THE ECONOMIC AND ENVIRONMENTAL BENEFITS FROM INCORPORATION OF COAL BOTTOM ASH IN CONCRETE

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ABSTRACT

Coal is a fossil fuel and an important natural resource. Combustion of coal provides high energy production. Total coal production in 2011 was 7678 Mt and lignite production was 1041 Mt. Coal provides 30.3% of the total world primary energy demand and 42% of the world's electricity is produced from the combustion of coal. Coal production will continue to increase and in the 2030's 44% of the world's electricity will be produced from coal (from Data courtesy). Coal combustion is provided in thermal power plants. A significant amount of coal ash is produced burning coal and utilization of ash is an important issue in the world. The sustainable utilization of coal ash could improve production efficiency, reduce production costs and diminish waste product disposal problems.

In this research coal combustion product – coal bottom ash - was investigated regarding its application as a micro filler in conventional concrete production. Coal bottom ash was taken from a local boiler house in Latvia and preliminary processing of coal bottom ash was done. Coal bottom ash was ground for 15, 30 and 45 minutes respectively. The grading analysis of obtained microfiller was done with standard sieves and grading curves were obtained. Scanning electron micrographs were obtained and energy-dispersive X-ray spectroscopy was performed.

In the current study, conventional concrete mixture with the cement amount of 350kg/m^3 and W/C 0.61 was chosen to integrate it with coal bottom ash as a microfiller. The integration ratio of microfiller was chosen 10, 20, 30 and 40% by the mass of cement for each type of prepared coal bottom ashes. Reference concrete mixture consisted of 0% coal bottom ash. The concrete workability was kept constant for all mixtures and the chosen cone slump class was S4 (160-210mm). Fresh and hardened concrete properties were obtained. Compressive strength was determined at the age of 7, 14 and 28 days.

Processed coal bottom ash could be used as a microfiller for conventional concrete production. Higher concrete strength class with the same amount of cement could bring economic benefit up to 3.6%. By incorporation of coal bottom ash in concrete environmental benefits could be achieved due to reduced cement consumption and effective disposal of coal bottom ash. The integration level of coal bottom ash could not exceed 30% by the mass of cement. At low rates of incorporation (<20%) coal bottom ash provides the same W/C for concrete and fresh concrete density increases. Mechanical and physical properties of concrete can be improved by choosing appropriate amount of coal bottom ash microfiller.

Key words: concrete, coal bottom ash, microfiller, environmental and economic benefit.

INTRODUCTION

Burning of coal generates a significant amount of coal combustion products (CCPs), especially in the countries where large quantities of low quality coal is used in thermal power plants; therefore coal ash recycling is an important environmental issue in the EU. Total production of CCPs is estimated to be more than 100 million tonnes annually in the EU 27 (ECCPA, 2011). CCPs endanger the environment if they are deposited without taking measures to reduce environment pollution. However, the overall situation is quite positive, because at least half of the coal ash is recycled in many developed countries. The CCPs are mainly utilised in the building material industry, in civil engineering, in road construction, for construction work in underground coal mining as well as for recultivation and restoration purposes in open cast mines (ECCPA, 2011). As coal is not among the natural resources available in Latvia and it has to be imported from the neighbouring countries for energy production purposes, it constitutes only 2.2 % from the total amount of primary energy resources compared to the overall indicators in the world (Ministry of Economics, 2011). However, coal burning in Latvia generates a significant amount of waste in the form of coal ash, which could cause serious environment pollution problems on a local scale.

Industry development in the local, national regional and the EU level is determined not only by the interests of companies operating in the respective industry, but also by the planning documents at multiple levels. The EU energy policy aims to ensure environmentally friendly energy production and use, and also to reduce energy delivery risks.

One of the problems is collecting, storage and recycling of waste generated in power and heating plants. In order to coordinate the reduction of industrial pollution among the EU member states more effectively, Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control was adopted aiming to achieve an integrated prevention and control of pollution arising from the activities listed in the directive. It lays down measures designed to prevent or, where it is not practical, to reduce emissions in the air, water and land (Council directive, 1996).

Integrated approach regarding environment pollution prevention and control is an important step towards legislation improvement. The above mentioned directive also concerns energy generation installations. According to the Council Directive 96/61/EC the national Law on Pollution was developed which came into force as of 1 July 2001 identifying the order of a gradual transition to the integrated environment pollution prevention and control.

As generation of waste is an integral part of the production process, it is necessary to coordinate proper waste management. Waste management in Latvia at the moment concerns building up the legal basis according to the basic principles of waste management in the EU, creation of an infrastructure for both municipal and industrial waste as well as implementation of legal provisions.

By burning solid fuel in furnaces at around 1700 – 1900 on the Kelvin scale, thermal power plants generate tons of solid mineral waste in the form of bottom ash and fly ash. Modern thermal power plants use pulverized coal. Bottom ash is formed from the completely melted and partially melted ash particles inside the furnace and fall through open grates to an ash hopper at the bottom of the furnace. Bottom ash particle size is 1 to 50 mm. Two types of ashes are formed in the process of pulverized coal burning: bottom ash that fall through open grates to the bottom of the furnace and fly ash that rise with the flue gas and can be collected by flue gas purification. The chemical composition of ash may vary significantly. It may contain SiO_2 47.5-57.32 %, Al_2O_3 19.00-30.22 %, CaO 2.53-28.75 %, Na_2O 0.9-1.22 %. The chemical composition depends on the coal mining area, their quality as well as the combustion process (We Energies, 2003). According to X-ray structural analysis the majority of ashes consist of quartz, anhydrite, calcium oxide together with iron and aluminium oxides (dicalcium silicate, tetracalcium aluminoferrite, calcium aluminates, calcium ferrites). These compounds are followed by glass phase, hematites and admixtures as well as CaO and MgO (Zakharova, 2008).

Several applications are found for coal combustion products. However, huge quantities of the coal combustion products are still deposited in waste sites. Recycling of the coal combustion residuals could bring an economic benefit to some of the production industries and contribute to environmental quality improvement. Use of coal ash leads to the economizing of natural resources as well as diminishing of costs associated with the storage and depositing of coal combustion waste. By using 30 million tons of coal combustion products, 620 million US dollars as well as an area of 1.416 km^2 necessary for the depositing of coal combustion products can be spared. Finding a useful application for the above mentioned amount of coal combustion products can bring a profit of 150 million US dollars, raising the total benefit to 770 million US dollars. (Data courtesy, 2001).

The angular form of coal ash particles allows using it as an anti-slip substance on driveways covered with snow and ice. As the coal combustion ashes do not have distinct pozzolanic properties and spheric form as do the electrofilter ashes (fly ashes), they latter are more often used as a partial replacement of cement in concrete mixes. However, coal ashes often are used to replace the traditional fillers in concrete mixes, asphalt concrete and the production of concrete blocks. Often they are used in cement production as flux and for clinker production, also as mineral additives in several commercial products and replacement for sand with wide possible application (Data courtesy, 2001).

There are several researches performed on the use of coal ash as a filler in traditional concrete. As it comprises large amount of carbon from partially burned coal, coal ashes are rinsed in separate cases. It allows to obtain ashes with a lower carbon level, but their production costs raise significantly (Mohd Sani et al., 2010). By using rinsed coal ash to replace 30% of sand in concrete, improved mechanical properties were obtained. Other researches show (Data courtesy, 2001), that washing or rinsing of coal ashes can have a negative impact on the mechanical properties of concrete, because in the rinsing process small particles rinse out thus weakening the bond between hydrated cement paste and filler. The rinsing process lowers effectiveness of coal ash as a pozzolanic additive, because usually the particles are small and can be rinsed out. In addition, researchers explain it with the properties of pozzolanic materials – pozzolanic materials react with calcium hydroxide in the presence of water and form calcium silicate hydrates. After reacting with rinsing water the activity of coal ash may decrease significantly. In addition, water may impact the transformation of chemical elements to the heavy metals thus having an important impact on the physical properties of concrete. For this reason it is essential to determine whether processing of coal ashes by rinsing is necessary, because it decreases their effectiveness.

Coal ashes have been used as a replacement for cement concluding that concrete containing coal ashes show higher mechanical properties in the later stages of curing. Possibly, it can be observed due to the pozzolanic reactions provoked by coal ashes

(Cheriaf et al., 1999; Garboczi, Bentz, 1991). After long-term curing (90 days) compressive strength of the specimens containing coal ashes exceeds the compressive strength of the reference mix.

Consulting with scientific literature sources, it has been decided not to include rinsing of coal ashes in this research to avoid the weakening of coal ash pozzolanic properties. In the framework of scientific research coal bottom ash was used as a micro and pozzolanic additive in order to improve the physical and mechanical properties of the concrete. Coal bottom ash was ground in a planetary ball mill for 15, 30 and 45 minutes before use. The prepared ashes were integrated into the concrete replacing 0; 10; 20; 30 and 40% of cement mass.

MATERIALS AND METHODS

Coal bottom ash

Coal bottom ash was obtained from burning coal in a thermal power plant. The obtained coal bottom ash was homogenised by grinding it in the planetary ball mill for 15, 30 and 45 minutes before use in the concrete preparation. Density of the homogenised coal bottom ash is 2.47 g/cm^3, which corresponds to the reference data taken from the literature ranging from 1.86-2.7 g/cm^3 (Federal Highway Administration, 2011; Shah et al. 2005).

From the results of particle size distribution analysis the impact of the grinding period on the particle size distribution of coal bottom ash is clearly visible. Coal bottom ash with a grinding period 15 minutes is coarser than others with longer grinding periods. Amount of particles with the size smaller than 0.125 mm constitute only 47.4%, by extending the grinding period up to 30 minutes the amount of smaller particles increases to 51.5% and up to 45 minutes – to > 74.9 %. Coal bottom ash with a grinding period of 15 minutes is coarser making their particle size distribution similar to particle size distribution of traditional fine sand. By extending the grinding period, the amount of smaller particles increases, which can raise the activity of coal bottom ash during the concrete curing process, because the specific surface area increases and the surface interaction with the hydrated cement paste intensifies. In the particle size distribution of coal bottom ash ground for a shorter period (15 minutes) particles that exceed size of 0.25 mm are observed and they constitute 36.4%. It may have a positive impact on the particle size distribution in concrete by ensuring optimal particle packing. Particle size distribution for coal bottom ash and traditional fillers is given in Figure 1.

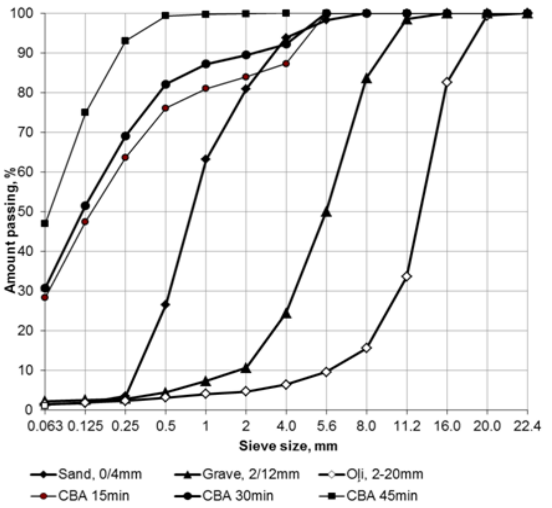

Figure 1. Particle size distribution of ground coal bottom ash and fillers used in concrete production

SEM scanning of coal bottom ash ground for 15, 30 and 45 minutes

The obtained coal bottom ashes from a grinding period of 15, 30 and 45 minutes were scanned by a SEM in order to determine structure of particles and their size. In the SEM it is possible to observe the ash surface as well as the evenness of particle distribution for ash with a different grinding period and to determine the particle size. Particles of coal bottom ash from a grinding period of 15 minutes are presented in Figure 2, particles from a grinding period 30 minutes magnified 10000 times – in Figure 3. Size of the bigger particles is 73.92 μm with a grinding period of 15 minutes and it decreases to 1-3 μm after a grinding period of 30 minutes. In addition, regardless of the grinding period, some of the particles are significantly larger compared to the overall particle size. These particles are harder and are not reduced to smaller pieces during the grinding process.

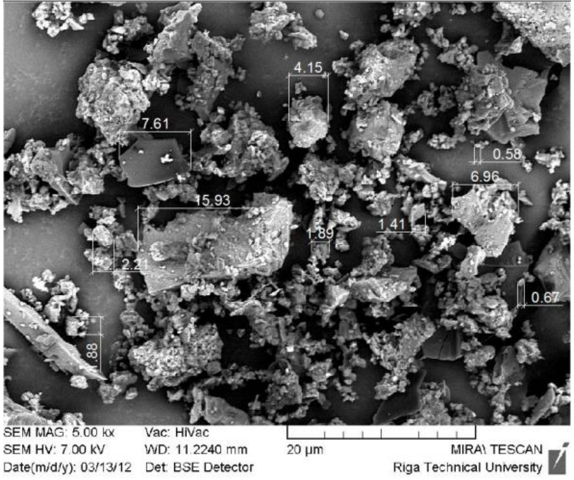

Figure 2. SEM image of coal bottom ash ground for 15 minutes

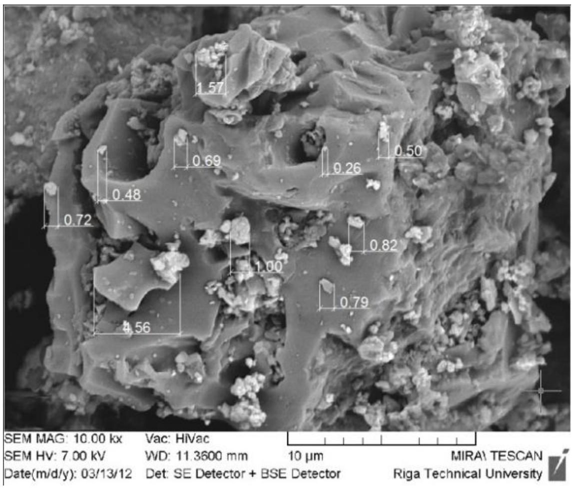

Figure 3. SEM image of coal bottom ash ground for 30 minutes

The ash particles mainly have an angular form. A lot of finer particles can be observed on the surface of larger particles, which have the appearance of metallic lustre and could be the metals present in the coal bottom ash. Larger particles could be partially burned pieces of coal according to literature sources (Pollocka et al., 2000; Karayigita et al., 2000). Additional EDX analysis is necessary in order to determine the elements present in the particles more precisely.

EDX analysis

EDX analysis was performed in order to determine the elements present in the coal bottom ash. It may consist of 88.78% carbon (C) and 10.44% oxygen (O), indicating presence of coal pieces which are not burned or burned partially. Presence of metallic elements were detected in separate locations. In most cases it is aluminium – 3.23 - 10.77%; silica with 3.41 - 11.49 % and calcium with 7.42 % are detected as well. Results are given in Table 1.

Table 1

Distribution of elements in typical locations of coal bottom ash

Elements, atomic weigh,%	EDX analysis location		
	Spectrum 1	Spectrum 2	Spectrum 3
C	88.78	23.63	34.36
O	10.44	54.1	49.82
Mg	0.22	-	1.26
Al	0.13	10.77	3.26
Si	-	11.49	3.41
S	0.26	-	0.18
Ca	0.17	-	7.42
Fe	-	-	0.3

Preparation of concrete mixtures

Concrete mix composition of traditional pumpable concrete was chosen with the mechanical properties meeting the demands of concrete technologists and civil engineers. Reference mix consists of a cement amount of 350 kg/m^3, gravel fraction 2/12 mm and 5/20 mm – 500 kg/m^3 of each fraction, sand 0/4 mm – 750 kg/m^3. The reference W/C ratio was 0.61. Coal bottom ash (with a grinding period of 15, 30 and 45 minutes) was added to the concrete mix replacing 10, 20, 30 and 40 % of the cement mass. Concrete mix compositions with various amounts of coal bottom ash and W/C ratio are given in Table 2. Water to the concrete mix compositions consisting of coal bottom ash was added according to the cone slump class of S4, which range from 160 – 210 mm. The added coal bottom ash may improve the concrete flow and reduce W/C ratio or increase W/C ratio depending on the amount of coal bottom ash added and their particle size distribution. As it can be seen in Table 2, adding 10% of coal bottom ash with a grinding period of 15 minutes does not increase the necessary W/C ratio in order to ensure the initial cone slump class, but increasing the amount of added coal bottom ash to 40% increases the W/C ratio up to 0.69. 10% of coal bottom ash with a grinding period of 30 minutes reduces the necessary amount of water and therefore the W/C ratio to 0.60, while adding 40% of the same coal bottom ash increases it slightly to 0.62. 10% of coal bottom ash with a grinding period of 45 minutes reduces the W/C ratio significantly to 0.58, but the larger amount of the coal bottom ash increases it to 0.63.

A gravity type concrete mixer was used for the concrete mixes. Initially the dry components were measured and put into the mixer. The dry components were mixed for 1.5 minutes in order to obtain a homogenous dry concrete mix. Water was added in two steps. At first 70% of the water was added to the mix and it was mixed for 1.5 minutes. Then the rest of the water was added and the concrete was mixed for an additional 1.5 minutes. If the concrete consistency (workability) still did not correspond to the initial demands, an extra amount of water was added, and the concrete was mixed for an additional 1 minute and its consistency was checked repeatedly. Fresh concrete was moulded into standard size moulds of 100x100x100 mm. Half of the mould was filled with fresh concrete mix, and then it was put on a vibrating table for 5 seconds in the intensive mode. Finally, the rest of the fresh concrete mix was added into the mould and it was put on the vibrating table for another 10 seconds in the intensive mode.

Testing methods

Testing of concrete workability was performed according to the standard LVS EN 12350-2:2009 Testing fresh concrete - Part 2: Slump-test. For the purposes of this research traditional concrete with the cone slump class of S4 was prepared. Cone slump (LVS EN 12350-2) and bulk density of fresh concrete was determined.

Compressive strength of concrete was determined according to the standard LVS EN 12390-3:2009 Testing hardened concrete - Part 3: Compressive strength of test specimens. Compressive strength was determined for the specimens sized 100x100x100 mm. Compressive strength of concrete was tested after an initial curing period of 7 and 14 days after a standard curing period of 28 days. Depth of penetration of water was tested according to the standard LVS EN 12390-8:2009 Testing hardened concrete - Part 8: Depth of penetration of water under pressure. Concrete specimens with the dimensions of at least 100x100x100 mm were tested under a pressure of 500 KPa for 72±2 h.

RESULTS AND DISCUSSION

Fresh concrete properties

Fresh concrete properties were tested in the process of concrete preparation. Reference consistency and workability demands were set for each of the concrete mixes. The amount of water added and cone slump varied depending on the amount of coal bottom ash added and their grinding period. Data on the cone slump is given in Table 3. For the concrete without coal bottom ash added cone slump is 180 mm and W/C ratio 0.61. Adding coal bottom ash with a grinding period of 15 minutes, the concrete workability decreases; by replacing 10% of cement with coal bottom ash without increasing W/C ratio, the cone slump decreased to 170 mm. Replacing up to 40% of cement with coal bottom ash it was necessary to increase the W/C ratio up to 0.69 in order to maintain the minimum cone slump. The workability of concrete improved by replacing 10% of the cement with coal bottom ash with a grinding period of 30 minutes – cone slump 165 mm with W/C ratio 0.62 was obtained. By increasing the amount of coal bottom ash up to 20%, W/C ratio remained 0.61; while cone slump decreased to 170 and 165 mm. Replacing 40% of the cement with coal bottom ash cone slump 165 mm with W/C ratio 0.62 was obtained. 10% of coal bottom ash with a grinding period of 45 minutes showed lower W/C ratio – 0.58 – and maintained the previous cone slump of 180 mm. However, further increase of coal bottom ash amount did not improve properties of fresh concrete; replacing 30% of cement W/C ratio 0.63 was necessary to ensure a cone slump of 160 mm. 40% of coal bottom ash resulted in a cone slump of 170 mm with W/C ratio 0.63.

Table 3

Cone slump of concrete mix

Cone slump, mm	CBA in concrete				
	REF	10%	20%	30%	40%
CBA15	180	170	160	160	170
CBA30	180	195	170	165	165
CBA45	180	180	180	160	170

Hardened concrete properties

Compressive strength of hardened concrete was determined. The results are given in Figure 4. Compressive strength of 7 days old concrete specimens reached 33-41 MPa depending on the amount of coal bottom ash added. Reference mix without coal bottom ash showed 38 MPa compressive strength. Coal bottom ash with a grinding period of 15 minutes replacing 10, 30 and 40% of cement decreased the compressive strength after initial curing period to 36, 37 and 33MPa respectively, but replacing 20% of cement slightly increased it to 39 MPa. Coal bottom ash with a grinding period of 30 minutes showed compressive strength 38 MPa that was equal to the reference mix. Coal bottom ash with a grinding period of 45 minutes showed the best results after 7 days of curing; replacing 10, 20 and 30% of the cement compressive strength increased to 41, 38 and 39 MPa, but replacing 40% of cement it decreased to 37 MPa. Compressive strength of 14 days old concrete specimens reached 42-47 MPa. Compressive strength slightly decreased in general. Reference mix showed compressive strength 45 MPa. Coal bottom ash with a grinding period of 15 minutes replacing 10-40% of cement showed slightly lower compressive strength – amount 10 - 30% showed 44 MPa and amount 40 % - 42 MPa. Coal bottom ash with a grinding period of 30 minutes showed equivalent results and 20-40% of coal bottom ash added increased the compressive strength of specimens exceeding the reference mix with 45; 47 and 47 MPa respectively, 10% ensured a compressive strength of 44 MPa. Coal bottom ash with a grinding period of 45 minutes showed a compressive strength of 43-45 MPa after 7 days of curing.

The lowest the compressive strength was observed for concrete specimens with 40% of cement replaced by coal bottom ash. Compressive strength after 28 days of curing is used to determine the concrete strength class. The compressive strength of the reference mix increased very slightly reaching 47 MPa. Mixes with the coal bottom ash with a grinding period of 15 minutes showed equivalent results to those of the reference mix; by increasing the amount of coal bottom ash to 30% the compressive strength reached 48, 50 and 51 MPa respectively, by 40% it remained at 47 MPa. Mixes with the coal bottom ash with a grinding period of 30 minutes showed a higher compressive strength of 53 - 54 MPa. However, mixes with the coal bottom ash with a grinding period of 45 minutes showed the highest compressive strength of 54 – 57 MPa. It was rising by increasing the amount of coal bottom ash up to 30%, where it slightly decreased to 55 MPa.

Table 2

Concrete mixture composition

	kg/m^3				
	REF	10%	20%	30%	40%
Portland cement Kunda CEM I 42.5 N	350	350	350	350	350
Gravel 5/20	500	500	500	500	500
Gravel 2/12	500	500	500	500	500
Sand0/4	750	750	750	750	750
Coal bottom ash	0	35	70	105	140
REF W/C	0.61	-	-	-	-
CBA 15min W/C	-	0.61	0.62	0.65	0.69
CBA 30min W/C	-	0.60	0.61	0.61	0.62
CBA 45min W/C	-	0.58	0.61	0.63	0.63

Taking into account the compressive strength results after 28 days of curing it is possible to conclude that the reference mix with a compressive strength of 47 MPa corresponds to the concrete strength class C30/37 with a guaranteed compressive strength of cube 37 MPa. The next concrete strength class C35/45 demands a compressive strength of cube 45 MPa, which is difficult to ensure with a compressive strength of 47 MPa. Concrete specimens with coal bottom ash with a grinding period of 15 minutes showed a compressive strength of 47-51 MPa, which corresponds to the concrete strength class C30/37 and specimens with 30% of coal bottom ash were closer to the concrete strength class C35/45 with 51 MPa exceeding the necessary 45 MPa. Concrete specimens with the coal bottom ash with a grinding period of 30 minutes reached 49-54 MPa, which is closer to the concrete strength class C35/45. Specimens with 10, 20 and 40% of coal bottom ash and compressive strength 53 - 54 MPa correspond to the strength class C35/45 already having a strength reserve and can be compared to the next strength class of C40/50 with the guaranteed compressive strength of cube 50 MPa.

Water permeability, splitting strength, water absorbtion

Water permeability or depth of water penetration in concrete specimens was tested after 28 days. Water absorbtion and tensile splitting strength was tested as well. Results of water absorbtion, water permeability and splitting strength are given in Table 4. Depth of water penetration for concrete reference mix specimen is 28 mm, other specimens with various amounts of coal bottom ash and grinding periods were compared to it. Depth of water penetration for concrete mix with 10% of coal bottom ash with a grinding period of 15 minutes showed the maximum depth of water penetration 30 mm. 20% of coal bottom ash decreased it to 14 mm, but 30 and 40% of coal bottom ash increased depth of water penetration to 25 mm un 32 mm respectively. Coal bottom ash with a grinding period of 30 minutes diminished depth of water penetration significantly. The lowest depth of water penetration was observed for 20% of coal bottom ash – 10 mm and for 30% of coal bottom ash – 12 mm.

Table 4

Results of water absorbtion, water permeability and splitting strength

Mixture design	Depth of water penetra-tion, mm	Splitting tensile strength, MPa	Water absorption, %
ET	28	2	6.1
CBA15/10	30	2	5.7
CBA15/20	14	2	5.7
CBA15/30	25	2	5.7
CBA15/40	32	2	6.2
CBA30/10	20	2	6.2
CBA30/20	10	2	6.1
CBA30/30	12	2	5.8
CBA30/40	18	2	6.1
CBA45/10	42	2	5.0
CBA45/20	18	2	4.9
CBA45/30	23	2	4.6
CBA45/40	16	2	4.7

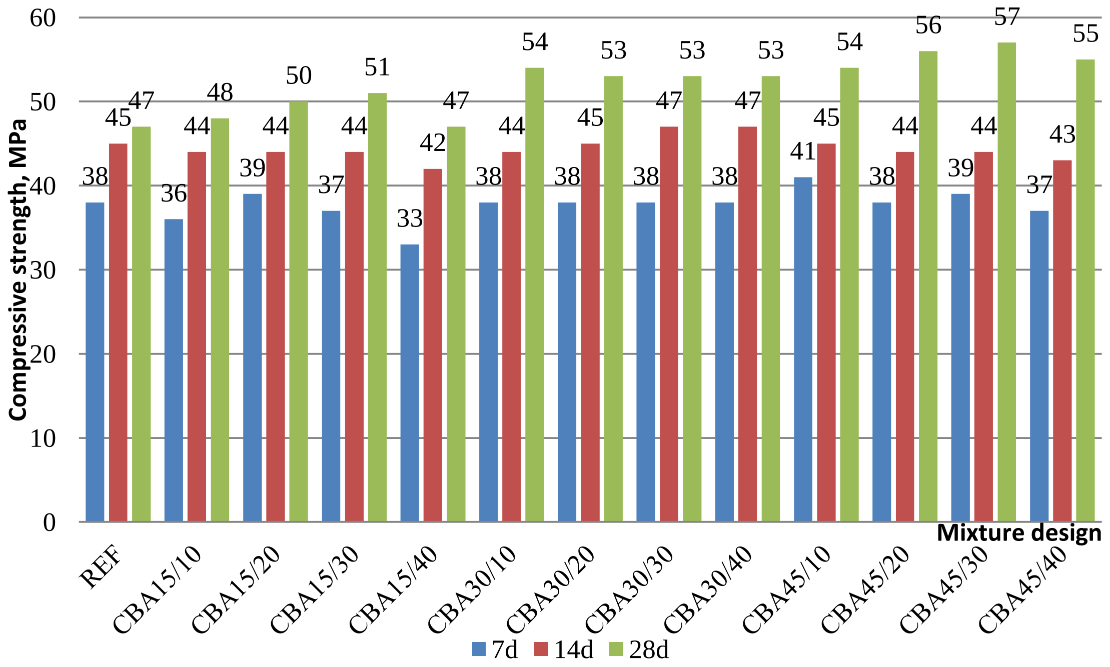

Figure 4. Concrete compressive strength after 7; 14; 28 days

For 10% of coal bottom ash it was 20 mm and for 40% of coal bottom ash – 18 mm. The highest depth of water penetration was observed for coal bottom ash with a grinding period of 45 minutes and replacing 10% of cement with it - 42 mm, replacing 20% of cement it decreased significantly to 18 mm and replacing 30 and 40% of cement it was 23 mm and 16 mm respectively.

In order to test the water absorbtion the concrete specimens were immersed in water for 72 hours. The excess water was wiped off afterwards and specimens were weighted. Finally, the specimens were dried and weighted. The concrete reference mix specimen showed water absorbtion rate of 6.1%. Coal bottom ash with a grinding period of 45 minutes added up to 30% lowered the water absorbtion rate to 5,7%, but 40% raised it to 6.2%. Coal bottom ash with a grinding period of 30 minutes showed water absorbtion rate to 6.2% by replacing 10% of cement with it. By increasing the amount of coal bottom ash up to 30%, the water absorbtion rate was 6.1 and 5.8% respectively, by 40% it slightly increased to 6.1% which corresponds to the water absorbtion rate of reference mix. Coal bottom ash with a grinding period of 45 minutes lowered the water absorbtion rate significantly compared with the results of the reference mix. Even replacing 10% of cement with it the water absorbtion rate was 5.0% and decreased up to 30% showing water absorbtion rate 4.9 % and 4.6 %. Replacing 40% of cement water absorbtion rate slightly increased to 4.7%.

Tensile splitting strength of concrete specimens was tested as well. As it is shown in the Table 4, it is 2 MPa and does not change adding various amounts of coal bottom ash with different grinding period.

Economic and ecological benefits

Economic substantiation of using ground coal bottom ash as a concrete micro additive is necessary for utilization of ash in the concrete industry to be cost effective. The economic benefit should be reasonable as recycling of coal bottom ash in concrete micro additives demands certain investments. Coal bottom ash recycling includes transportation costs from heating plants and costs related to the grinding of coal bottom ash for fixed period of time to obtain the necessary fineness. As transportation costs occur by transporting the natural resources for the concrete production as well, it can be assumed that this price formation factor is equal with the delivery of raw material to the concrete plant. Grinding is one of the most energy-intensive processes related to the ash preparation for use in concrete production. Ash grinding for industrial use is similar to the cement clinker grinding. As the fineness of clinker and ash is similar, energy and costs of ash grinding will be equivalent to the power-intensity and costs of cement grinding. Output data for energy and costs of ash grinding will be assumed equivalent to those of cement clinker grinding.

The grinding process is an important stage both in cement production and ash processing for their use in concrete production. Considerable amount of CO_2 is generated in cement production process. Cement production industry generates 5% of the total amount of CO_2 emissions. Cement production generates 222 kg of CO_2 in average on 1 ton of cement produced (Jankovic, Valery, 2004). Energy consumed by mills in the cement grinding process generates 50 kg of CO_2 in average on 1 ton of cement produced (50 kg CO_2/t) (Research profile letter, 2011). An equivalent amount of CO_2 would be generated in the process of ash grinding as well. Cement production industry consumes 110 kWh of electricity to produce 1 ton of Portland cement. Around 40% of the energy necessary for 1 ton Portland cement production is consumed for clinker grinding (Jankovic, Valery, 2004). The current standard that allows estimating energy consumption in the grinding process is specified with the empiric formula which is based on cement specific surface area (Blein method) and specific energy consumption for grinding. A relation is discovered experimentally that defines energy consumption according to the specific surface area (cement fineness). It can be observed that cement consists of two components which demand different energy consumption in order to obtain equivalent fineness. Consequently ~47 kWh of energy is necessary for producing 1 ton of cement with specific surface area 450 m^2/kg (Research profile letter).

Economic benefit

Ecological and economic benefits were determined for the concrete mix with the highest compressive strength, where 30% of coal bottom ash with grinding period 45 minutes were added, which is 105 kg/m^3 of coal bottom ash in the concrete. The highest compressive strength was chosen, because this is one of the most important concrete properties and the choice of concrete is based mainly on the strength class of concrete. Economic benefit can be determined by the strength class and current market price of concrete. Reference mix with 0% of coal bottom ash has the compressive strength class C30/37 with compressive strength of cube 47 MPa. The concrete mix with where 30% of coal bottom ash with a grinding period of 45 minutes were added has compressive strength class C40/50 with compressive strength of cube 57 MPa. For the purposes of economic comparison it will be assumed that the respective concrete mix has the compressive strength class C35/45 leaving a compressive strength reserve. Economic comparison is given in Table 5. Concrete price is indicated according to information on company Kolle Beton website in April, 2012 (Kollebeton, 2012). The price of traditional concrete is 53.24-55.66 LVL depending on the compressive strength class (C30/37-C40/50). Based on data of the reference mix C30/37 with the price 53.24 LVL/m^3, economical calculations were made and costs for m^3 of concrete estimated, replacing 30% of the cement mass with coal bottom ash ground for 45 minutes (assuming that for the concrete C30/37 it would be 350 kg/ m^3). The price of the energy consumed for coal bottom ash grinding is assumed 0.1074 LVL/kWh. As coal bottom ash was ground for 45 minutes and the amount 30% of the cement mass (350 kg/m^3) constitute 105 kg/m^3, the price of coal bottom ash preparation for 1 m^3 is 0.48 LVL. The price of new concrete with higher compressive strength is calculated by adding this price to the price of concrete C30/37. Economic benefit is 0.70 LVL for 1 m^3 of concrete assuming that it corresponds to the compressive strength class C35/45 or 2.00 LVL if the compressive strength class is C40/50. Costs of concrete decrease by 1.4 and 3.6% respectively compared to the market price for the particular compressive strength class concrete without coal bottom ash micro additive.

Ecological benefit

In addition to the economic benefit there is an ecological benefit as well. Ecological benefit comes from the economizing of cement and deposition costs of coal bottom ash. Estimation of deposition costs differs in each individual case and therefore it is difficult to assess them, therefore the ecological benefit will be based on the theoretical reduction of CO2 emission in the cement production.

Table 5

Economical comparison for concrete with coal bottom ash added

	Compressive strength class of concrete		
	Concrete C30/37	**Concrete C35/45**	**Concrete C40/50**
Market price for m^3 of concrete* [17]	53.24	54.45	55.66
Amount of coal bottom ash in concrete, kg/m^3	0	105	105
Price of coal bottom ash grinding, LVL/t**	4.03	4.03	4.03
Price of coal bottom ash for 1m^3 of concrete (140kg), LVL	0	0.42	0.42
Costs of concrete with coal bottom ash (price for concrete 30/37)	53.24	53.66	53.66
Economic benefit LVL/m^3 concrete	0.00	0.79	2.00
Price changes, %	0.00	-1.4	-3.6

*Concrete C40/50 (B40) with the maximal aggregate size 16 mm;
Concrete C30/37 (B30) with the maximal aggregate size16 mm

** Calculated for the electricity consumption 50 kWh/t, tariff 0.1074 Ls/kWh

Table 6

Calculations of CO_2 emission amount of cement production for 1 m^3 of concrete

	Concrete C30/37	**Concrete C35/45**	**Concrete C40/50**
Amount of cement for concrete without coal bottom ash, kg/m^3	350	370	390
Concrete with coal bottom ash, kg/m^3:			
Cement	350	350	350
Ash with grinding period 45 min 40 %	0	105	105
CO_2 emissions for cement without coal bottom ash, kg/m^3 concrete	78	82	87
CO_2 emissions for cement with coal bottom ash, kg/m^3 concrete:	78	83	83
$CO_2$from cement	78	78	78
CO_2 from grinding of ashes	0	5.25	5.25
CO_2 emission changes, kg/m^3 concrete:	0	1	-4
CO_2 changes, %	0	1.0	-4.2

By including coal bottom ash in the concrete mix it raises the compressive strength class of concrete (from C30/37 to C35/45 or C40/50). If coal bottom ash would not be included in the concrete mix it can be assumed that the amount of cement necessary for 1 m^3 of concrete would be increased in order to raise the compressive strength. By estimating economizing of cement for 1 m^3 of concrete it is possible to calculate CO2 emission reduction for 1 m^3 of concrete with ground coal bottom ash. By estimating the necessary amount of cement, it was assumed that compressive strength of cube for specimens correspond to the standards of compressive strength classes. Namely, it is 53 MPa for compressive strength class C35/45 and 58 MPa for compressive strength class C40/50, which is close to the compressive strength of the specimens with coal bottom ash (57 MPa).

In order to produce concrete with a definite compressive strength class without the coal bottom ash micro additive, 370 kg/m^3 of cement is necessary for concrete with the compressive strength class C35/45 and 390 kg/m^3 of cement is necessary for concrete with the compressive strength class C40/50. Calculations of CO_2 emission amount in production of 1 m^3 of concrete including various compressive strength classes and option of replacing 30% of cement with coal bottom ash ground for 45 minutes are given in Table 6. CO_2 emission from production of 1 m^3 of concrete constitutes 78 kg for concrete C30/37 with the cement amount 350 kg/m^3. Increasing the amount of cement, the amount of CO_2 emissions grows proportionally reaching 82 kg/m^3 for concrete C35/45 and 87 kg/m^3 for concrete C40/50. If the amount of cement does not change (350 kg/m^3) and 30% of cement is replaced with coal bottom ash ground for 45 minutes, the amount of CO_2 emissions is constituted from the cement production emission and coal bottom ash grinding emission. As it is seen in Table 6, for the concrete with the compressive strength class of C35/45 the amount of CO_2 emissions grows, if 20 kg of cement is replaced by 105 kg of ashes, but for concrete with the compressive strength class C40/50 the amount of CO_2 emissions decreases. Amount of CO_2 emissions for concrete with the compressive strength class C35/45 would increase by 1 kg/m^3 compared to the reference mix without coal bottom ash. The increase would be 1% compared to the reference mix without coal bottom ash, but the amount of CO_2 emissions would decrease from 87 kg/m^3 to 83 kg/m^3 or by 4.2% for the concrete with a higher compressive strength class. Taking into account the possible amount of CO_2 emissions, grinding of coal bottom ash would be cost effective for concrete with the compressive strength class C40/50. However, there is only a slight difference with the compressive strength class C35/45 and the concrete possibly should be adjusted according to the workability criteria and concrete plasticizers possibly should be used.

CONCLUSIONS

Conclusions

The grinding period influences particle size distribution of coal bottom ash. Extending the grinding period from 15 to 45 minutes, the amount of smaller particles grows (< 0.25 mm from 63 – 93 %). In addition, the form of particles becomes less angular. The extension of the grinding period and the increasing of the coal bottom ash amount change the particle size distribution and the amount of fine particles grows as well as the density of concrete structure increases. Coal bottom ash consists of 88% carbon indicating the presence of coal pieces which are not completely burned. Si, Al, Ca and oxides were observed in separate particles, which could further pozzolanic reactions and increase the concrete compressive strength. Adding coal bottom ash to the concrete mix changes the amount of water, which is necessary to obtain the definite consistency of fresh concrete. Coal bottom ash from a grinding period of 30 and 45 minutes replacing 10% of the amount of cement decreases the W/C ratio without decreasing the cone slump. If the amount of coal bottom ash is increased, the W/C ratio should be increased in order to preserve cone slump class S4. Coal bottom ash in the concrete mix increases its compressive strength compared to the reference mix. The most efficient combination is 30% of coal bottom ash with the grinding period 45 minutes. The compressive strength increased from 47.0 MPa for the reference mix to 56.7 MPa for the concrete mix with coal bottom ash. Water permeability and water absorbtion of concrete specimens were tested, which are important indicators of the concrete durability. Water permeability of the specimens after 28 days was 10-42 mm. The best result was for mix with coal bottom ash with the grinding period of 30 minutes replacing 10 and 20% of cement with it - 10 and 12 mm compared to the 28 mm of the reference mix. Water absorbtion decreased significantly for mix with coal bottom ash with the grinding period of 45 minutes replacing 10-40% of cement with it, namely, 4.6-5.0% compared to the 6.1% for the reference mix. For mix with coal bottom ash with the grinding period 15 and 30 minutes changes were insignificant (5.7-6.2%). Coal bottom ash could be used as a micro additive in the concrete production. The most effective is replacing of 20-30% of cement with coal bottom ash with a grinding period of 45 minutes.

By increasing the concrete compressive strength class from C30/37 to C40/50 the economic benefit was observed – the concrete price reduction of 3.6%. Costs of prior processing of coal bottom ash were included. The ecological benefit comes from the economizing of cement which would be necessary to ensure the compressive strength class of concrete as well as from the possible deposition costs of coal bottom ash. In order to increase the concrete compressive strength class from C30/37 to C40/50 using 105 kg of coal bottom ash, 40 kg of Portland cement are economised, namely, the amount of CO_2 emissions is decreased by 4 kg or 4.2% for each m^3 of concrete.

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