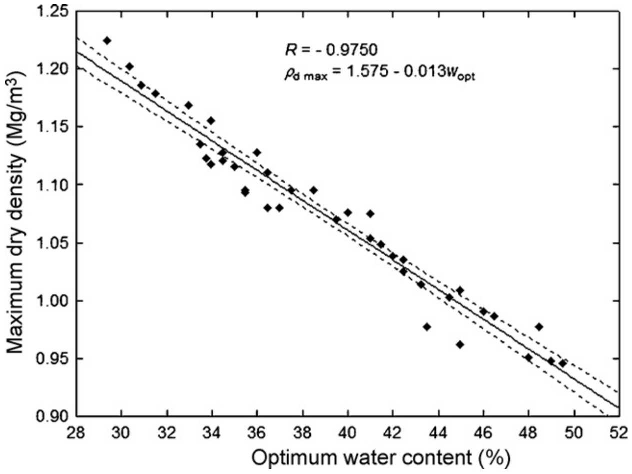


Fig. 11. Scatter diagram of $\rho_{\mathrm{d\,max}} = f(w_{\mathrm{opt}})$, determined on the basis of all fly ash shipments and compaction methods, with linear function fitting (confidence level 0.95).

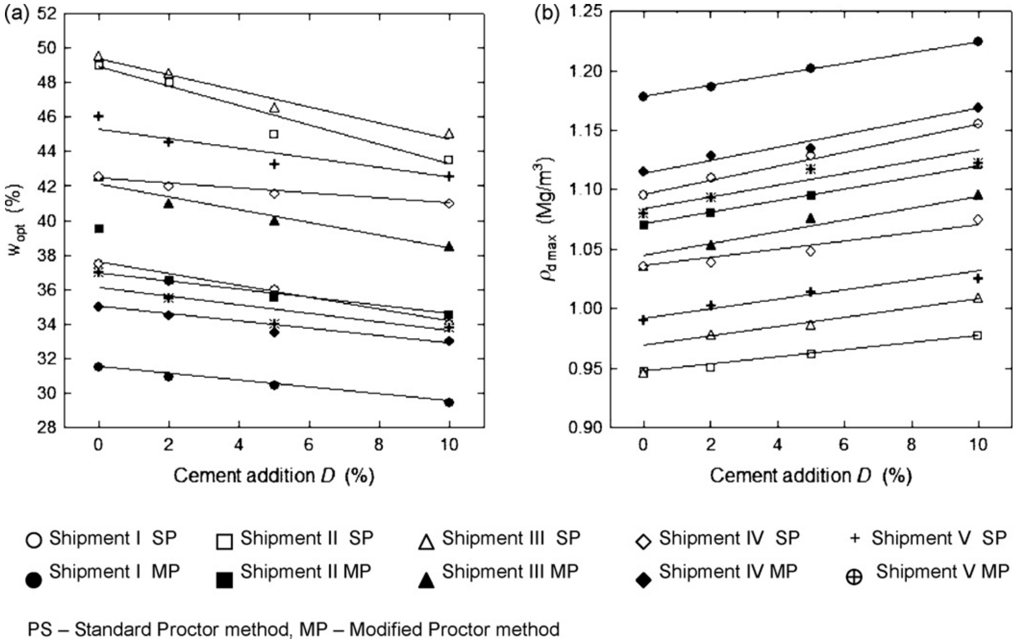


Fig. 12. Relationship graphs of compaction parameters in dependence on cement addition, determined for individual fly ash shipments: (a) $w_{opt}(D)$ dependence and (b) $\rho_{d\,max}(D)$ dependence.

given by the equation:

$$\rho_{d\,max} = 1.575 - 0.013 w_{opt} \tag{6}$$

Eq. (6) explains over 95.1% $\rho_{d\,max}$ changeability ($R = -0.9750$); thus, a linear model is sufficient.

The dependence of compaction parameters, $\rho_{d\,max}$ and $w_{opt}$, on percentage cement addition, $D$, is shown in Fig. 12. The lines, obtained for a particular fly ash shipment compacted by the Standard or Modified Proctor method, are placed regularly as straight lines with similar slopes, especially in the case of $\rho_{d\,max}(D)$ dependence. These date are positioned as lines of linear regression in Fig. 13, depending on differences in $(w_{opt\,0} - w_{opt})$ and $(\rho_{d\,max\,0} - \rho_{d\,max})$ from percentage cement addition, $D$. The relationships were determined as:

$$w_{opt} = w_{opt\,0} - 0.3417D - 0.3302 \tag{7}$$

$$\rho_{d\,max} = \rho_{d\,max\,0} + 0.0047D + 0.002 \tag{8}$$

where $w_{opt\,0}$, $\rho_{d\,max\,0}$ are the values of compaction parameters for fly ash without cement addition and $w_{opt}$, $\rho_{d\,max}$ are the compaction parameters for fly ash with cement addition at 2, 5 or 10%.

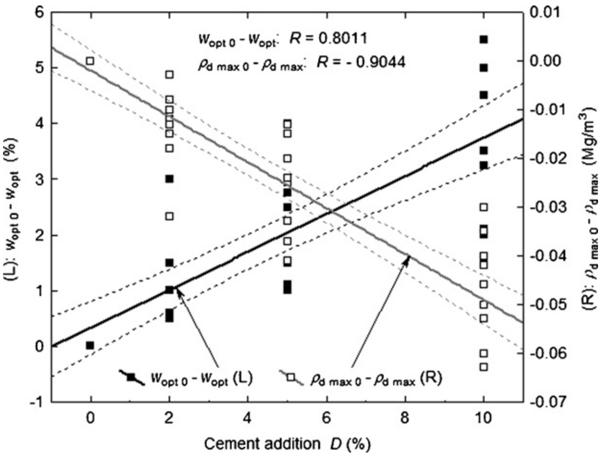


Fig. 13. Linear regression curves of the optimum water content and maximum dry density dependence on cement addition (confidence level 0.95), where $w_{opt\,0}$ and $\rho_{d\,max\,0}$ are the optimum water content and maximum dry density obtained for particular fly ash shipments in natural state ($D = 0\%$) and $w_{opt}$, $\rho_{d\,max}$ are the optimum water content and maximum dry density for fly ash with cement addition 2, 5 or 10%.

The relationships, given by Eqs. (7) and (8), allow the estimated determination of the compaction parameters of cement-improved fly ash. To establish the regression relationship, the initial compaction parameters (determined for fly ash in a natural state, when $D = 0\%$) were used, given the great diversity of fly ash shipments, even from the same combustion source. The stated dependencies can be used only in the event of fly ash improvement by cement additions of 2, 5 or 10%.

## 4. Conclusions

Based on compaction test results for fly ash or fly ash with cement addition, it can be stated that:

1. Re-compacted fly ash samples cannot be considered as representative samples. Laboratory-determined parameters with repeated compaction of the same fly ash specimen, which is a frequent practice in many laboratories, lead to incorrect estimation of fly ash compaction effects. Working with re-compacted specimens, the obtained maximum dry densities were higher and optimum moisture contents lower than those achieved with virgin specimens were, under the same compaction conditions.

2. Methodology of fly ash compaction tests should be standardized. Each point of the compaction curve (moisture/dry density relationship) ought to be determined for separately prepared fly ash specimens.
3. Fly ash re-compaction causes partial crumbling of dynamically rammed grains and increases its specific surface, which improves waste compactibility but does not affect density of solid particles.
4. Fly ash compactibility depends not only on its grain-size distribution but on the structure of individual grains as well. Spherical ash grains, crushed during compaction, can be stuffed with smaller grains, which improve their packing.
5. Cement addition influences fly ash compactibility. With increasing cement percentage in the fly ash/cement mix, the maximum dry density increases and optimum water content decreases. Changes of compaction parameters, $\rho_{\mathrm{d\,max}}$ and $w_{\mathrm{opt}}$, after cement addition, are caused by an increase in solid particle density, a moisture content decrease and a change in the grain-size distribution of the mix.
6. Simply linear relationships were obtained for the estimated calculation of compaction parameters for fly ash with cement addition, when compaction parameters of fly ash without cement addition were known.

## Acknowledgements

The investigations were carried out at Bialystok Technical University in Poland. State Committee for Scientific Research supported this work under research project number 5 T07E 05124, in years 2003–2006.

## References

[1] S. Pisarczyk, Embankment Soils. Geotechnical Properties and Test Methods, Warsaw Technical University Publishing House, Warsaw, 2004 (In Polish).

[2] L.R. Blotz, C.H. Benson, G.P. Boutwell, Estimating optimum water content and maximum dry unit weight for compacted clays, J. Geotech. Geoenv. Eng. 124 (1998) 907–912.

[3] G.P. Korfiatis, C.N. Manikopoulos, Correlation of maximum dry density and grain size, J. Geotech. Eng. Div. 108 (1982) 1171–1176.

[4] I.A. Basheer, Empirical modeling of the compaction curve of cohesive soils, Can. Geotech. J. 38 (2001) 29–45.

[5] K. Zabielska-Adamska, Compaction as an effective way of fly ash property improvement, in: Proceedings of the 19th International Conference on Solid Waste Technology and Management, Philadelphia, 2004, pp. 1049–1058.

[6] S. Raymond, P.H. Smith, Shear strength, settlement and compaction characteristic of pulverised fuel ash, Civil Eng. Public Works Rev. 8 (1966) 1107–1113.

[7] G.A. Leonards, B. Bailey, Pulverized coal ash as structural fill, J. Geotech. Eng. Div. 108 (1982) 517–531.

[8] K. Zabielska-Adamska, Fly ash compaction, in: R.W. Sarsby, A.J. Felton (Eds.), Geotechnical and Environmental Aspects of Waste Disposal Sites, Taylor & Francis, Balkema, 2007, pp. 295–302.

[9] A. Trivedi, V.K. Sud, Collapse behaviour of coal ash, J. Geotech. Geoenv. Eng. 130 (2004) 403–415.

[10] K. Kayabalı, G. Buluş, The usability of bottom ash as an engineering material when amended with different matrices, Eng. Geol. 56 (2000) 293–303.

[11] B. Kim, M. Prezzi, R. Salgado, Geotechnical properties of fly ash and bottom ash mixtures for use in highway embankments, J. Geotech. Geoenv. Eng. 131 (2005) 914–924.

[12] J.K. Lee, A. Karim, R. Salgado, C.W. Lovell, Compaction and shear strength of fly ash and bottom ash mixtures, J. Solid Waste Technol. Manage. 27 (2001) 137–145.

[13] S.R. Kaniraj, V. Gayathri, Permeability and consolidation characteristics of compacted fly ash, J. Energy Eng. 130 (2004) 18–43.

[14] A. Rico Rodrigues, H. del Castillo, G.F. Sowers, Soil Mechanics in Highway Engineering, Trans Tech Publication, Clausthal-Zellerfeld, 1988.

[15] M. Mollamahmutoğlu, Y. Yilmaz, Potential use of fly ash and bentonite mixture as liner or cover at waste disposal areas, Env. Geol. 40 (2001) 1316–1324.

[16] S. Kumar, J. Stewart, Evaluation of Illinois pulverized coal combustion dry bottom ash for use in geotechnical engineering applications, J. Energy Eng. 129 (2003) 42–54.

[17] Ch.J. Poran, F. Ahtchi-Ali, Properties of solid waste incinerator fly ash, J. Geotech. Eng. 115 (1989) 1118–1133.