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Power Boiler's fly ash fineness as an parameter determining the usability in concrete industry

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Abstract

In relation to the new emission restrictions for power units a combined firing of coal and biomass is widely used in power boilers. The new fuel entails new boiler operation conditions suggesting that there should be performed a new research including the detailed analysis of the combustion by-products. One of the combustion by-products is fly ash, which can be successfully applied in building materials like concrete. The classification of fly ash according to the parameters like fineness allows to use the fly ash as a partial substitution of cement in different types of concrete. This paper presents an analysis of the fly ash fineness determined by the wet sieving method. The obtained results demonstrate the changes of fly ash fineness in a separate sections of an Electrostatic Precipitator (ESP), what lead to a conclusion that not all of the collected fly ash fulfil the requirements of the standard BS EN 450-1 + A1: 2007. Addition of fly ash in cement influences composition, chemical and physical parameters of concrete, what makes this combustion by-product valuable. Furthermore, its usage is beneficial from the point of view of CO_2 emission and utilisation of combustion residues.

Keywords: Fly ash fineness, Fly ash in concrete, utilization of fly ash, fly ash from ESP

Streszczenie

Badania miałkości popiołu lotnego z kotłów energetycznych w celu ich wykorzystania w przemyśle cementowym

W związku z nowymi obostrzeniami z zakresu emisji substancji szkodliwych dla bloków energetycznych coraz powszechniej stosuje się współspalanie węgla z biomasą w kotłach energetycznych. Nowy typ paliwa powoduje zmiany w warunkach pracy kotła, co wymusza przeprowadzenie nowych badań dotyczących między innymi produktów procesu spalania. Jednym z nich jest popiół lotny, który może być wykorzystany w produkcji cementu. Klasyfikacja popiołu lotnego według parametrów takich jak miałkość pozwala na częściową substytucję popiołu lotnego w cemencie. Artykuł ten dotyczy badań miałkości popiołu lotnego metodą na mokro. Na podstawie otrzymanych wyników przedstawiono zmiany miałkości popiołu w poszczególnych sekcjach elektrofiltra ESP, co świadczy o tym, że nie każdy zgromadzony popiół spełnia wymagania normy BS EN 450-1 + A1: 2007. Dodatek popiołu lotnego do cementu wpływa na jego skład i właściwości, co czyni ten odpad pożądanym składnikiem. Ponadto, jego użycie w produkcji cementu jest korzystne z perspektywy emisji CO_2 i utylizacji odpadów procesu spalania.

Słowa kluczowe: miałkość popiołu lotnego, popiół lotny do betonu, utylizacja popiołu lotnego, popiół lotny z elektrofiltra

1. Introduction

1.1. The aim of the project

The main goal of the project was to examine the fly ash resulting from power boiler while fossil fuels firing in perspective of its usability in the concrete industry. The measurements were conducted on fly ash samples collected from the electrostatic precipitator (ESP) of a $520MW_{th}$ power boiler firing mixture of coal and biomass. After biomass feeding as a fuel to the power boilers a completely new fly ash properties have emerged, which have to be taken into account while building engineering, where fly ash is used as a concrete additive. During the measurements presented in this report, only the fineness of fly ash as one of the main attributes was studied.

1.2. Fossil fuels firing originate fly ash

Fly ash together with slag is a residue in the process of coal combustion in power and heat plants. Nevertheless, from the point of view of concrete materials producers fly ash is much more valuable firing by-product. It has been successfully used in production of cement and concrete for years. There is a wide range of factors influencing the properties of fly ash [1]

- the type of coal used for firing (brown or hard coal) – determines the chemical composition of the collected fly ash
- technological combustion processes – the efficiency of combustion processes influences the heat losses (i.e. content of unburned coal in fly ash)
- preparation of the fuel – the process of mining and grinding of the fuel (particle size distribution of pulverized coal powder fed to the furnace)
- capture and storage methods

Only in Poland, by the year 2015, Green Energy Investors can apply for the European Union Fund subsidies, which reach the level of 1.1 milliard EUR. It is assessed that the amount appropriated for biomass co-combustion with coal will be about 264 million EUR, what is equal to 24% of total budget predicted for supplying the green energy development [2]. This procedure isn't founded by the state in other countries firing coal in energy production like United States or Japan [3]. It makes a wide range of possibilities to improve the system of energy production from hard coal and biomass.

There are also some technological problems which have to be solved. The negative aspects of biomass co-combustion are inter alia: problems with fuel preparation and its continuous delivery to the furnace (drying, mining associated problems), decrease of thermal efficiency and performance of the boiler and additional side effects associated with mineral composition of the biomass [4].

When considering the design of the concrete as building material, fineness can be as well important as chemical analysis of the fly ash [5].

1.3. Standards related to production of concrete from fly ashes in Poland and Europe

The usage of fly ash in cement has an origin in 1960's in some European countries, although the application of co-firing of coal with biomass occurred within recent 20 years. Combined firing demand initialised the process of modernisation of conventional power boilers, what in consequence caused a lot of changes in parameters of combustion by-products like fly ash. The limitations were established by each country separately in view of different development level of particular nation. To unify the regulations concerning the usage of fly ash in concrete, the European standard EN 206 has been established [6].

The new standards include only suggested types and classifications of fly ash and the research procedures as well. The limits and requirements should be assessed by the governments separately, due to individual conditions in particular country. This new research methodology may cause the differences between the results of previous and new examinations. That is why there should be written uniform standard, fulfilling the new European requirements and taking into account the specific aspects of Polish coal combustion process. Introducing new classifications of fly ash enables the usage of wider range of fly ashes generated in power boilers [7].

Holland is a country which constitutes a good example of effective unification of national and European standards, enclosing both the share of biomass in fuel and the limits of fly ash as an additive in cement. All these aspects are included in recommendation CUR 94, which is supported by wide research programme. The results of these researches shown that fly ashes coming from combined firing of coal and biomass aren't less valuable from the concrete performance point of view (in comparison with fly ash from coal firing) [8].

Polish normalisation system needs a lot of modifications to make the possibility of fly ash application more approachable. The major step in this direction would be suitable research programme to characterise the fly ash from polish power boilers in details. The results would be a base in the process of polish and European standards harmonisation.

1.4. Fly ash fineness

In Poland, there are valid a few standards describing the demands, which must be fulfilled to produce selected concrete materials using fly ash:

- PN-EN 197-1:2002 Cement. Part 1: Composition, demands and compatibility criteria concerning cements of common usage.
- PN-EN 450-1:2006 Part 1. Fly ash in concrete. Definitions, demands and compatibility criteria.

Both mentioned standards include different classification criteria of the fly ash as an additive to cement. In the measurements presented in this report only fly ash fineness was examined. Concerning the fly ash fineness, the most important classification is the one presented in the norm PN-EN 450-1:2006, which sets the fly ashes into two categories:

- N (the fineness is ≤ 40%)
- S (the fineness is ≤ 12%)

Thanks to significant reduction of batched water demand in concrete, the S-type fly ash is desirable in high-strength concretes [1]. Fly ashes, which are less fine (N-type), can be a supplement in commonly used cements like Portland. The fineness of the fly ash is expressed as a percentage mass ratio between the mass of the particles captured on the sieve of diameter 0,045mm and the total mass of the examined sample.

1.5. Influence of the fineness of fly ash on properties of the concrete

Fly ash used in the building engineering is a silica type mainly [1]. The shape of the fly ash particles is spherical, but some particles (for example unburned coal) has an irregular shape and they are an overdue on the sieve. The particles size and shape (and in consequence fineness) have an influence on some crucial parameters of the concrete. The shape of sphere of a single particle increases the workability of the concrete material, what makes easier the mixing and transporting of the concrete. Easy mixing influences pumps and concrete mixers power consumption. The shaping of the concrete is also easier, the amount of air gaps in the material is smaller [9]. Graining has an impact on the amount of batched water used in the process of concrete production, what is shown on the Fig 1.1 , which illustrates this relation for different fractions of fly ash in concrete. In other words, addition of fly ash decreases the water absorbability, especially in the case of the fly ash of S category (classification presented in chapter 1.4). Fine ashes, which are captured on the sieve 0,045mm, added to a concrete material are decreasing amount of consumed water, what further changes the water to cement ratio, which decreased, makes the concrete more firm [9], what is certainly an advantage.

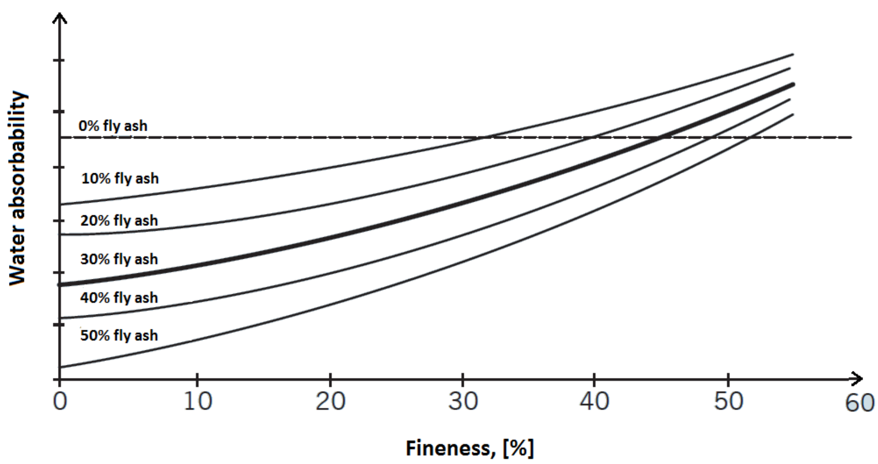

Fig 1.1 The relation between the grinding of the ash and water demand [9]

Moreover, the concrete with addition of fly ash gives off less wash milk than in concrete in which the fly ash was not used. That's because of the same reason as it was explained in the case of concrete absorbability [9]. The main benefit of this phenomenon is the saving of free water and preventing the wash out of the cement from concrete with the wash milk. In the Fig 1.2 the percentage amount of water that goes out from the concrete after pouring out into the form is shown.

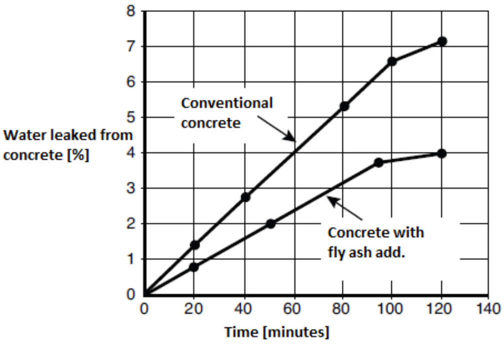

Fig. 1.2 Losses of water in concrete samples [9]

There are also some negative aspects of mixing the ashes with concrete like decreased resistance for compression. Fly ash decreases the concrete strength only in the initial period of hardening of the material. Concrete conditioned with fly ash is also more susceptible to corrosion caused by aggressive chemicals and is less resistant for low temperatures also [9].

2. Fly ash fineness test station

2.1. Measuring equipment and principle of operation

All the measuring steps required for credible results are described in the standard PN-EN 451-2:1998 [10], which directly presents the requirements for the measuring equipment. The method of determination of fineness of the fly ash is the wet type. For this purpose there was bought a brand new device fulfilling all the restrictions included in the mentioned standard. The test station is presented on the Fig. 2.1 and it consists of:

1. Water Input
2. Cut-off valve
3. Reduction Valve
4. Water manometer Φ100mm
5. Spraying sieve with holes Φ 17.5mm
6. Sieve #0,045mm in the frame Φ 50mm

Fig. 2.1 Measuring equipment view [11]

Test station is connected to the water grid in the point (1). The pressure of water has to be set to value of 80kPa (4) with use of the regulation valves (2) and (3). Water at set pressure goes to the spraying sieve (5), which dissipates water into few streams flowing with direction strictly specified in the standard [10]. Spraying sieve is put into the measuring sieve 0,045mm (6) with the sample inside (dried to the constant mass before measuring procedure). Sprayed water forces the particles of ash with diameter smaller than the sieve grid through. The residue mass of fly ash which didn't pass through the measuring sieve is moved to the dryer and stays there until complete moisture lost. After drying the sample is put into the exiccator and cooled down to the ambient temperature.

2.2. Examined fly ash characteristics

Fly ash used in this research was collected from the power boiler firing hard coal with biomass. The mass share of biomass in total fuel fed to the furnace was set to 20%. There were 12 samples (marked L1 to L12) collected from 12 corresponding hoppers of two electrostatic precipitators (ESP). The flue gas cleaning system is presented in simplified form in the Fig. 2.2.

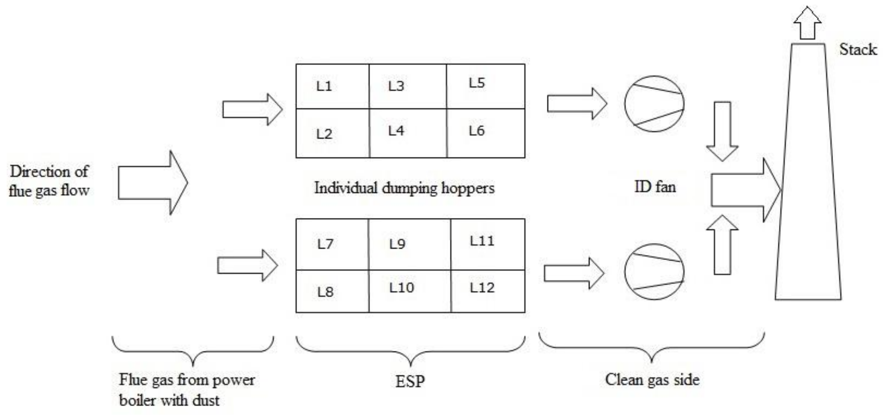

Fig. 2.2 Scheme of flue gas cleaning system

The electric precipitators are three-section type. For each section there are two hoppers. In the Fig. 2.3 the setting of particular hopper in the precipitator and the directions of flow of flue gas and captured ash is presented.

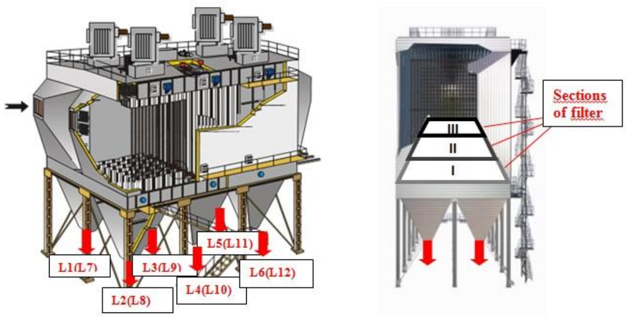

Fig. 2.3 ESP representation [18]

2.3. Procedure of experiment

Before sieving, each of the samples of fly ash has to be dried to the constant mass. The mass of about 2.0g of ash is weighted on the digital scale with 0,001g measuring accuracy. After samples weighting, its fineness is determined by means of the wet-measuring-sieve. The mass residue of ash present on the sieve is weighted after drying. There have to be done several series of examination for each ash sample, until the difference between obtained results of fineness will not be greater than 0,3% [10]. All the steps which have to be done during the experiment are precisely described in the standard [10].

3. Fly ash fineness results

3.1. Fineness results

As it was mentioned in the section 1.3, fineness can be expressed as a ratio of mass of the residue of fly ash on the sieve to the sample mass before wet sieving. It can be expressed by simple formulae [10]:

$$r = \frac{f \times m_o}{m_s} \times 100\ \% \qquad (3.1)$$

where:

r - fly ash fineness, %
m_s - fly ash sample mass, mg
m_o - residue mass left on the sieve 0,045mm, mg
f - correcting coefficient, -

f is a sieve's correcting coefficient. It is used to verify the accuracy of the sieve after specified time of operation. It should be in the range between 0.8 and 1.2. In this case, when measuring equipment is brand new, this coefficient was assumed as equal to 1.0.

Tab. 3.1 Table of measurements results

Ash sample mark -	Initial mass mg	Residue on the sieve 0,045mm mg	Fly ash fineness %
L1	2011	727	**36.2**
L2	2149	639	**29.7**
L3	1989	292	**14.7**
L4	2085	321	**15.4**
L5	2090	110	**5.3**
L6	2019	121	**6.0**
L7	2054	1324	**64.5**
L8	2023	1253	**61.9**
L9	2001	336	**16.8**
L10	2006	458	**22.8**
L11	2051	167	**8.1**
L12	2010	213	**10.6**

Basing on the results in the Tab. 3.1, the fineness of the samples coming from individual hoppers in the Fig. 3.1 is presented

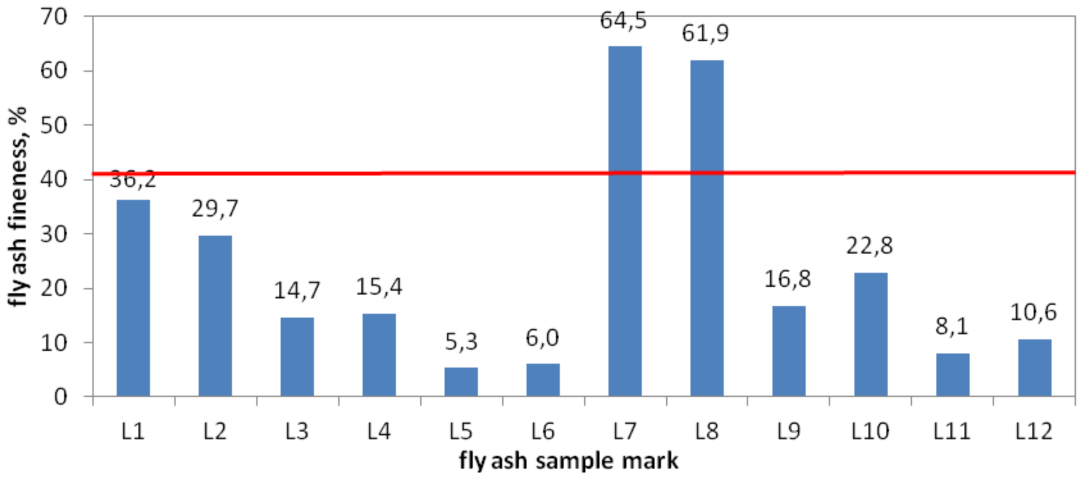

Fig. 3.1 Fly ash fineness in individual hoppers

3.2. Measuring errors and uncertainties analysis

Every performed measurement is burdened with some uncertainty coming from the inaccuracy of the measurement. That is why analysis of the uncertainties is crucial when solving measurement problems and conducting researches. Due to the fact, that quantities are measured by use of the SI unit system, uncertainties of these quantities are also strictly described and standardized uniformly in the international convention [12]. The basic concept for the description of the questionability in the measurements is the measuring uncertainty. In other words, it is quantitative measure of the uncertainty of the measured value. The uncertainty may be influenced by many factors, such as [12]:

- incomplete definition of the measured value
- insufficient number of measurements
- incomplete knowledge about the influence of external factors
- observer's errors (mostly in analogue meters)
- inaccuracy of the reference values and standards
- assumptions and rounding in the measuring process
- scale of measuring equipment

The way which the uncertainty is determined is also dependent on the methodology and the type (direct or indirect) of the measurement. There can be two types of uncertainty determination distinguished:

A-type – by means of the normal distribution, based on statistical analysis of the measuring series. It can be expressed by standard deviation [12]:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x-\bar{x})^2} \tag{3.2}$$

where: s – standard deviation, expressed in unit of measured value
n – number of measurements in the series
x – current value of measured quantity
$\bar{x}$ – arithmetic mean of the values in series

B-type – by means of additional information, which is not statistic (i.e. scale interval value, or the accuracy class of the measuring instrument) and which is associated with systematic error [12]:

$$u(x) = k\frac{\Delta x}{\sqrt{3}} \tag{3.3}$$

where: k – expansion coefficient
Δx – elementary graduation of the scale

Combined standard uncertainty – includes both statistical and systematic errors. In indirect measurements, combined standard uncertainty could be expressed by using the uncertainty propagation law. If the calculated quantity is a function of two variables x_1 and x_2, its combined uncertainty would take the following form [12]:

$$u_c = \sqrt{\left(\frac{\delta f}{\delta x_1}\right)^2 u(x_1)^2 + \left(\frac{\delta f}{\delta x_2}\right)^2 u(x_2)^2} \tag{3.4}$$

where: u_c – combined standard uncertainty
x_1, x_2 – variables of a function f
$u(x_1), u(x_2)$ – uncertainties of variables x_1 and x_2

3.3. Measuring uncertainty calculation

Total uncertainty of conducted measurements and calculations is influenced by uncertainties of sample mass measurement, residue mass measurement and the accuracy of the measuring sieve #0.045mm. During the measurements the automatic scale of 0.001g accuracy was used. The loss of sample mass during the pouring of the fly ash (for example from the weight's vessel to the sieve) was omitted. The accuracy of the sieve (calibration error) is defined by the producer and certified by authorized laboratory – for the sieve 0.045mm it is equal to 0.001g and it depends on the sieve's manufacturing accuracy.

$$\Delta m_{cal} = 0.001 \text{ g}$$

The sample mass as well as residue mass measuring error is equal to the accuracy of the scale.

$$\Delta m_s = \Delta m_o = \Delta m = 0.001 \text{ g}$$

Knowing that each mass measurement (sample or residue) is also loaded with the calibration error of the sieve, by means of the B-type standard uncertainty determination method, the systematic uncertainty of the single mass measurement can be calculated from the formulae 3.4 (chapter 3.2):

$$u(m_s) = u(m_o) = u(m) = k\sqrt{\frac{(\Delta m)^2}{3} + \frac{(\Delta m_{cal})^2}{3}} = 0.002 \text{ g}$$

Where k is an extension coefficient, in this case assumed as equal to 3.

The mass measurement was conducted separately before and after the sieving of the fly ash sample. The influence of the previous measurement on the current one was negligible. Taking into account all the assumptions it is possible do determine the uncertainty of the fly ash fineness results (1) using the total differential method, due to the uncertainty propagation law:

$$r_i = \left(\frac{m_{oi}}{m_{si}}\right) * 100\%$$

The formulae 1 determining the fly ash fineness (chapter 3.1) is introduced in 4 (chapter 3.2):

$$u_c(r_i) = \left(\sqrt{\left(\frac{\delta r_i}{\delta m_{si}}\right)^2 u(m)^2 + \left(\frac{\delta r_i}{\delta m_{oi}}\right)^2 u(m)^2}\right) * 100$$

what further gives:

$$u_c(r)_i = \sqrt{\left(\frac{m_{oi}}{m_{si}^2}\right)^2 u(m)^2 + \frac{u(m)^2}{m_{si}^2}} = \frac{u(m)}{m_{si}}\sqrt{\left(\frac{m_{oi}}{m_{si}}\right)^2 + 1} * 100\%$$

where:
- m_{oi} – residue mass measuring error, g
- m_{si} – sample mass measuring error, g
- $u_c(r_i)$ – combined uncertainty of the fineness result, %
- i – fly ash sample mark

The uncertainty is influenced by the mass measurements – before and after wet sieving, as well as the uncertainty of the sieve. The mass of the residue changes during the measurements, what has an effect in uncertainty value (i.e. for measurements L7 and L8, where the residue masses on the sieve had the highest value, the uncertainty value is slightly greater). Due to the high accuracy of the digital scale, the uncertainty values didn't exceed the value of 0.13%.

The results of fly ash fineness combined uncertainty for individual measurements are presented in the Tab. 3.2

Tab. 3.2 Uncertainty values for each of the measurements

Fly ash sample mark	L1	L2	L3	L4	L5	L6
uncertainty, %	0.11	0.10	0.10	0.10	0,1	0.10

Fly ash sample mark	L7	L8	L9	L10	L11	L12
uncertainty, %	0.12	0.12	0.10	0.10	0.10	0.10

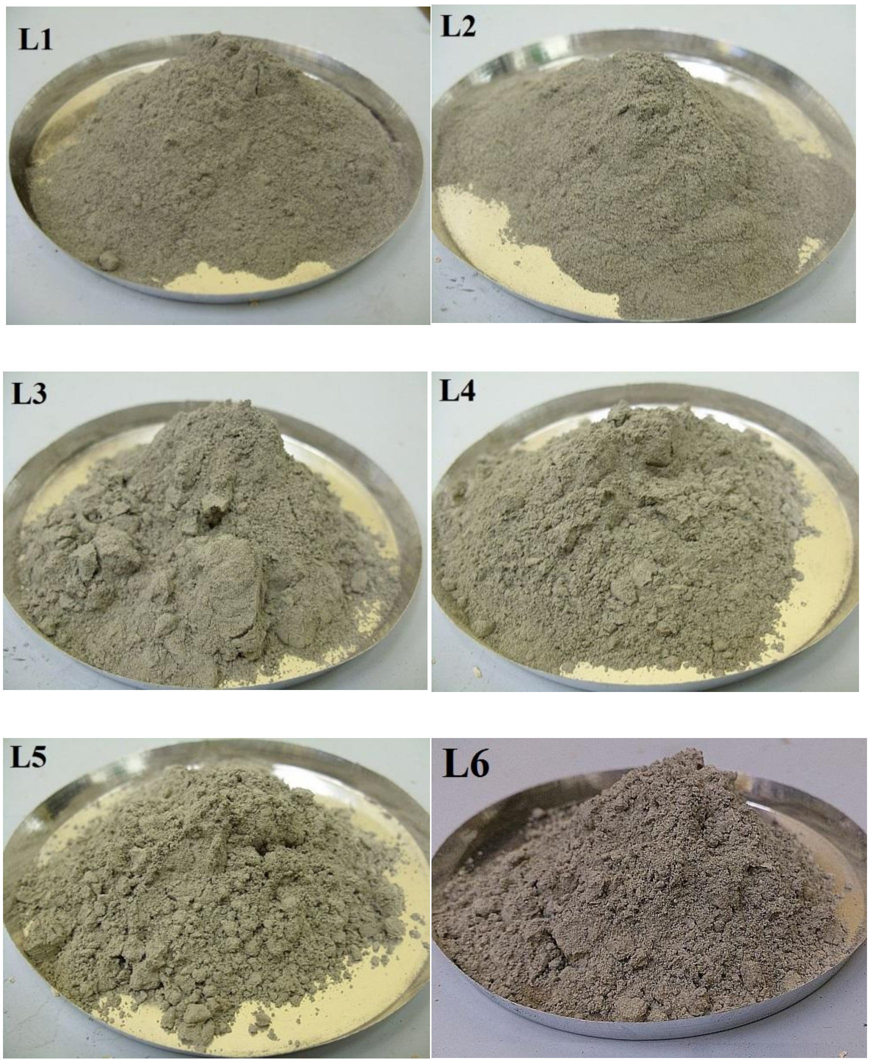

Fig. 3.2 Fly ash samples from ESP hoppers

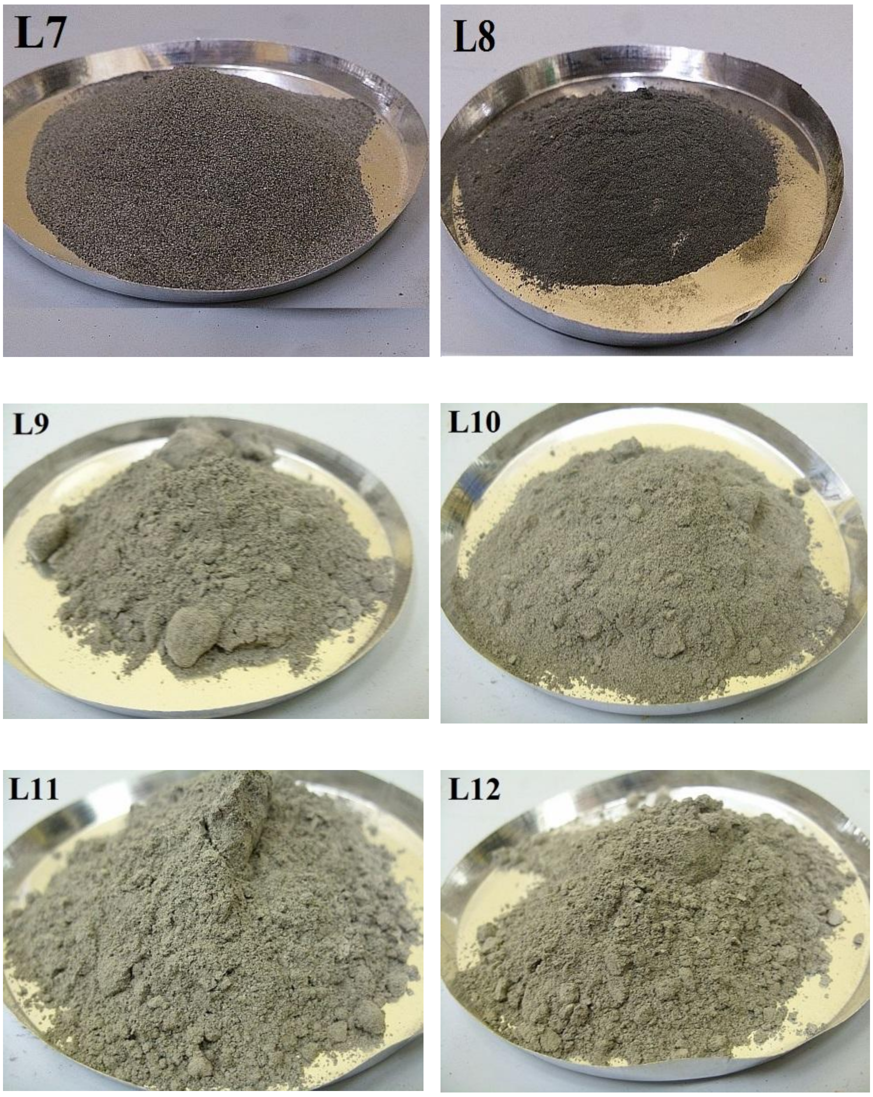

Fig. 3.3 Fly ash samples from ESP hoppers (2)

4. Observations and conclusions

4.1. Observed relations

During the measurements there was a visible difference in the structure and color of the fly ash samples observed. In the Fig. 3.2 and Fig. 3.3 it can be seen that in separate hoppers the fly ash has different properties. The obtained fly ash fineness results are in visible trend with ESP sections arrangement. The fineness of the fly ash collected from the hoppers increases along the ESP flue gas pass. This relation is also noticeable in other independent research regarding the fineness of the fly ash coming from ESP [19]. The fly ash fineness depends strictly on the size of the particle of the ash. The bigger the particle, the easier it is to be captured by the electric precipitator. In the first stage of ESP relatively big particles were captured, so the fineness has a high value too.

Analyzing the table of results (Tab. 3.1) and the chart (Fig. 3.1) it is clearly seen that the fly ash present in the individual hoppers can be assigned to different fineness categories mentioned in chapter 1.4. Samples L7 and L8 have the fineness greater than 40%, so they can't be directly used in the concrete. It means that the fly ash from this gas cleaning system can be used in different types of building material - it depends on the concrete producer requirements.

Even if the fly ash doesn't fulfil the requirements concerning the addition in concrete, it can be successfully applied in many other fields of building industry (i.e. stabilization of ground, road building, light aggregate production), or in gardening and agriculture [13].

As it was described in the section concerning the procedure of the measurement (chapter 2.3), the difference between two results of the fineness of the same fly ash sample shouldn't be greater than 0.3%. In this case, after several attempts this difference was equal to about 1.0%, but never reached the error value 0.3%. The error could be made by oscillation of the masses of the vessels and sieves. Moreover, the influence on the varied results might have the structure of the fly ash stored in 1.0kg bags. In different regions of these bags (for example on the top or bottom) the structure could slightly differ.

4.2. Environmental and economic aspects

It could be said that hard-coal firing power plants are far from the ecologic modern power producing systems, considering the greenhouse gases production. Although, there can be observed a paradox when talking about usage of fly ash in the concrete, which can be even found as a "ecological" material [14].

In year 2013, there was produced about a 2.6 billion of tones of Portland cement in the world. The CO_2 emission during this process is about 8.0% of total greenhouse gases world-wide production [14]. Nowadays, every company wants to reduce the costs associated with fuel demand and simultaneously decrease the carbon footprint. During the production of 1.0 ton of cement 1.0 ton of carbon dioxide is emitted [15]. Thanks to very good pozzolanic properties of the fly ash, its addition to Portland type cement can reach even 35% [7]. If the maximum content of fly ash in cement is considered, the worldwide CO_2 emission would be reduced by 0.9 billion of tones per year. That's why the usage of fly ash in concrete can be considered as very beneficial. Not only from the economical (fly ash as cheap waste from the power plants, the landfilling costs are also decreased), environmental protection (decreased emission of carbon dioxide), but also technological point of view (properties of the concrete, which were described in the section 1.4).

There is no one rigid composition of concrete, which would be the most suitable. There are different types of the concrete, with different sizes and shapes. It is also important the conditions in which the material is planned to be used (outdoor, indoor, the climate, humidity). The time of usage is also important. The type of the load which would be exerted on the material. There is a lot of aspects which would have to be taken into account when composing the concrete [16]. Fineness is undoubtedly one of them.

5. Summary

Comparing the fly ash fineness results with the other, independent analyses of the fly ash coming from ESP confirms that the fineness of the fly ash increases when passing through sequent stages of the ESP unit. The values divergences result from different solutions of the ESP and different fuel characteristics.
Fly ash usage in the concrete (and other building materials) is the process which is very universal. Only in 2006, there were 15 million of tones of fly ash used in concrete production, what is equal to 20% of worldwide coal combustion products. Fineness is just one of a lot of issues which have to be taken into account when composing the fly ash with concrete. There have to be done more and more investigations to optimize the usage of fly ash in concrete, because the potential of this waste is very large. More researches should be done to encourage concrete producers to change the process of concrete production.

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