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Application of Fluidized Bed Furnance Bottom Ash in Civil Engineering – A Review

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Abstract. For several years there has been widespread and open discussion about climate problems and human responsibility for the generated waste. The number of regulations has led to a search for applications for by-products of combustion. Moreover, the forecasted economic crisis additionally motivates to use every possible material to reduce the cost of manufacturing activities. Efficient waste management is a key element for Polish companies in their efforts to reduce their negative impact on the environment. Fluid combustion of fuels in the Polish power and heat industry still belongs to relatively new technologies. Despite the application of the most technologically advanced processing methods, bottom ashes from fluidized bed boilers are still reluctantly used. The author sees possibilities of using bottom ashes in geotechnical works. The aim of this review is to present the existing source papers relating to the use of bottom ashes in construction processes. A particular area of interest is the use of said ashes in jet-grouting (JG). The paper briefly refers to fluidized bed combustion technology as a source of combustion by-products. The author pay special attention to the characteristics defining the characteristics of the ashes. The reader's attention will then be drawn to jet-grouting technology. References can be found to the methodology of general cement-soil testing. Due to the nature of the use of JG, the focus is particularly on their strength, water-permeability and frost resistance properties. Due to the need to determine the internal structure of the cement-ground, attention was also paid to the possibility of using X-ray computed tomography for soil cement testing.

1. Introduction

Despite the economic changes taking place, the Polish energy sector is still dependent on coal-fired power plants. What is more, apart from the currently operating fluidized bed boilers, further constructions and upgrades are planned. The technology is justified by its economic advantages, and fluidized bed boilers are starting to operate in more countries. The combustion of hard coal or lignite in fluidized bed boilers results in the production of combustion by-products (*polish: UPS*) - fly and bottom ash mixed with sorbent residues used to reduce toxic NO_x and sulphur emissions into the atmosphere. These combustion products can be macroscopically distinguished already on the basis of grain size. For years, research has been carried out to indicate the direction of by-products management in order to maximize their use in the economy. One of them is the widely understood use in the production of concrete and products based on mineral binding materials. The possibility of using additives to concrete is specified in PN-EN 206 [1]. According to it, an additive is a fine-grained, inorganic component used to improve certain properties of concrete or to obtain special properties. It is usually added in an amount of more than 5% by weight of cement. The additive can significantly modify the properties of both the concrete mix and the hardened concrete.



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The aim of this paper is to review the literature related to the application of fluidized bed combustion bottom ash in geotechnics, where we often encounter the use of various types of mineral binder materials. The information obtained will allow to design studies defining the usefulness of bottom ashes in terms of mixture rheology, strength, frost resistance and water permeability and may be a basis for further exploration of the issue in terms of other applications.

2. Description of the issue

2.1. Characteristics of ashes produced in fluidized bed furnaces

Details of fluidized bed furnace operation are described in the paper [2]. The first publications on the attempt to manage waste were presented at the end of the last century [3], and their authors' research continues to feed the discussion on fluidized bed furnace waste management. Focusing on the fluidized bed combustion by-products themselves, two types of waste should be distinguished:

- those characterized by a better grain size ($1\text{--}300\ \mu\text{m}$) ash from the dedusting of the waste gas stream (cyclone ash), accounting for 40-70% of the waste,
- fluidized bed ash with a diameter of 0.3-5.6 mm representing 30-60% of the total combustion by-products [4]–[7].

It can be concluded that both types of ash produced as combustion by-products consist of ash from solid fuel and residues of unburned coal, anhydrite II which is a product of desulfurization and unreacted compounds - CaCO_3 and CaO from thermal decomposition of sorbent [2], [7], [8]. The exact compositions of the ashes depend on the quality of the fuel and the detailed technology. The parameters are therefore determined based on the specific furnace that is part of the power plant. [4]

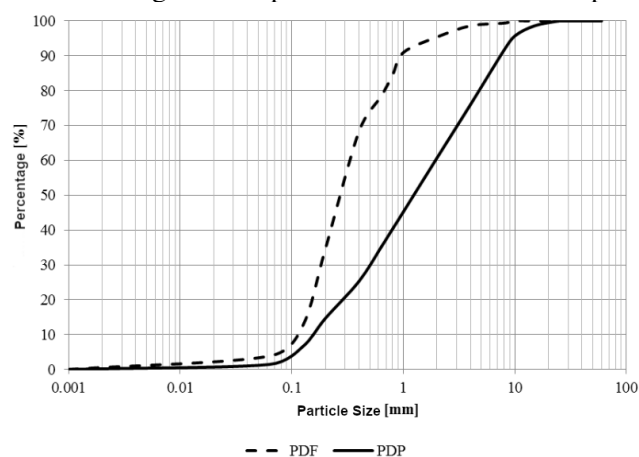
Polish literature has been trying to find applications for fluidized bed furnace ash for years [9]–[14]. The properties of fluidized bed ash are described in papers [9], [13]. The authors identified the chemical formulation of the ash based on tests conducted at a local power plant. Based on chemical analyses, specific reactions important for fluidized bed ash considerations were indicated. The authors presented in a tabular form the applications in general and in detail. Directions of development are indicated and an exemplary technological installation for the mass utilization of fluidized bed ash is proposed. The concepts of securing fluidized bed ash as a future mineral resource were described at length. In the article [10] the authors focused on the grain fraction below 0.5 mm isolated from the fluidized bed furnace of the "Łagisza" power plant. Examination of the phase composition by X-ray diffraction indicated a dominance of anhydrite as a crystalline component. Analyses with the use of analytical scanning electron microscopy made it possible to isolate calcium and magnesium sulfates, quartz, iron oxides, aluminosilicates and rare earth phosphates in the phase composition of the examined ash samples.

Despite the continuous increase of waste in the form of bottom ash from fluidized bed furnaces, still not enough research has been done to allow the use of this combustion by-product on the industrial scale. It should be pointed out that there are significant differences between the more widely used bottom ash from pulverized fuel and fluidized bed boiler. The issue is discussed in more detail in Polish [11] and Estonian studies [15]. According to sources, it is the lower combustion temperature that significantly affects the difference between the combustion byproducts of fluidized bed boilers and those of conventional combustion - fluidized beds do not produce a liquid phase [4], [11], [15]. Scope of Polish [11] as well as Estonian researches [15] are a comparison of the chemical composition, X-ray Diffractometry (XRD) Analysis and scanning electron microscopy of ash. Both publications - based on different ashes indicate significantly higher levels of anhydrite in fluidized bed boiler ashes. The Table 1 (below) shows the results of the chemical analysis [15].

Table 1. Chemical analyze of CFB- ja PF-ashes, % [15].

Description	Bottom ash		Ash from EP field I	
	PF-boiler	CFB-boiler	PF-boiler	CFB-boiler
Chemical analyse				
SiO ₂	18.90	11.26	22.79	38.58
Fe ₂ O ₃	5.28	3.12	4.11	4.88
Al ₂ O ₃	4.59	4.38	10.45	11.86
CaO	55.35	48.90	39.60	27.98
CaO _v	26.63	13.88	14.75	8.36
MgO	7.77	6.37	4.69	4.53
K ₂ O	1.36	1.15	4.58	4.47
Na ₂ O	0.12	0.10	0.13	0.24
SO ₃ total	2.43	13.88	7.65	4.10
CO ₂	2.70	11.90	1.91	5.28
Calculated extent of carbonates decomposition				
CO ₂ CaO	43.09	38.07	30.83	21.78
CO ₂ MgO	8.20	6.72	4.95	4.78
CO ₂ total	51.29	44.79	35.78	26.56
k _{CO2}	0.95	0.73	0.95	0.80
Distribution of CaO between ash minerals				
CaO _{carb}	3.44	15.15	2.43	6.72
CaO _{sulf}	1.70	9.72	5.36	2.87
CaO _{free}	26.63	13.88	14.75	8.36
ΣCaO _{carb+sulf+free}	31.77	38.75	22.54	17.95
CaO _{tm}	23.58	10.15	17.06	10.03

Grain size analyses have also been performed in the past [16]. The subject of this study was energy waste from coal combustion in a fluidized bed boiler and in a pulverized bed boiler, which was separated on a 0.63 mm sieve. The curves of grain compositions of ashes used are presented in Figure 1 [17].

**Figure 1.** Particle size composition curves of bottom ashes [17].

The bottom ashes were characterized by grain diameters up to 10 mm for fluidized bed boiler bottom ash (PDF) and up to 25 mm for pulverized bed boiler bottom ash (PDP). The content of fraction below 0.63 mm in bottom ash was for PDF: 78.3% and for PDP: 35.0%. Significant differences in the grain composition of bottom ash were the result of the coal combustion technology in individual boilers

and the method of collecting this waste from the bottom of the furnace. The average density of fluidized bed ash (PDF) was 2.68 g/cm³. Bottom ash from the pulverized coal boiler had a lower density of 2.27 g/cm³. The ignition loss of the bottom ash PDF was 4.4%, with a lower loss for the finer fraction (3.6%) and 5.3% for the fraction >0.63 mm [17]. All these values meet the requirements of the standard PN-EN 450-1:2012 Fly ash for concrete, in which the maximum ash ignition losses are defined at 9%. [18].

The general use of fluidized bed ash for road construction is demonstrated in the article [12]. The authors searched for the proportions of components of soil-binder mixtures for road stabilization and lean concrete. The considerations were based on the study of strength increase of binders with different mixtures and frost resistance tests. As the main conclusion, an opinion was presented pointing to the possibility of using fluidized ash as a basic component of hydraulic binders for road construction.

Fluidized ash was also tested as an additive for concrete [7]. Comprehensive strength, water absorption, pressurized water penetration depth and frost resistance tests were performed during the team's work. The research indicates wide possibilities of shaping the strength growth rate in the range of 7-28 depending on the amount of the introduced additive. The presented results show that fluidized bed ash can successfully partially replace conventional fly ash in ready-mixed concretes. Moreover, fluidized bed ash can replace such expensive materials as metakaolinite and silica dust as an additive in HPC concretes. Polish power plants have prepared promotional materials and data sheets especially for such applications [19].

2.2. *Mixes used in jet-grouting*

Jet grouting (JG), i.e. high-pressure injection to improve the bearing capacity of soil, is widely used in civil engineering or hydroengineering and can be applied in almost all types of soil. The history and development of this technology is described in the following publications [20]. The method came to Europe from Japan in the early seventies. It consists in destroying the natural structure of soil by means of an injector introduced under a pressure of 30-50 MPa and a flow rate of 50-450 l/min, as well as mixing and partially replacing the existing soil with a binding agent. Injection elements (columns, walls, slabs, blocks) are formed in this way, which are fragments of scaled soil whose compressive strength depending on the type of soil medium may be approx: 1 MPa in organic soils, 5 MPa in clays, 15 MPa when forming columns in sands and 20 MPa in gravel medium [21]. JG uses in the rock mass are also known [20]. It is also used in mining structures [22]. Requirements for the design, execution, testing and monitoring of jet injection works are contained in the standard [23]. Due to the relatively young age of the method, scientific and experimental work is still being carried out to develop the current state of knowledge. There are publications [24]–[26] based on mixtures containing bottom ash or fly ash [27], [28]. Studies are being conducted to better estimate the diameters of columns formed under different geological conditions [29]. In the context of recent studies, it is important to note the increasing use of JG to strengthen the substrate of seas and oceans. Three rows of high-pressure jet grouting with a diameter of 0.8 m were to ensure safety and watertightness during the construction of the Shenzhen-Zhongshan Tunnel [30]. Analyses showed that the correctly applied technology provided the desired strength while at the same time retaining the effect of a waterproof curtain.

The search for new blend compositions is often driven by the need to ensure specific performance of the final product and economic considerations. Authors of the paper [31] compared rheological, strength and permeability parameters. SEM image analysis was also performed. Fine-grained cement (DMFC-800), Ordinary Portland Cement (OPC) and the mixture of OPC cement including 10% silica fume (SF) by weight were used as binders. The study indicated a positive effect of the additives on the strength development. Silica dust 10% in the limiting case of W/C=1.5 caused a threefold increase unconfined compressive strength according to OPC. SEM analyses show that the C-S-H product that supplies binding and strength characteristics for cement was denser in samples obtained

from DMFC-800 and OPC + 10% SF induced JG columns. Also, the pores on the interface between cement and soil decreases owing to the small grain size of binders, a denser and impermeable structure is obtained.

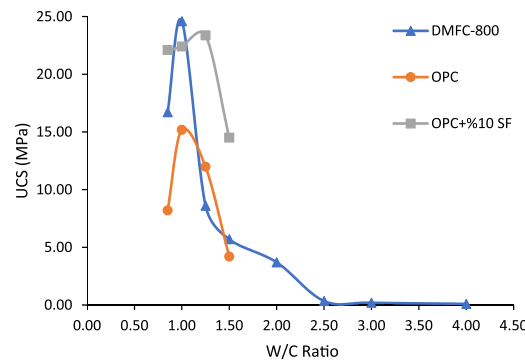


Figure 2. UCS values of samples obtained by the manufactured JG columns [31].

Paper [24] refers to the rheology of mixtures that can be used in JG. However, the analyses did not show the ash composition itself or the combustion technology from which the sample was derived. The research was reduced to a comparison of various mixtures in terms of viscosity tests, yield stress, the behaviour through the flow curves of shear stress–shear rate and model comparison. The binder in the grout mixture in the experimental study was defined as cement + stabilizer (i.e., cement + clay, cement + sand, cement + lime and cement + bottom ash). The paper presents many graphs showing the results of the research. The research was for the author a prelude to the development of a computer method for the prediction of mixture parameters. Study [25] presents a review of available research methods and the capability of a new author's methodology in soft computing techniques, called gene expression programming (GEP), to predict the rheological behaviour. Author claims, the GEP technique is relatively promising for predictions of the rheological behaviour of grout with bottom ash as an alternative to the conventional rheological models.

Publication [26] shows the chemical composition of ash and the particle size distribution curves. The parameters differ significantly from those determined in the European literature, and the particle size distribution curves suggest that the largest grains' diameter were <1 mm. The test program included 28 different mixtures having 0% (for control purposes), 5%, 10%, 15%, 20%, 25% and 30% bottom ash content and four water to binder ratios ($w/b = 0.75, 1.00, 1.25$ and 1.50). Plastic viscosity, apparent viscosity, and the yield stress of the mixtures based on rheological properties were measured for all mixtures. After all workability test results were evaluated, it was understood that Bottom Ash amount addition to the grout mixtures does not have so much effect on workability features of the mixtures. The author also proved that there are small effects on the yield stress with the substitution of BA.

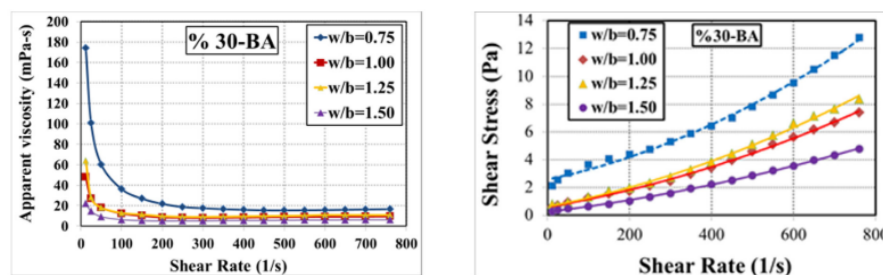


Figure 3. a) Apparent viscosity value; b) Shear stress versus shear rate flow curves based on Modified Bingham Model for 30% substitutions of BA at different w/b ratios (0.75, 1.00, 1.25 and 1.50) [26].

In the study [28] data on properties of alkaline activated fly ash used in jet grouting applications can be found. The paper briefly presented the JG technology. Description of methodology included material characteristics, description of sample preparation, setting time and short description of fluidity. It also brought up the issue of capillary absorption, problematic of shrinkage and expansion. A comparison of X-ray diffractograms of the original fly ash and the GJG8 mixture after 28 days curing was made. Studies points lower strength value obtained, corresponding to the best fluidity result, which is acceptable for a jet grouting application. Authors also claim that to improve fluidity without compromising strength, it is necessary to increase the alkali/ash ratio of the grout, in order to maintain Na_2O concentration.

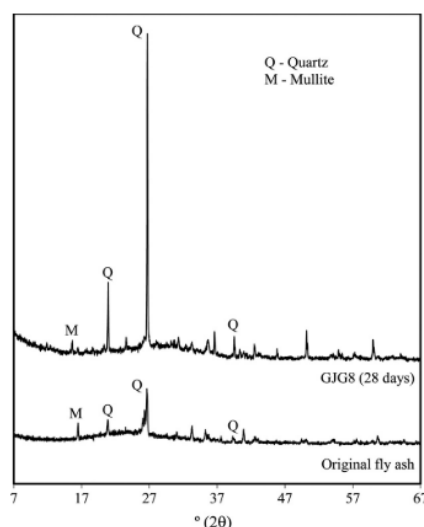


Figure 4. X-ray diffraction pattern of the activated fly ash (mixture G8) at 28 days curing [28].

Authors [27] searched for solutions that could affect the use of fluidized bed furnace fly ash in Deep Soil Mixing and JG. The paper referred to compression strength tests results of soil-binder specimens made with addition of fly ash (Knapik and Bzówka, 2013). No rheological studies have been performed. The authors conclude that fly ash from fluidized bed combustion can be successfully used in various types of engineering practice. They also point out the problem of ash quality - chemical composition of this material can vary significantly in terms of the type of the combusted coal and its origin and the quantity of sorbent.

3. Tests of cement-grounds

3.1. Strength tests

Strength tests of cement-grounds were carried out as an integral part of a doctoral dissertation carried out at Gdańsk University of Technology [32]. The author tested the strength in uniaxial compression test on specimens of 70 mm diameter and 140 mm height. The tests were performed after 3, 7, 14, 28, 60 and 90 days. In Japan, laboratory testing of cementitious soil is performed on specimens with a diameter of 50 mm and a height of 100 mm. The detailed description of cement-soil testing procedure is given in the standard of Geotechnical Association of Japan. In addition, triaxial compression tests were performed in this dissertation to determine the effect of lateral (i.e., radial) stress on the strength characteristics of the cement-ground. The DSM columns analysed in this study are loaded by lateral soil push in practice, which affects the stress distribution in various ways.

Extensive strength testing of concrete with ash additives is presented in the article [16]. The testing of the hardened concretes included determining the following properties: the development of uniaxial compressive strength after 3, 7 and 28 days in accordance with PN-EN 12390- 3:2002 [33], the development of splitting tensile strength after 3, 7 and 28 days in accordance with PN-EN 12390-

6:2001 [34], brittleness characteristics (f_c/f_t relations), apparent density after 3, 7 and 28 days in accordance with PN-EN 12390-7:2001 [35].

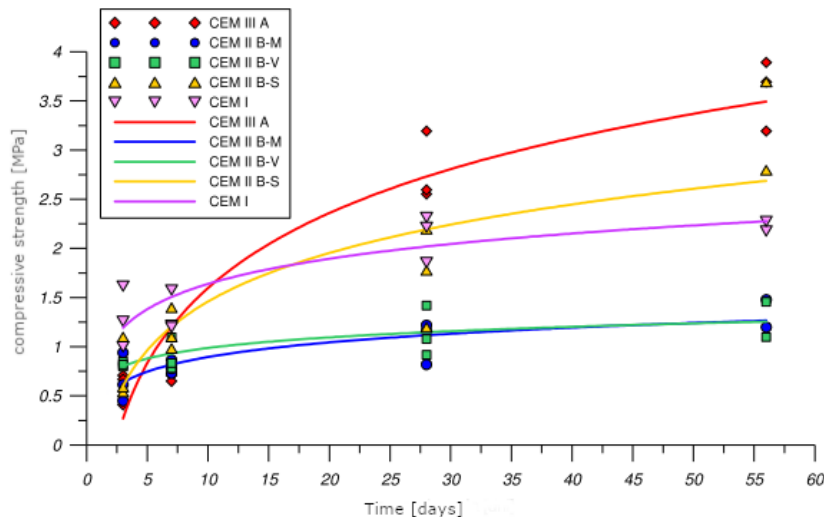


Figure 5. Effect of cement type on the strength of cement-grade soil. [32].

Table 2. Results of the concrete compressive strength tests [16].

Mix	Compressive strength after 3 days [MPa]	Compressive strength after 7 days [MPa]	Compressive strength after 28 days [MPa]
B1- reference mix	24,74	27,65	38,3
B2 – 15% PDF>0.63 mass of sand and gravel	37,41	38,82	51,25
B3 – 30% PDF>0.63 mass of sand and gravel	42,64	54,74	59,33
B4 – 15% PDF<0.63 mass of cement	10,25	16,93	26,2
B5 – 15% PDF (non-separated) mass of sand and gravel	26,08	28,42	30,51
B6 – 15% PDP>0.63 mass of sand and gravel	24,57	33,21	47,33
B7 – 30% PDP>0.63 mass of sand and gravel	33,75	37,12	40,86
B8 – 15% PDP<0.63 mass of cement	17,14	26,67	29,31

3.2. Frost resistance tests

Frost resistance tests are performed in accordance with PN-88/B-06250 06250 [36] by a standard method using an automatic freezing chamber [17]. The frost resistance test consists in subjecting 3 concrete samples of dimensions 150×150×150 mm, from each series soaked in water, to 100 cycles of freezing (4 h at $-18^{\circ}\text{C} \pm 2^{\circ}\text{C}$) and thawing (2÷4 h at $+18^{\circ}\text{C} \pm 2^{\circ}\text{C}$). According to the analyses [7] fluidized ash as an additive to concretes slightly affected the frost resistance results. However, concretes with fluid ash can be classified as having good frost resistance and good resistance to de-icing agents.

3.3. X-ray computed tomography studies and analysis

When trying to design a new material, it can be extremely helpful to see what happens to the internal structure of the sample. Any cuts or breaks can cause damage to the internal structure. In the era of widespread computerization and availability of computers with high computing power, X-ray computed tomography (CT) technology is developing rapidly. An important publication from the point of view of possibility analysis seems to be [37]. The authors cite extensive applications of CT in materials science. The main part of the article focuses on possibilities of working with data. Results of Sadowski and Stefaniuk are quoted [38]. They used the results of the pore structure obtained from

the micro-CT image to evaluate the microstructure characteristics of typical concrete surfaces. Modern CT image analysis programs are excellent at distinguishing such large absorptions as occur between concrete and air [39]. There are known works that visualize the air distribution at different dosages of air-entraining admixtures [40]. Visually, the reconstruction allows observation of defect propagation and pores [41] used in fire damage assessment [42], frost action [43], [44], structural overloads [45] whether the distinction between compression and tension damage [46]. In addition to simply assessing the internal structure, the key to the JG topic seems to be prediction of permeability based on 3D CT image [47]. The permeability of the cementitious materials is due to the presence of pore channels and depends on the size of pores and their network of connections. With the development of CT and increase in accuracy it becomes possible to simulate fluid flow through scanned samples [48].

4. Conclusions

The paper presents and discusses articles being in connection with the issue of utilization of fluidized bed boiler bottom ashes with jet grouting technology. There are clear indications that ashes allow to reduce cement consumption while maintaining desired strength characteristics. The current state of knowledge indicates some possibilities in the use of bottom ash as an additive in the soil improvement process. The author recognizes a certain research gap in the form of lack of studies of local fluidized bed bottom ash. Allowing the use of further waste would positively affect the situation of Poland in the face of climatic closed loop. The planned research is part of the zero-waste and the concept of green-concrete [49]. Replacing part of the cement also saves on the CO₂ produced, moreover, the research is also supported by the economic aspect [50].

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