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The effect of blended lignite bottom ash as a fine aggregate in concrete mixes

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Abstract:*The use of concrete as a main material in construction industry results in Environmental damage and also in the use of more natural sources. The need for a more sustainable solution would be the replacement of concrete with other materials and especially solid wastes. It is known from literature that Coal fly ash is used extensively as a material substitute in concrete and in the present paper seems that also blended lignite ash would offer great economic and technical advantages in order to be used as a material substitute in concrete mixes. In the present experiment sample after it was blended in order to increase its pozzolanic activity with specific surface that was set at 3500* cm^2/gr*. The sample was characterized by chemical analysis and X-ray diffraction (XRD). Furthermore, there were measurements after the mix of lignite bottom ash with Portland Cement I 52.5 Mpa and especially setting times, soundness and compressive strength of mortars with different content in lignite bottom ash and cement. All the experimental measurements led to important conclusions about the suitability of the lignite bottom ash as a fine aggregate in concrete mixes.*

Keywords:*portland cement, coal bottom ash, characterization, leaching tests, utilization, properties of coal bottom ash, pozzolanic material, compressive strength.*

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I. INTRODUCTION

High consumption of natural sources, high amount production of industrial wastes and environmental pollution are some of the factors which are responsible for obtaining new solutions for a sustainable development. A sustainable development can be achieved only if the resource efficiency increases and this target can be achieved from the reduction in use of energy and materials (Aggarwal et al., 2014). Worldwide the use of the concrete as a prime material in the construction sector was extensively high with the use of concrete as main material and the use of river sand as a fine aggregate in the production of concrete (Singh, et al., 2013). The scarcity of the natural sources resulted in the abnormal rise in its price and subsequently increased the cost of production in concrete. On the other hand, enormous volumes of coal at the thermal power plants results in production of coal bottom ash (Singh et al., 2014).

In Greece the 70%-75% of the electrical power is produced in power plants by coal fired with the lignite (coal) bottom ash production amounts to 1×10^6 tons/year, while the fly ash production has exceeded 12×10^6 tons/year (Pliatsikas, 2020). On burning of coal in furnace of coal fired thermal plants, the non-combustible material present in it results in production of coal ash. The finer and lighter particles of coal ash escape with the flue gases and are extracted in the Electrostatic precipitators before reaching the environment (Singh et al., 2012). The coal ashes obtained from Electrostatic precipitators are termed as fly ash and the coal ash collected at a bottom from a furnace is called coal bottom ash (Singh et al., 2014). Fly ash accounts for 60 wt% of the coal combustion residue (80 wt% of the ash produced) (Tsakiridis et al., 2016). On the other hand, bottom ash (15 wt% of the combustion residue) is produced from the heavier particles of the agglomerated remaining matter, which are precipitated and accumulated usually in the boiler first combustion chamber (Tsakiridis et al., 2016). Coal bottom ash is formed from the melting of coal ash particles because the temperature in the kiln is higher than the melting point of coal ash. Therefore, coal bottom ash has large particles with high porosity (Abdulmatin et al., 2018). Because of its high porosity, it exhibits relatively decreased specific weight and good mechanical properties (Pliatsikas, 2020). Coal bottom ash is composed of mainly silica, alumina and iron with small amounts of calcium, magnesium, sulfate mainly in the form of large granules (Singh et al., 2013 ; Pliatsikas, 2020).

Some other authors name the coal bottom ash to Silico-Aluminous Bottom Ash (SABA) because Si, Fe and Al are the three predominant elements. Utilization of coal combustion products is an important issue involving reduction of in technical and economical problems of plants, besides reducing the amount of solid wastes, greenhouse gas emissions and conserving existing natural resources (Aggarwal et al., 2014). Although the fly ash utilization by the cement industry is today a widespread practice, mainly as secondary hydraulic material, substituting cement clinker in the final mixture the corresponding of bottom ash is limited (Pliatsikas, 2020). Regarding the fly ash utilization several investigations have been carried out in the last three decades including the use of as an additive cement, in manufacturing of glass and ceramics, as a low cost adsorbent, as light weight aggregate, as a filler material in concrete and road bases, in the production of zeolites, in the synthesis of geopolymers and as a soil amelioration agent in agriculture. On the other hand, little attention has been given to the possible utilization of the bottom ash as a raw material in the raw meal for the production of ordinary Portland cement clinker (Tsakiridis et al., 2016).

Other authors refer to the fact that there is either no or little utilization of coal bottom ash as a pozzolanic material in concrete construction because the knowledge regarding the use of coal bottom ash as a pozzolanic material is limited (Abdulmatin et al., 2018).This fact confirms the need for scientifically investigation of coal bottom ash with focus the pozzolanic properties in order to be used as a fine aggregate in the production of concrete (Singh et al., 2013). However, it has been proved that the physical and mechanical behavior of composite cements with coal bottom ash is similar with those of fly ash cement-based materials, as both ashes present similar physical, chemical and mineralogical properties with the exception of the bottom ash higher particle distribution (Pliatsikas, 2020). In this conclusion, many authors have been referred who found that the major chemical composition of coal bottom ash is similar to the fly ash when both materials obtained from the same source of coal and power plants with a general drawback for bottom ash using as a pozzolanic material is its large particles.

Based on the facts above the subject of the present investigation is to present the results of the utilization of coal bottom ash derived from lignite combustion power plants, as an alternative raw material for the development of blended cements. If the coal bottom ash could be used in the concrete construction industry it would not only reduce the environmental problems due to their disposal to landfills but also increase the economic value of the construction material.

II. EXPERIMENTAL – MATERIAL AND METHODS

2.1 Raw Materials & Preparation

The coal bottom ash was supplied by the lignite power plant in Megalopolis (central Peloponnese) which produces electricity for the southern Greece and islands. The Megalopolis lignite presents high water and ash content while its calorific value is relatively low as the lignite consumption amounts approximately 2.3 kg/kWh (Pliatsikas, 2020). The lignite bottom ash prior to milling, is dried in a drying oven at 110℃ for 24 hours (h). The material is subjected to grinding a laboratory ball mill with capacity of 1500 grams for 30 minutes in order to be obtained a fineness. Then the material is removed from the mill in order the specific surface area to be controlled. The target of the specific surface of the grinded and crushed material was set at 3500 cm^2/gr. In the case the lowest value of the specific surface in the grinding process was lower the process was repeated in order to be achieved the final and targeted value of the specific area.

2.2 Particle Size distribution

The particle size distribution of the sample is measured with the analyzer Mastersizer 2000 with a “Low Angle Laser Light Scattering”. During the laser diffraction measurement, particles are passed through a focused laser beam. These particles scatter light at an angle that is inversely proportional to their size. The angular intensity of the scattered light is measured by a series of photosensitive detectors. The map of scattering intensity versus angle is the primary source of information used to calculate the particle size (Malvern, 2015).

2.3 Purification of Derivatives

The products obtained with the reactions were purified on a chromatographic column using as adsorbent silica gel 60 (Φ = 0.025-0.020 mm), brand VETEC. The length and diameter of the columns varied according to the amount of sample to be purified and of silica used. As eluent, hexane and ethyl acetate of the Synth analytical standard (P.A.), pure or in binary mixtures in the ratio 8:2 v/v respectively and /or varying as required.The column reactions and eluates were analyzed by thin layer chromatography (TLC). For this purpose, glass plates coated with a layer of approximately 0.5 mm thickness of silica gel 60 (Φ = 0.004-0.005 mm) of the VETEC brand doped with 0.01% flurescein. After elution of the substances in (TLC) with hexane: ethyl acetate (8: 2 v / v) binary solvent mixture, the substances were visualized by use of UV light.

2.4 Chemical analysis& Mineralogical examination

X-ray Fluorescence (Spectro-Xepos) has been used for the chemical analyses determination of all raw materials (Pliatsikas, 2020). In general spectroscopic techniques exploit the properties of X-Rays such as scattering, absorption and fluorescence. In addition to the X-Ray fluorescence method which has its primary objective the elemental synthesis there is X-ray diffraction which provides important information on the phase composition and the three dimensional molecular structure of the sample. Mineralogical examination has been carried out using a Brucker D8- Fokus diffractometer with nickel filtered CuKa radiation (λ=1.5406 A°), at 40 KV and 40 mA. The measurement provides the intensity distribution as a function of angle θ. If Bragg's law is fulfilled, maximum intensity is observed. This fact can identify the unique crystalline phase in any sample.

2.5 Blended mixtures of cement and coal bottom ash

Various mixtures of Portland Cement CEM I 52.5 was used in final mixing step with coal bottom ash. There was also a chemical analysis for the cement and the physical properties of the prepared cement mixtures such as water demand for standard consistency, setting times (Vicat Apparatus) and soundness (Le Chatelier Method) were determined according with the European Standard EN 196-3. Compressive strengths determination has been carried out after 2, 7, 28, 90 days of curing on 40mm×40mm×160mm mortar bars prepared in accordance with European Standard EN 196-1 (Pliatsikas, 2020).

III. RESULTS AND DISCUSSIONS

According to the result of particle size distribution (Figure 1) the size of coal bottom ash ranges from 10-1300 μm, with 67% w/w has size over 100 μm. The coal bottom ash is a coarse grained material that has a larger size distribution compared to other aggregates like sand or coal fly ash. Its size could be explained due to the fact that after the effect of the high temperature of the lignite in the furnace the sample is cooled and the various agglomerates remain in such a grained form.

Regarding the lignite bottom ash chemical analysis (Table 1) its high silicon (SiO_2: 49.22 wt%) and aluminum (Al_2O_3: 18.82 wt%) but also the content of Iron oxide (Fe_2O_3: 8.25 wt%) classifies the bottom ash in "Class F". According to the ASTM C618 when the sum of silicon, aluminum and iron oxides is greater than 70% then the bottom ash has same characteristics as a class F fly ash, where enlist ashes from harder, older anthracite and bituminous coal (Pliatsikas, 2020). Correspondingly in view of chemical aspect the presence of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) in coal bottom ash are the prime compounds which attribute to its additional pozzolanic nature similar that in coal fly ash. The desired pozzolanic activity can be obtained after grinding the coal bottom ash particles until 70-80% by weight is passed through 45 μm sieve (Singh et al., 2020). However, the relative high calcium content (CaO: 13.85 wt%) is indicative for the nature of the bottom ash under investigation which originates from the combustion of younger lignite. The CaO composition in other literature sources was found up to 18.7% by weight which was notably high.

Other studies found that coal bottom ash could be classified as an intermediate calcium oxide content when the composition of CaO varies between 10%-20% (Abdulmatin et al., 2018). As a result lignite bottom ash except pozzolanic properties due to the amorphous glassy silica and aluminum content is expected to present also hydraulic self-cementing properties (Pliatsikas, 2020). Coal bottom ash is lighter and more brittle as compared to other aggregates like sand. The specific gravity of the coal bottom ash was measured 3.16 gr/cm^3 (Table 1) in other studies this number varies between 1.39 and 2.33 depending upon its chemical composition. The low specific gravity of bottom ash is explained by its low iron oxide contents. It is believed that for iron content greater than 10% the specific gravity value is directly proportional to iron content but for lime content greater than 15% the specific gravity value is more irrespective of iron content (Singh et al., 2012). Coal Bottom Ash with a low specific gravity has a porous texture that readily degrades under loading or compaction. The loss on ignition (LOI) values for coal bottom ash indicates the presence of unburnt carbon. According to the Table 1, LOI was measured 2.27. Increased figures of LOI also confirm the porous nature of coal bottom ash particles which captivates more water. The inclusion of coal bottom ash with higher values of LOI leads to discoloration, weak air entrainment, segregation and low compressive strength (Singh et al., 2020).

Figure1. Particle size distribution (Pliatsikas, 2020)

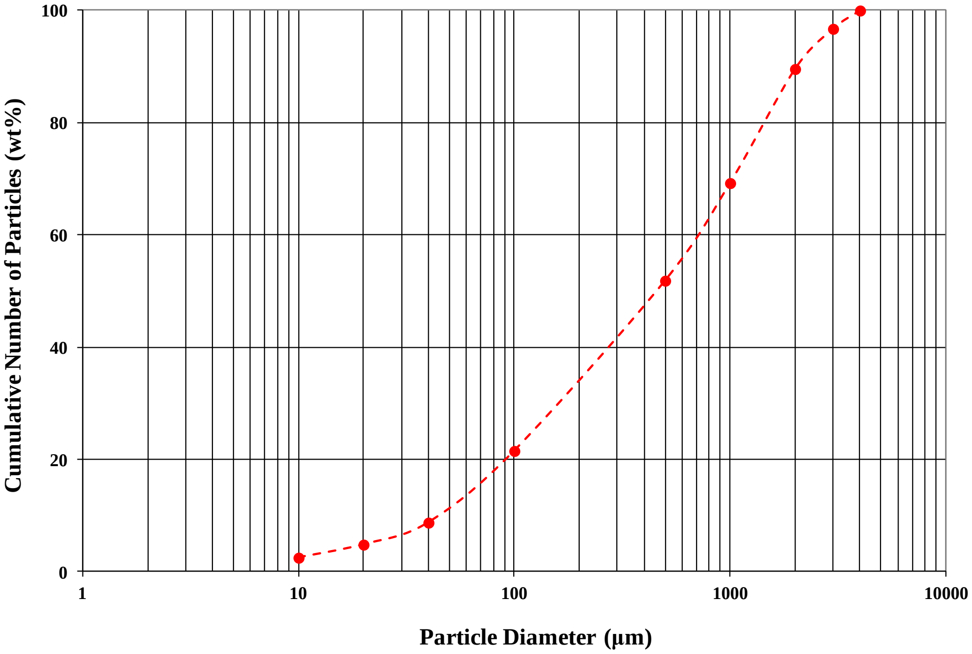

Table 1.Chemical Composition of cement and lignite bottom ash (Pliatsikas, 2020)

Oxides	CEM I-52.5	Lignite Bottom Ash
SiO_2	19.96	49.22
Al_2O_3	5.45	18.82
Fe_2O_3	3.31	8.25
CaO	62.83	13.85
MgO	1.98	3.22
K_2O	1.03	1.54
Na_2O	0.25	0.53
SO_3	3.35	1.18
TiO_2	0.15	0.81
free CaO	0.85	-
LOI	1.15	2.27
Physical Characteristics		
Specific Surface (cm^2/g)	3,550	3,600
Specific Gravity (g/cm^3)	3.16	2.30

According to the British codes ASTM C618-05 2010 coal bottom ash with LOI less than 7% can be inculcated in cement mortars and concretes. Also as per recommendations the content of silicon trioxide (SO_3) must not exceed by 5% out of total composition to avoid loss in strength and bulging phenomenon (Singh et al., 2020).

The main mineralogical phases of coal bottom ash confirms its mixed siliceous-calcareous nature as it is mainly consisted of quartz (SiO_2), gehlenite ($Ca_2Al_2SiO_7$) and anorthite ($(Ca,Na)(Si,Al)_4O_8$) with calcite ($CaCO_3$), lime (CaO) and anhydrite (CaSO4) (Figure 2) (Pliatsikas, 2020). The small diffused band detected in the range of 20°-40° denoted the presence of an amorphous aluminosilicate glassy matrix, indicating pozzolanic characteristics. Similar findings are described in literature which coal bottom ash is described as amorphous besides the presence of crystalline phases like mullite, feldspar, magnetite and quartz (Singh et al., 2020).

Figure 2. X-Ray Diffraction analysis of the Lignite bottom Ash (Pliatsikas, 2020)

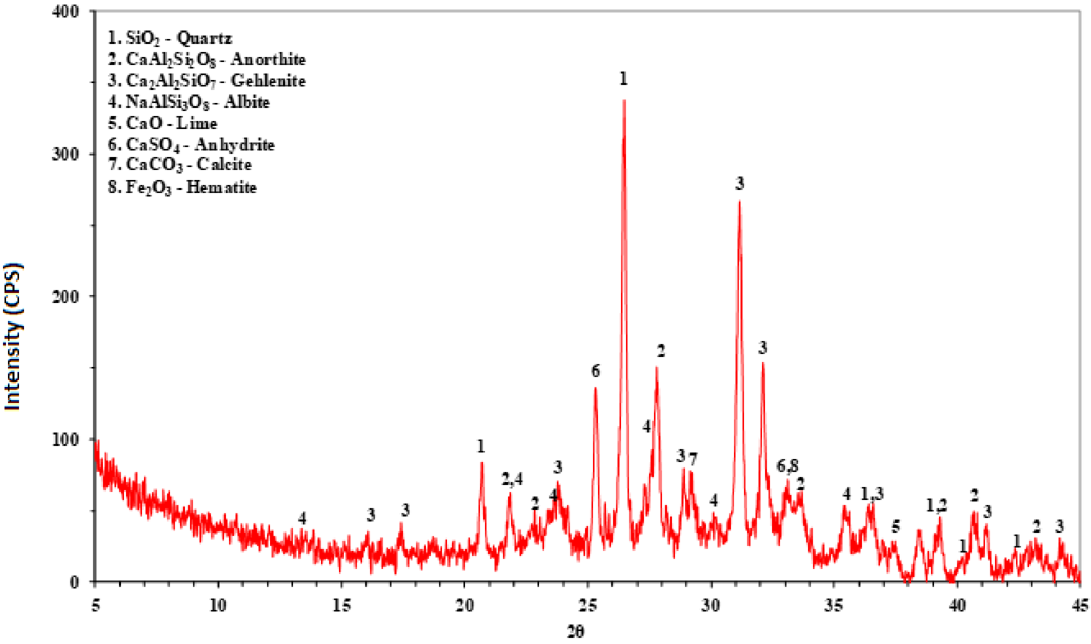

Table 2.Specific Surface Area & Gravity of cement mixtures (Pliatsikas, 2020)

Code	CEM I 42.5 (wt%)	Bottom Ash (wt%)	Specific Surface Area (cm^2/g)	Specific Gravity (g/cm^3)
C_{Ref}	100	0	3550	3.14
C_5	95	5	3550	3.10
C_{10}	90	10	3550	3.05
C_{15}	85	15	3560	3.00
C_{20}	80	20	3560	2.95

Table 3.Physical properties of cement mixtures (Pliatsikas, 2020)

Sample	Bottom Ash (wt%)	Water demand for Standard Consistency (wt%)	Setting Times (min)		Soundness Le Chatelier (mm)
			Start	End	
C_{Ref}	-	27.7	150	200	0.8
C_5	5	26.9	155	205	0.8
C_{10}	10	26.6	155	210	1.0
C_{15}	15	26.4	160	220	1.2
C_{20}	20	26.3	170	220	1.5

The influence of coal bottom ash used as partial replacement of Portland Cement on physical properties like specific surface area and specific gravity and setting times and soundness are illustrated in Table 2 and 3. According to Table 2 increasing the presence of coal bottom ash and reducing simultaneously the quantity of cement, it shows a small increase in the specific surface area that could be explained due to the fact that coal bottom ash has a greater specific surface area. The same impact occurs during the increase of coal bottom ash in the specific gravity as the Portland cement is substituted with coal bottom ash, a material with smaller specific gravity.

The initial setting time is the moment characterized by an increase in the temperature of the concrete after the dormant period and also the moment at which the mix begins to show a certain level of stiffness (Andrade et al., 2009). The initial stiffness is of great importance for the concrete to bear the tensile force caused by the plastic shrinkage. Delays in the time at which setting starts may reduce durability of concretes subject to plastic shrinkage with physical restrictions. If the setting starts earlier, together with a longer bleeding time this can be beneficial in the prevention of deformation and cracking through plastic shrinkage.

Table 3 identifies that the addition of coal bottom ash to cement materials increases the initial and final setting time, in relation to the reference mix. This fact could be explained due to the increase of in the quantity of water present in the mixes with coal bottom ash resulting in the maintenance of greater workability. The increased mixing water lowers the pH value of the medium and increases the distance between cement hydration products and thus results in delay or decrease in hydration activities of the cement particles (Singh et al., 2012). The delay in hydration of cement in coal bottom ash concrete results in increase in its initial and final setting times. This increase in initial and final setting times could also be explained from the increase of porous coal bottom ash and also the reduction of Tricalciumsilicate in the paste on replacement of cement by bottom ash (Pliatsikas, 2020).

As concerns the soundness, Table 3 identifies that in the specimen with 20% coal bottom ash content soundness is 1.5 mm and the limit according the EN 196-3 have remained numerically the same at 10 mm, meaning that coal bottom ash does not affect the volume expansion and could be used as a fine aggregate for concrete (Pliatsikas, 2020). The compressive strength of mortars at the curing ages between 2 and 90 days are presented in Table 4. The mortar with 100% cement content had the highest compressive strength in all days of curing. As it seems (Table 4) all the mixtures have the same tendency as with the increase in curing age all the mixtures with the coal bottom ash have increased their compressive strength. All the bottom ash mixtures compared with the 100% cement content mortar have lower compressive strength. As the coal bottom ash increases the compressive strength compared with the 100% cement content mortar decreases in all curing ages. This decrease tends to be reduced after 90 days of curing age. The mortar with 20% coal bottom ash content has the lowest compressive strength compared to the mortar with cement content 100% in all curing ages. The C_{20} shows a deviation of 18.6% during the curing age of 2 days compared with C_{ref} and for curing ages 7, 28 and 90 days showed a deviation of 15.6%, 14.3% and 7% respectively.

Table 4.Compressive strength of mortar (Pliatsikas, 2020)

Curing Age (days)	**Compressive Strength (MPa)**				
	C_{Ref}	**$C_{5\%}$**	**C_{10}**	**C_{15}**	**C_{20}**
2	26.3	24.9	23.5	22.7	21.4
7	39.8	38.1	36.5	35.4	33.6
28	53.8	51.3	49.3	46.8	46.1
90	56.7	55.2	54.8	54.5	52.7

The strength development of concrete is influenced by porosity of hydrated paste which is controlled by water / cement ratio and the presence of bond cracks at the interface of aggregate and hydrated paste. The bottom ash particles are more porous and weak and that fact affects the compressive strength of mortars. The factors responsible for the decrease in compressive strength of bottom ash concrete mixtures could be summarized as the replacement of the stronger material with the weaker material, the increase porosity of concrete and the decrease in free water cement ratio of the bottom ash concrete mixtures due to the absorption of part of water by the porous particles of the coal bottom ash internally during the mixing process. Other studies also showed that pozzolanic activity of coal bottom ash is slow until 14 days of curing age and after this period the coal bottom ash particles start react with calcium hydroxide and forming C-S-H gel and needles (Singh et al., 2013). Table 4 identifies that after 90 days of curing even the mixture with the highest content with coal bottom ash (C_{20}) had a small deviation proving that could be used as an excellent fine aggregate for the replacement of cement. Finally, the fact that C_{20} mortar have 52.7 MPa compressive strength greater than 52.5 which Portland cement should have according to the EN 197-1 in 28 days of hydrations show that after 90 days of curing the mixtures have the same characteristics as a cement mixture after 28 days of curing.

IV. CONCLUSION

The experimental research was carried out to evaluate the suitability of coal bottom ash as a pozzolanic admixture for the development of blended cement. From the experimental facts can be concluded that:

- ✓ Coal bottom ash chemical resembles to the coal fly ash and it could be classified as a class F.
- ✓ The presence of amorphous aluminosilicate glassy matrix indicates pozzolanic characteristics
- ✓ The cement mixtures with coal bottom ash exhibited a slight increase on water demand values for standard consistency and relatively longer setting times indicating a short decrement on the reactivity evolution in the first hours of hydration.
- ✓ The soundness found very low from the limit of 10 mm indicating the suitability of the coal bottom ash as pozzolanic admixture in blended cement.
- ✓ At early stages all mixtures presented lower compressive strengths compared to the reference sample however after 90 days all the cement mixtures developed more than 90% of the pure reference cement’s strength whereas all cement mixtures satisfied the requirements for strength class 52.5 as per EN 197-1.

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