The Strength of Lightly Cemented Power Plant Ash

Felix N. Okonta(✉), Thabo Falayi, and Roshuma Makhado

Department of Civil Engineering Science, University of Johannesburg,
Johannesburg, South Africa
fnokonta@uj.ac.za

Abstract. Coal ash from most of Eskom power plants consists of 70–85% fly ash and 15–30% bottom ash. A total of 25 million tons of ash is produced from approximately 109 million tons of coal per annum. Small percentage of the ash were used in cement production and other construction applications and almost 80% of the ash were disposed into ash dams. The need for high volume utilization is important because of the cost of disposal and associated environmental impact. The mechanical properties of Eskom ash that were stabilized with cement was investigated. Specimens of ash were stabilized with 2% to 10% of rapid hardening Portland cement (52.5R), and compacted at two different moulding water content; (a) the optimum moisture contents of stabilized specimens (15%–19%) and (b) moisture content wet of the OMC (30%). The unconfined compressive strength (UCS), soaked UCS, secant modulus and microstructure of the stabilized specimens were evaluated. The result indicated that specimens that were compacted at 30% moisture content mobilized greater UCS than those that were compacted at OMC. For specimens that there stabilized with high cement content of 8%–10% and compacted at OMC, soaking for 24 h only indicated a marginal reduction in UCS. The increase in secant modulus with cement content was nonlinear and indicated a decreasing rate with increase in cement content. The XRD and SEM results revealed that strength development was associated with the predominance of calcium silicate hydrate (CSH) and needle shaped ettringite in cement stabilized ash. Based on limited test data, only specimens that were stabilized at 30% moisture content and with greater than 4% cement met the SANS (2007) criteria for masonry and TRH (2010) criteria for pavement backfill.

1 Introduction

Coal is the major source of electricity in South Africa and approximately 92.8% of the electricity demand is generated by coal fired power stations (Bada et al. 2015). South Africa have a total of 18 coal fired power stations and 13 of them are in Mpumalanga province due to coal fields concentrated in that province. Currently a total of 16 power stations are operational while 2 stations are under construction. The 13 coal fired power stations in the Mpumalanga Province (coordinates 25:26:15 S/30:58:19 E), are Arnot, Camden, Duvha, Grootvlei, Hendrina, Kendal, Komati, Kriel, Majuba, Matla and Tutuka. The others are Lethabo power station in the Free State Province (coordinates 26:44:31 S/27:58/39 E), Matimaba power stations in the Limpopo province

L. Struble and G. Tebaldi (eds.), *Materials for Sustainable Infrastructure*,
Sustainable Civil Infrastructures, DOI 10.1007/978-3-319-61633-9_15

(coordinates 23:40:06 S/27:36:38 E), Gauteng province (coordinates 25:45:28 S/28:08:49 E) have three power stations while the city of Tshwane have two in Pretoria West. Kusile power stations and Medupi power stations are under construction.

Up to 109 million tons of coal feedstock are produce per annum and this generates approximately 25 million tons of ash, and 70–85% of the total ash produced is fly ash while 15–30% is bottom ash (Nyale et al. 2013; Singh and Rafat 2015). The management of ash is a major concern in the country because annually millions of tons are disposed in ash dams which covers large area of land and there are potential groud water pollution problems (Kruger and Krueger 2005).

Sasol Synfuels by comparison consumes approximately 45 million tons of coal annually and yield over 4 million tons of fine ash (Nyale et al. 2013).

Bottom ash unlike fly ash, is coarse, porous, glassy, granular, greyish material with grain sizes ranging from fine sand to fine gravel, (Sivakumar and Kameshwari 2015). However, bottom ash is lighter and more brittle than natural fine aggregate. It has a specific gravity of 1.39–2.33 and contain more particles with diameter smaller than 75 um as compared to river sand or natural fine aggregates. In addition it has water absorption by mass of 31.58% while river sand has water absorption by mass of 2.46% (Singh and Siddique 2013). The major compound found in most power plant ash are silica, alumina and iron with small portion of calcium, magnesium sulfate. Both the physical and chemical properties makes coal ash a good candidate for cement additives and fine aggregate in concrete mixes for use in the construction industry (Singh and Siddique 2013).

This research was focused on the utilization of coal ash for civil engineering applications with the aim of reducing the use of natural river sand from main river channels and adjacent sandbanks. It is noted that currently the rate of sand utilization has exceeded the natural regenerative capacity of the sand, resulting in net loss of the sand. Thus there is a need to explore the use of large ash dump materials as potential replacement for natural sand as fine aggregate in concrete (Chevallier 2014).

Low cost construction rely on the use of cheap materials that are available locally. South Africa construction industry is growing at a rapid rate with both the private and public sectors investing 76% and 24% respectively in the industry, however there is scarcity of building and construction material especially river sand. In addition, the construction industry relies heavily on the transportation sectors for the distribution of construction materials locally (CIDB 2007). The use of waste for low cost construction is attractive since the growing demand of natural construction cannot be fully met (Sivakumar and Kameshwari 2015). Singh and Siddique (2013), Sivakumar and Kameshwari (2015) have demonstrated that large volume coal stabilized materials can be used for civil engineering construction.

In order to investigate the potential use of large volume of power plant derived coal ash for construction application, series of laboratory tests were conducted to determine the physical properties of coal ash as well as the mechanical properties and microstructure of cement stabilized coal ash after compaction and curing for 28 days.

2 Materials

The Eskom ash investigated was obtained from Eskom Camden Power Station. The station is located in the Mpumalanga province, with coordinates 26:37:13 S 30:5:38 E.

The cement used for stabilization of the coal ash was Afrisam 52.5R rapid hardening cement.

3 Experimental Methods

Specimens were compacted into moulds of 130 mm height and 58 mm diameter. The specimen height to diameter ratio is less than 2.5 and based on ASTM D2938 criteria, a significant variation in compression strength will not occur.

The major tests that were performed on the ash material was detailed in Table 1.

Table 1. Major geotechnical tests

Major tests	Specimens
Grain size analysis of coal ash (ASTM D422)	Eskom coal ash
Compaction tests using the modified proctor effort (ASTM D698)	(a) Eskom coal ash (b) Cement stabilized Eskom ash (2, 4, 6, 8, 10% cement)
Specific gravity (SG) The test was determined using ASTM D854	Eskom coal ash
Unconfined compressive strength after curing period for 28 days	(a) Eskom coal ash (b) Cement stabilized Eskom ash (2,4,6,8,10% cement)
X-ray power diffraction (XRD)	Cement stabilized Eskom ash (2, 4, 6, 8, 10% cement)
X-ray Fluorescence (XRF)	
Scanning Electron micrograph (SEM)	

4 Results

4.1 Physical Properties

The particle size distribution of the ash was detailed in Fig. 1 and Table 2. The ash consists of predominantly fine particles with more than 50% passing the 0.075 mm size. The large percentage of particles less than 0.075 mm implies high specific surface and obviates the need for mechanical activation by pulverization. The ash material is a good candidate for light weight construction material as the specific gravity is 2.35 which is lower than quartz and most clay particles. The pH is greater than 5.5 and thus the ash is not an acid generating material.

The compaction properties of Camden ash material was presented in Fig. 2. The shape of the curve is bell like and reflected the high content of particles less than 0.075 mm. The maximum dry density was 1244 kg/m^3 and the optimum moisture content was 22%, thus the ash materials can be compacted to lightweight materials that

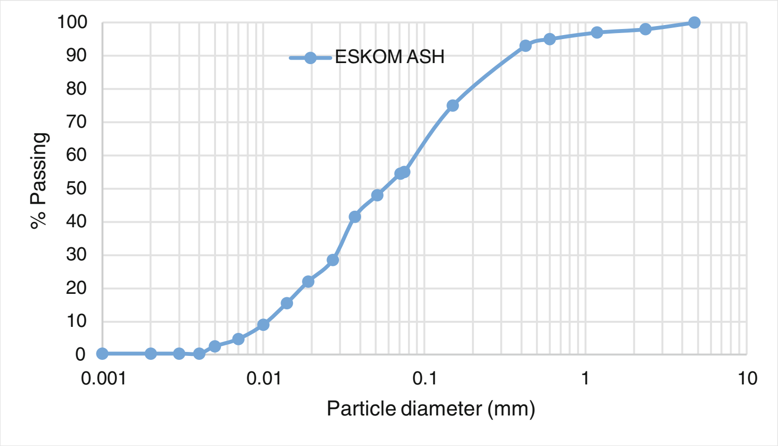

Fig. 1. Particle size curve of eskom ash

Table 2. Physical properties of camden ash

D_{10}	0.012 mm	**Cu**	7.5	**%Gravel**	0	**%Clay**	0.3
D_{30}	0.29 mm	**Cc**	78	**%Sand**	45	**Specific gravity**	2.35
D_{50}	0.055 mm	**>4.75 mm**	100	**%Fine**	55	**Relative Density**	2.28–2.47
D_{60}	0.09 mm	**>0.075 mm**	55	**%Silt**	54.7	**pH**	10.54–11.26

require some moisture for remoulding. Specimens of ash that were stabilized with cement did not exhibit a defined trend of increase or decrease of density with binder content.

The pozzolanic potential index of ash materials that were sampled from different location in the Ash dam in Eskom Camden station was presented in Table 3. There is no major difference in the glass content and quartz with respect to samples taken from the surface A and B, however samples taken at depth of 4 below the surface indicated significant difference in quartz and haematite ratio. All three samples have glass content and mullites ratio that supports pozzolanic reaction upon hydration and thus the ash materials requires chemical activation to increase the PPI.

The loss on ignition LOI was within the range of 4–9% SANS 50450 (2011) thus the material is category C ash and also by ASTM C618 classification. The major compound were presented in Table 4. The sum of oxides of aluminium, iron and silica was greater than 70% and thus the material was essentially pozzolanic (Cadersa et al. 2014; Menéndez et al. 2014). However because of the low calcium content, there is need for addition of more calcium from either lime or Portland cement to increase the amount of hydration products, especially the calcium hydrates.

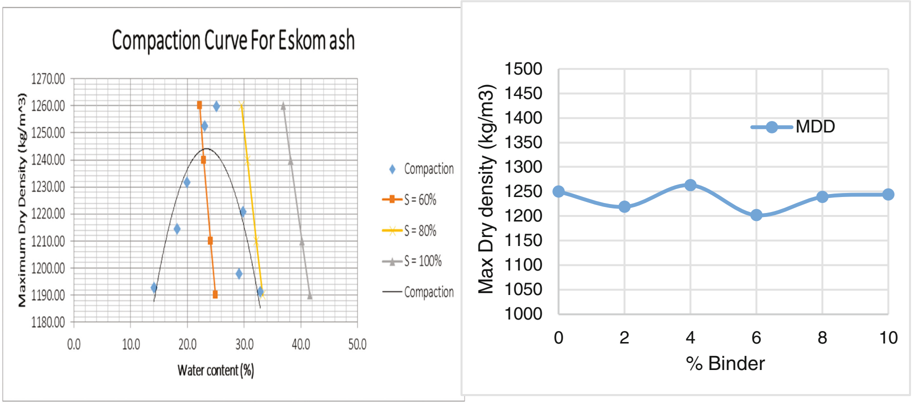

Fig. 2. (a) Compaction curves of eskom ash and (b) maximum dry density of cement stabilized ash.

Table 3. PPI of various camden ash samples %m/m

Sample	PPI	Glass content	LOI	Quartz	Mullite	Magnetite/maghemite	Haematite
A	0.46	47.52	7.22	20.96	20.96	2.85	0.44
B	0.4	45.82	7.82	21.02	21.43	3.45	0.46
C	0.54	49.97	10.76	5.17	20.48	8.61	5.02

Table 4. Chemical properties of eskom ash.

Content (% m/m)	Eskom ash	Content (% m/m)	Eskom Ash	Content (% m/m)	Eskom ash
Na_2O	0.060333	CaO	7.311	Ga_2O_3	0.01161
MgO	0.538667	TiO_2	2.403333	Rb_2O	0.009333
Al_2O_3	24	Cr_2O_3	0.053233	SrO	0.202333
SiO_2	43.43333	MnO	0.0591	Y_2O_3	0.181
P_2O_5	0.631	Fe_2O_3	9.833333	ZrO_2	0.09
SO_3	1.183	NiO	0.0178	BaO	0.138667
Cl	0.0225	CuO	0.0135	PbO	0.096667
K_2O	1.106667	ZnO	0.015767	ThO_2	0.009667

4.2 Mechanical Properties

Specimens of freshly mixed ash and different percentages of Portland cement with high liquid limit (52%–59%) and shrinkage limit of (2.6–2.29) were divided into two sets (1) Specimens were compacted at OMC and cured for 28 days at 20 °C (2) Specimens were compacted at 30% moulding water content and cured for 7 days at 35–40 °C.

Typical Ash containing 2% cement and typical 8% cement stabilized ash were presented in Fig. 3. Low cement composites were brittle, rough textured and cracks

Fig. 3. (a) Typical ash containing 2% cement (b) Typical 8% cement stabilized ash

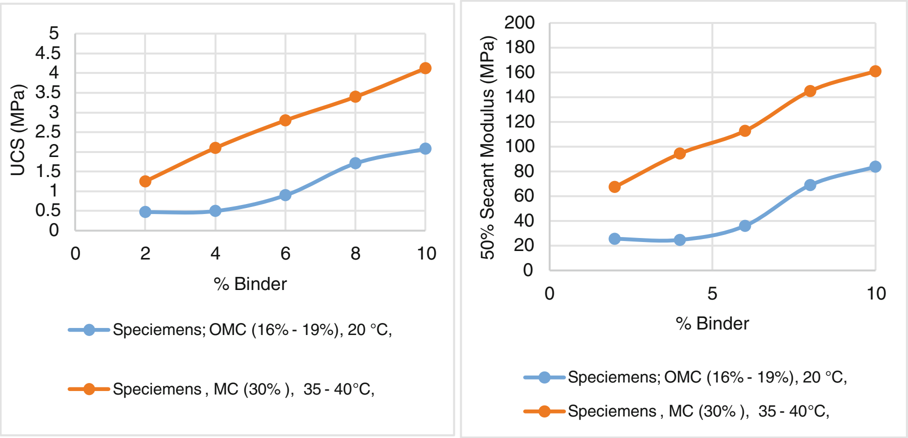

Fig. 4. (a) UCS of specimens cured for 28 days at 20 °C and 7 days at 35–40 °C (b) 50% Secant modulus of cement stabilized ash

easily. The UCS of specimens that were cured at the respective OMCs of 15%–19% for 28 days were presented in Fig. 4a. Also specimens that were compacted with moisture content of 30% and cured in a chamber with temperature of 35 °C–40 °C and humidity of 70% for 7 days was also presented in Fig. 4a. The specimens that were compacted at 30% and cured at 35 °C–40 °C mobilized greater UCS than specimens that were cured at their respective OMC. For specimens that were cured at OMC, there was no significant change in UCS for binder content between 2% and 6%. Thus while specimens containing 4% binder that were cured at OMC mobilized UCS less than 0.5 MPa, similar specimens that cured in chamber at 35 °C–40 °C mobilized UCS that were greater than 2 MPa. In addition only the specimens cured in the chamber mobilized UCS greater than the 3.5 MPa (SANS 2007) recommended for load bearing walls (Table 5).

Table 5. Atterberg limits of stabilized ash

% of cement	Liquid limit	Plastic limit (%)	Plastic index (%)	Linear shrinkage (%)
2	53.2	Nonplastic (N.P.)	Nonplastic (N.P.)	2.6
4	56.9	Nonplastic (N.P.)	Nonplastic (N.P.)	1.28
6	57.4	Nonplastic (N.P.)	Nonplastic (N.P.)	1.29
8	59.2	Nonplastic (N.P.)	Nonplastic (N.P.)	1.3
10	58.3	Nonplastic (N.P.)	Nonplastic (N.P.)	1.28

The 50% secant modules of the stabilized ash were also presented in Fig. 4(b) and showed that irrespective of curing condition, the secant increase increased with binder content, due to the precipitation of dense calcium silicate gels. The ash cement reaction is beneficial for the development of material stiffness because bottom ash typically decreases the thermal expansion of concrete.

4.3 Microstructure

The XRD of ash showing Q = Quartz, M = Mullite, and H = Haematite was presented in Fig. 5(a) and (b) showed the XRD result of 8% cement stabilized ash indicating the presence of major hydration products calcium silicate hydrate CSH and Ettringite. In addition, in Fig. 6(a) the SEM of Eskom ash indicated the absence of needle shaped ettringite and Fig. 6(b) showed the SEM of 8% cement stabilized ash with strong evidence of spokes of hydration products ettringite. Similar results were obtained by Singh and Rafat (2015) in 28 days cured concrete containing 40% replaced cement.

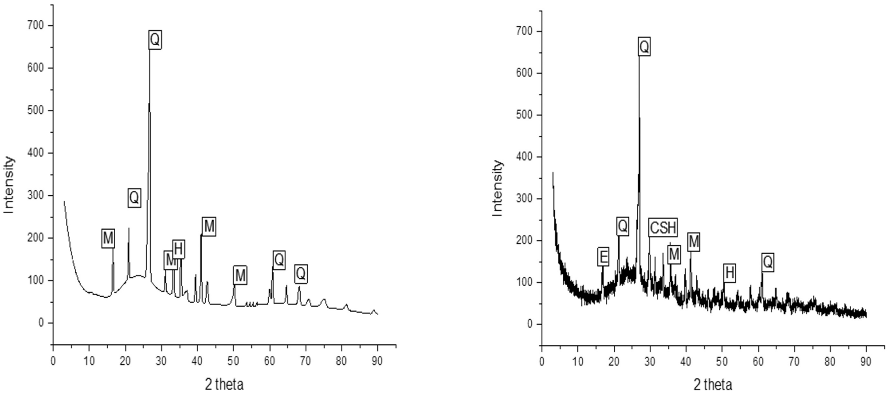

Fig. 5. (a) XRD graph of ash showing Q = Quartz, M = Mulite, and H = Haematite and (b) 8% cement stabilized ash indicating the presence of hydration products calcium silicate hydrate CSH and Ettringite

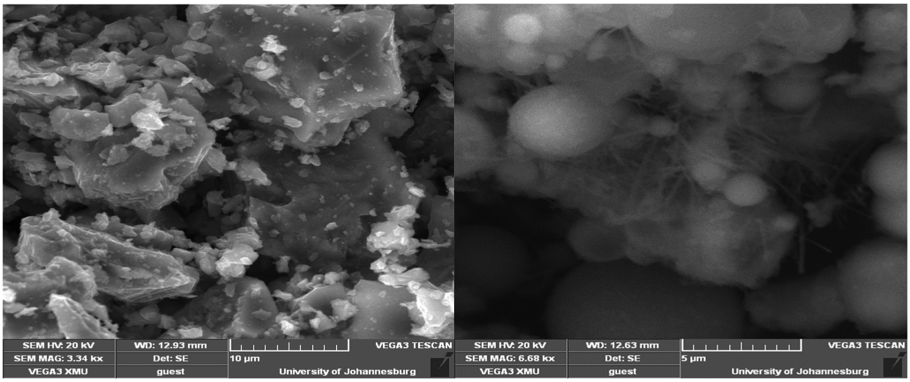

Fig. 6. SEM of Eskom ash and (b) SEM of Eskom+Cement: the spokes shows evidence of hydration

5 Conclusion

Camden power station ash materials was made up of more than 50% particles less than 0.075 mm and with specific gravity of 2.35, thus it is a good candidate for light weight construction. The PPI was below 0.5 but the sum of the oxides of iron, aluminium and silica were greater than 70% and thus the ash is a good candidate for pozzolanic induced strength development in the presence of external sources of calcium hydroxide.

The UCS of cement stabilized specimens was dependent on moulding water content and curing condition. Materials produced at curing conditions of temperature of 35–40 °C and moulding water content of 30% for 7 days developed greater compressive strength than those cured at optimum moisture content for 28 days. The strength development in cement stabilized ash was associated with the predominance of CSH and needle like etrringite.

References

Afrisam, n.d. Cement technical reference guide. Cement (2010)

Bada, S., Falcon, R., Falcon, L.: Characterization and co-firing potential of high volume ash coal with Bambusa Balcooa, p. 9. School of Chemical and Metallurgical Engineering Faculty and the Built Environment, University of the Witwatersrand (2015)

Chevallier, R.: Illegal sand mining in South Africa. Policy Brief. **11**(6), 6 (2014)

Cadersa, A.S., Rana, J., Ramjeawon, T.: Assessing the durability of coal bottom ash as aggregate replacement in low strength concrete. J. Emerg. Trends Eng. Appl. Sci. (JETEAS) **5**(5), 344–349 (2014)

Kruger, R.A., Krueger, J.E.: Historical development of coal ash utilisation in South Africa. In: World of Coal Ash, p. 8 (2005)

Menéndez, E., Álvaro, A.M., Hernández, M.T., Parra, J.L.: New methodology for assessing the environmental burden of cement mortars with partial replacement of coal bottom ash and fly ash. J. Environ. Manage. **133**, 275–283 (2014)

Naganathan, S., Linda, T.: Effect of fly ash fineness on the performance of cement mortar. Jordan J. Civil Eng. **7**(3), 326–331 (2013)

Nyale, S.M., et al.: Synthesis and characterization of coal fly ash-based foamed. In: 2013 International Symposium on Environmental Science and Technology (2013 ISEST), pp. 722–730 (2013)

Singh, M., Rafat, S.: Properties of concrete containing high volumes of coal bottom ash. J. Cleaner Prod. **91**, 269–278, 67 (2015)

Singh, M., Siddique, R.: Effect of coal bottom ash as partial replacement of sand on properties of concrete. Resour. Conserv. Recycl. **72**, 20–32 (2013)

Sivakumar, S., Kameshwari, B.: Influence of fly ash, bottom ash, and light expanded clay aggregate on concrete. Adv. Mater. Sci. Eng. **2015**, 9 (2015)

South African National Standard: Burnt Clay Masonry Units. SABS, Pretoria (2007)

The Construction Industry Development Board. The Building and Construction Materials Sector Challenges and Opportunities, s.l. Building Research Strategy Consulting Unit cc. (2007)