Laboratory investigation on using coal ash as selected formation layer in a railway track substructure

R. Mokoena & G.M. Mvelase
Council of Scientific and Industrial Research (CSIR), Pretoria, South Africa

ABSTRACT: The study presented in this paper aims to promote the use of coal ash in railway infrastructure as a more economical and sustainable material. The study serves as a preliminary investigation on using coal ash as one of the structural layers within the railway track substructure during formation rehabilitations in close proximities to coal power stations. A laboratory investigation was carried out to characterise and assess the suitability of ash in a typical railway track formation. The ash was sourced from two power stations in Mpumalanga, South Africa. The samples were evaluated against Transnet specifications for railway earthworks, the coarse ash met all specifications while the grading of the fine ash limited its suitability for use as one of the formation layers. Additional tests were performed according to national specifications for road works as no such testing is required for railway material. The tests were done to quantify any potential deleterious nature of the ash, which include pH and electrical conductivity. The soluble salt content and pH was found to be within acceptable limits. Two blends of bottom ash containing 25% and 50% fly ash from Kriel power station were tested in an attempt to reduce the OMC. Results showed a reduction in OMC and increase in MDD and CBR as the fly ash content increased.

Keywords: *coal ash; formation layer; railway earthworks; alternative materials; laboratory investigation; granular materials*

1 INTRODUCTION

Majority of the Southern Africa rail network consists of ballasted track that is typically constructed using conventional granular materials. Transnet Freight Rail (TFR) is responsible for the management, maintenance and operations of most of the national freight rail network (George *et al.*, 2018) which can be separated into two categories namely, the core network and the branch lines (Transnet SOC, 2016). Transnet has further sub-divided its core network into four systems namely (i) the iron ore and manganese system, (ii) the coal system, (iii) the north-eastern system and (iv) the intermodal and general freight system. The dedicated coal rail line connects the coal mines in Mpumalanga, where the vast majority of the country's power stations are situated, to the Richards Bay Coal Terminal, which is the main harbour for coal exports.

Coal is undoubtedly an important national energy resource accounting for almost 80% of electricity generation, according to the Department of Energy, and approximately 12% of the country's total merchandise exports (Minerals Council South Africa, 2018). An unavoidable consequence of burning coal is the ash produced which is often stockpiled or used for effluent sinks at the power stations. According to Reynolds-Clausen & Singh (2016), the country produces over 36 million tons of ash per annum and approximately 10% of that ash is utilized.

The utilization of coal ash in railway infrastructure could be an attractive option to coal power stations and rail maintenance companies particularly in areas of close proximity to dump sites where the produced coal ash is easily accessible and more economical than crushed aggregate material.

A typical cross-section of a ballasted railway track is shown in Figure 1. The primary function of the track substructure is to provide a stable foundation by reducing traffic-induced stresses from the upper layers and to prevent penetration and mixing of the subgrade and ballast layers (Grabe *et al*., 2012; Li *et al*., 2016).

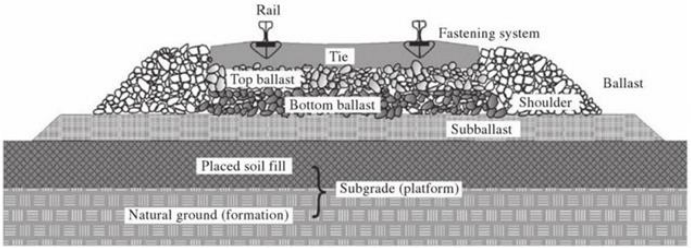


Figure 1. Typical railway track structure (Selig & Waters, 1994)

According to Grabe *et al*. (2012), older lines in the country typically do not contain a sub-ballast layer designed for the current traffic loads and common materials on these lines which underlie the ballast layer consist of fouled old ballast or slag. Naturally occurring soil is conventionally used for preparing the subgrade except in situations where the soil is deemed unsuitable or is required to be raised to a certain elevation. In such cases, a layer of placed soil can be used on top of the naturally occurring soil to meet structural requirements. The utilization of coal ash as a placed soil layer will be the focus of the investigation presented by the authors of this paper.

Aside from the economic advantages of using an industrial by-product in the rail substructure some negative environmental impacts from the stockpiling of coal ash can be minimised, and in some cases, avoided such as the loss of usable land, contamination of groundwater, production of wind-blown particulates, adverse effects on indigenous vegetation and aesthetic effects.

It is therefore proposed to use coal ash as a selected formation layer in railway substructures where it is a more feasible option in comparison to conventional granular material. The properties of coal ash, pertaining to its use as a selected layer is investigated and discussed in this paper. The work done in this study serves as a preliminary investigation to promote the use of coal ash within the railway substructure.

2 LITERATURE REVIEW

A limited number of studies are available in literature on the use of alternative material in the railway substructure.

Sol-Sanchez *et al*. (2015) were able to replace 10% of conventional ballast material with crumb rubber resulting in decreased ballast breakage and reduced settlement in comparison to a ballast layer containing elastic mats and no crumb rubber. The replacement of conventional material thus alleviated natural resource depletion while recycling waste from end of life tyres.

With particular reference to coal ash, Vukicevic *et al*. (2018) recognized that large quantities are required for rail construction and that borrowed soil is not always easy to obtain considering large haulage distances. They investigated the suitability of treated and untreated ash-slag mixtures from Serbian thermal power stations as well as Class F fly ash for railway construction in and around the power plant. The mixtures investigated met all the technical requirements such as grain size distribution, Atterberg limits, specific gravity, moisture-density relationship, shear strength parameters in terms of effective stresses and California Bearing Ratio (CBR). Their investigation was based on the success of a similar application on a French high speed rail line designed to cater for speeds of 320 km/h. In 2002, the construction project utilized approximately 150 000 m^3 of landfilled ash from a local thermal power plant.

Viswanadham & Mathur (2014), conducted centrifuge model tests of clay confined coal ash embankments as well as a geogrid reinforced coal ash embankment, have also investigated rail embankments using coal ash. Their study looked at the stability and deformation of coal ash as a structural fill when subjected to applied pressure loading and found that a minimum thickness of 1.5 m should be used for the clay-confining layer and that appropriate drainage would need to be provided for. Stability analysis for the clay-confined models were also found to correlate well with the centrifuge models. The geogrid coal ash embankments were found to require high strength layers in the top half of the embankment at bearing pressures in excess of 250 kPa. Potential concerns such as impacts of wind erosion, surface-water erosion and dissolution in surface runoff and rainfall percolation (Viswanadham & Mathur, 2014); can be counteracted by the incorporation of a confinement layer while maintaining the strength properties of the coal ash embankment. Researchers such as Lewis (1976) found that, on average, a slope of 26.5° with the horizontal surface can be used safely with a confining layer of 450 mm to 2000 mm for constructing highway embankments.

In comparison to rail applications, more literature can be found on the use of coal ash in road construction as a partial or even full replacement of the substructure layers. Many researchers have investigated and established the potential use of coal ash as a granular road layer, a stabilizing agent or as a stabilized layer using activating agents such as cement or lime. The use of coal ash within the road structure will be discussed below given the similarity in the nature of structural layers being used to resist applied traffic loading.

Lewis (1976) conducted a case study in Illinois of a trial highway embankment near a local power plant. The embankment was constructed in thin lifts, scarified and compacted using a vibratory roller. A clay seal was then used for confinement and to support vegetation growth.

As a stabilized layer, Heyns (2016) found that up to 18% of South African dump ash can be used with 1% cement as a stabiliser on G5 material. In the study, Unconfined Compressive Strength (UCS) and Indirect Tensile Strength (ITS) tests were performed on experimental and reference samples containing 4% and 5% cement as a stabilising agent. Saranya Raj *et al*. (2018) used coal ash to stabilise a rammed earth structure. Various proportions of fly ash and bottom ash were investigated to find the optimal binder composition. Based on the compaction behaviour, the optimal binder amount was found to be 30% for stabilization. Mgangira *et al*. (2015) demonstrated that fly ash can be used as a complete replacement when stabilised with cement, lime or a biological enzyme-based liquid stabiliser.

Prasad *et al*. (2009) further demonstrated the potential of increased utilization of waste materials by reinforcing fly ash and murrum sub-base layers with waste tyres and plastics. By applying cyclic loading to constructed test section, they were able to assess the performance of the alternative road materials and found that the murrum reinforced subbase showed lower rebound deflections than the fly ash reinforced subbase thus requiring slightly more quantities of waste plastic and waste rubber for reinforcement.

Given the amount of research and findings on the use of coal ash in the road substructure, the Federal Highway Administration (FHWA) of the United States have compiled a user guideline for the use of coal ash in road construction activities. They also have various reports on construction projects that have been implemented using coal ash in a road context. These include granular base layers, sub-base layers, embankments and other types of civil engineering applications in the road projects. The FHWA also highlights the need to satisfy conventional material specifications as an initial study to the use of coal ash as a structural layer.

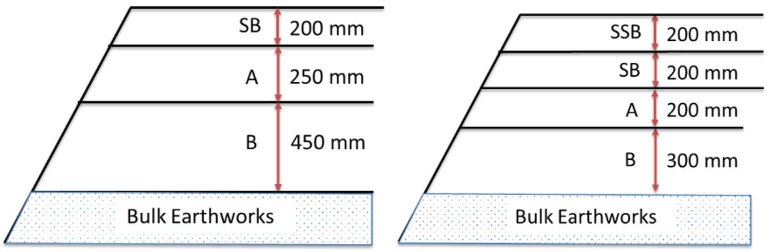
It is also worth noting that the chemical and mechanical properties of ash may vary according to the power station as well as the quality and type of coal used in the combustion process. It is therefore important to conduct a laboratory investigation on the ash prior to use depending on the ash source.

The current study being reported in this paper, aims to add to the existing body of knowledge in order to promote the use of industrial by-products, such as coal ash, in railway infrastructure. The initial laboratory investigation is thus presented in this paper, which discusses the properties of coal ash from the Kriel and Camden power stations in Mpumalanga, South Africa.

3 METHODOLOGY

3.1 *Specification requirements*

As described earlier, a typical railway substructure can be divided into the ballast layer, sub-ballast layer and the subgrade layer. National specifications for railway earthworks (Spoornet, 2006) prescribe the minimum requirements for the track formation structural layers depending on the design axle loading for the railway line. These include prescribed layer thicknesses, depicted in Figure 2, as well as the required material properties, presented in Table 1.



(a) (b)

Figure 2. Structural layers for (a) 20 tonne axle loading and (b) 26 tonne axle loading (Spoornet, 2006)

Depending on prevailing soil conditions, the track formation can consist of placed soil and bulk earthworks (in-situ material). The ash samples analysed for this investigation were assessed against the requirements for a placed soil layer, i.e. Layers A and B as well as the subgrade, referred to as bulk earthworks in the specification. It should be noted that the compaction requirements presented in Table 1 are for non-cohesive soils considering the non-cohesive nature of the coal ash.

Table 1. Material requirements for Layers A and B (Spoornet, 2006)

Property	Specification		
	Layer A	Layer B	Bulk Earth-works
Max. SAR Index	110	155	n/a
Min. Grading Modulus	1.0	0.5	n/a
Max. % passing 0.075 mm sieve	40	70	n/a
Max. Plasticity Index	12	7	25
Max. CBR Swell	n/a	n/a	2
Min. CBR	20	10	5
Min. % MOD AASHTO Compaction	100	98	95

3.2 *Material description*

Three samples of bottom ash from two coal fired power stations were investigated, namely (i) coarse ash from Kriel power station (ii) coarse ash from Camden power station and (iii) fine ash from Camden power station. Class F fly ash from Kriel power station was also used for blending the coarse ash from the same power station during the optimum water content and compaction analysis.

All the ash samples were tested against Transnet specifications for rail earthworks and the results are analysed and discussed below in relation to the specifications.

4 ASH PROPERTIES

4.1 *Grading analysis*

The particle size distribution up to a minimum sieve size of 0.075 mm is presented in Figure 3. It can be observed from the graph that majority of the ash distributions fall within the sand particle size with 76%, 54% and 68% being of sand size for the Camden fine ash, Camden coarse ash and Kriel coarse ash respectively. According to Craig's (1974) classification of composite coarse soils the fine ash from Camden can be described as a very silty sand based on the particle size because it contained over 20% of particles falling below the 0.06 mm sieve. The coarse ash from the same power station can be described as a very gravelly sand as it contained over 20% gravel sized particles. The Kriel coarse ash can be described as a gravelly sand as it contained 20% gravel sized particles and can be categorized as a poorly graded given that the coefficient of curvature (C_Z) was calculated to be 0.6, this falls below the minimum threshold of one for well-graded soils.

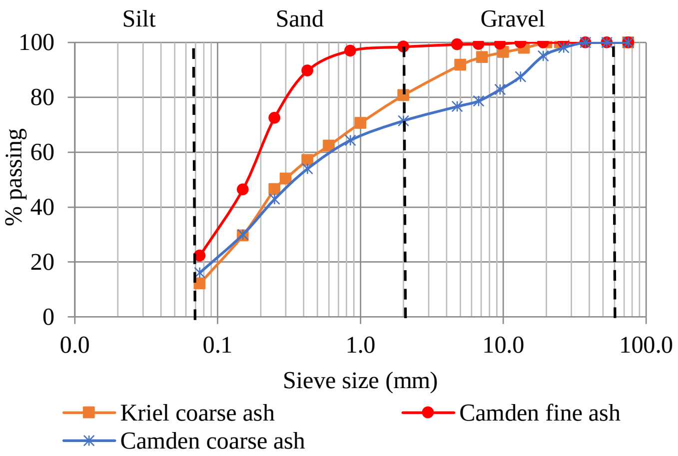


Figure 3. Particle size distribution of ash samples

It is also observed from Figure 3 that grading of the Camden coarse ash can be described as gap-graded while the fine ash appears to be more uniformly graded in comparison. The grading modulus was determined to be 0.90, 1.59 and 1.50 for the Camden fine ash, Camden coarse ash and Kriel coarse ash samples respectively. The respective percentage of material passing the 0.075 mm sieve for the above samples was 22.2%, 16.1% and 12.1%.

Based on the calculated grading modulus and percentage passing the 0.075 mm sieve, all the ash samples met the grading requirements for Layers A and B with the exception of the Camden fine ash, which is not suitable to be used for constructing Layer A.

4.2 *Ash composition*

In order to understand the chemical composition of the ash samples, an analysis was conducted using a scanning electron microscope (SEM). This included SEM images of the silt sized ash particles, which gave an indication of the particle shape, as well as Energy Dispersive X-Ray Spectroscopy (EDS) analyses which were able to give an indication of the chemical composition of the ash samples.

The captured SEM images at 200X magnification can be seen in Figures 4-6 and it was observed that most particles were irregular in shape as opposed to spherical which is typically seen in fly ash SEM images.

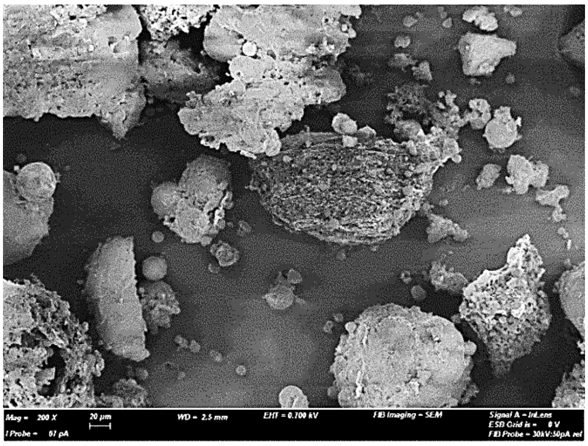


Figure 2. Fine ash from Camden power station at 200X magnification

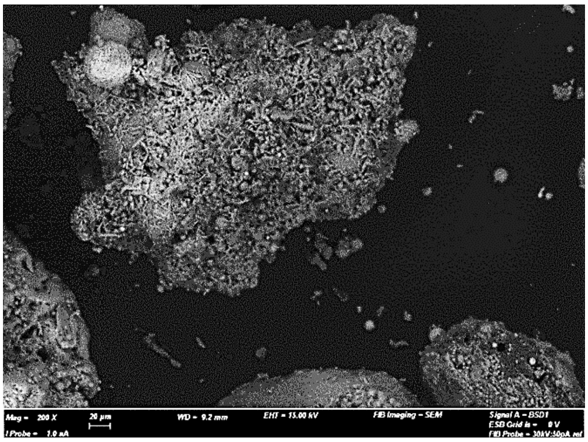


Figure 5. Coarse ash from Camden power station at 200X magnification

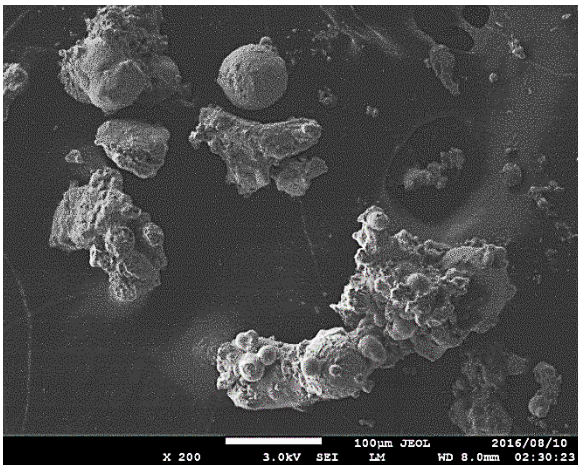


Figure 6. Coarse ash from Kriel power station at 200X magnification

The elemental composition is presented in Table 2 that shows the mean elemental composition distribution by weight for the different ash samples. All ash samples showed comparatively high Silicon content, followed by Aluminium, with the exception of the Camden coarse ash which had a higher Calcium content than Aluminium.

Table 2. Elemental composition of ash samples

Description	% weight					
	O	Si	Al	Ca	Fe	K
Kriel coarse	42.2	15.2	10.1	1.8	10.6	0.7
Camden coarse	51.1	17.4	7.4	17.0	5.3	0.6
Camden fine	50.2	17.5	15.2	8.9	5.7	0.8

The EDS analysis also correlated with an X-Ray Fluorescence (XRF) analysis conducted to assess the molecular composition of the Kriel ash samples thus indicating that the elements listed in Table 2 occurred in the form of oxides, hence the high oxygen contents observed.

The XRF analysis was also able to provide the Loss on Ignition (LOI) values of the Kriel coarse ash which was found to be 1.93% where the LOI value is indicative of the unburned coal content present in the ash. Trifunovic *et al*. (2010) investigated the effect of unburned coal in bottom ash mixtures and found that samples with higher amounts of unburned coal had reduced compressive strengths. This finding was also linked to the particle size distribution of the coal ash samples where larger fractions tended to have higher amounts of unburned coal compared to the finer fraction (<2mm). This was also found to be true for the Kriel coarse ash in comparison to the fly ash assessed from the same power station. A minimum value for LOI is therefore recommended for use in railway structural layers.

There is no existing criteria for the chemical composition of material used in railway earthworks but it is prudent to understand the make-up of alternative materials prior to use which will inform how the material performs during application as well as to assess the potential impacts resulting from its use. The FHWA recommends bottom ash material to be investigated for corrosivity prior to use as an unbound or granular base or subbase material. The presence of soluble salts in the Kriel coarse ash was therefore tested according to Method A21T of the Technical Methods for Highways (TMH1) and an average value of 0.098 S/m was measured at 25°C; this is below the specification for road works of 0.15 S/m as per COLTO (1998). In addition, the pH of the coarse ash was found to be 9.3 and the coarse ash can therefore be described as alkaline in nature. Given the measured electrical conductivity of the ash, the estimated soluble salt content is less than 0.2% (TMH1, 1986) by mass and therefore no further treatment with lime would be required according to COLTO (1998).

4.3 *Compaction characteristics*

The relationship between the maximum dry density (MDD) and optimum moisture content (OMC) of the ash samples is shown below in
Figure 7.

A higher maximum dry density was achieved from the Camden fine ash samples compared to the coarse ash samples as seen in Figure 7; this is largely attributed to the lower water requirement of the fine ash in comparison to the coarse ash samples. The OMC values were determined to be above 24% with the OMC for Kriel coarse ash being 31.8%.

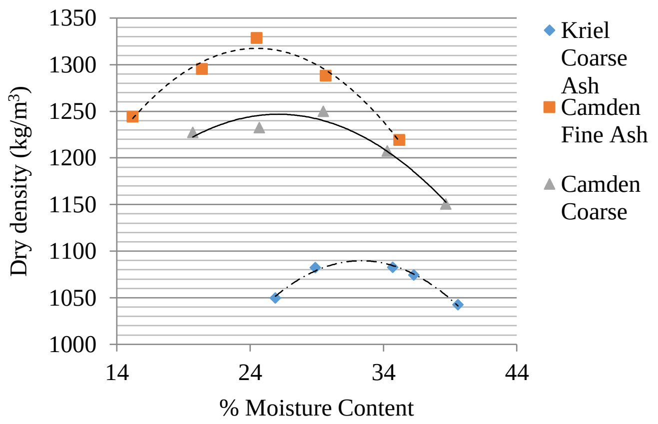


Figure 7. Optimum moisture content curves of ash samples

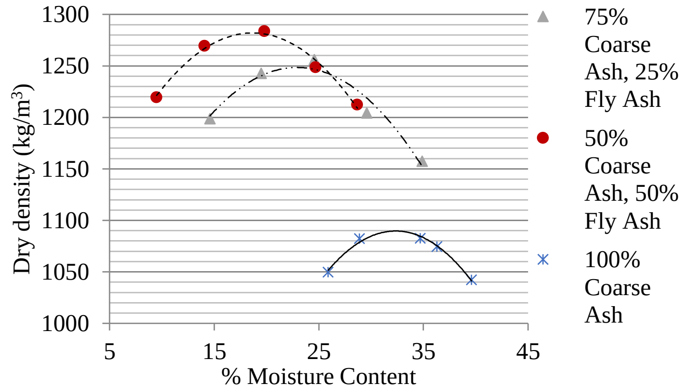


Figure 8. Optimum moisture content curves of blended ash samples

In an attempt to reduce the water content required to reach the maximum density, two further blends incorporating 25% and 50% replacement of coarse ash with fly ash were prepared. Both fractions were obtained from Kriel power station and the OMC curves are presented in Figure 8. Results showed a 38% decrease in OMC as the fly ash content increased from 0% to 50% as well as an increase in MDD by 18%.

4.4 *California Bearing Ratio*

Figure 9 shows a consistent increase in CBR for all the ash samples with an increase in compaction levels. The Camden fine ash exhibited the highest California Bearing Ratio (CBR) values out of all the ash samples. The CBR value for the Camden coarse ash was found to be, on average, half the CBR value for the Kriel coarse ash at all four compaction levels that were tested for. This is likely due to the gap graded particle size distribution exhibited by the Camden coarse ash.

A general improvement in strength and compaction was therefore observed as more fly ash was blended with the coarse ash while also reducing the OMC.

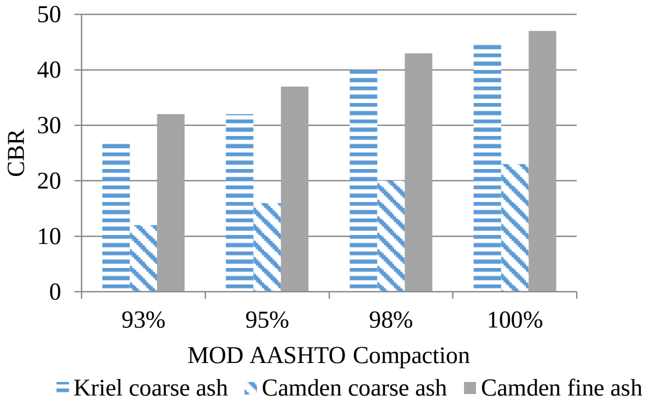


Figure 9. CBR values at varying compaction levels

4.5 *Plasticity*

The ash samples were all found to be non-plastic according to the Atterberg limits tests. This was the determination even though the ash samples were relatively fine in nature, particularly the Camden fine ash; it was observed that ash has an unconventional relationship with water in comparison to traditional soils. This was also found by Campbell (1999) who described ash as highly sensitive to the amount of water added during sample preparation for plasticity tests thereby making the liquid and plastic limits of ash complex to obtain due to its thixotropic nature.

Although the ash has a higher water demand than conventional soils and a complex relationship with water, the low CBR swell values indicate that potential swell from water ingress is minimised.

5 CONCLUSION

The ash properties in relation to the railway specification are listed in Table 3 and all the technical requirements for Layers A, B and bulk earthworks are met for the Kriel coarse ash as well as the Camden coarse ash when measured against Table 1. The grading modulus of the Camden fine ash does not permit its use in Layer A; however, it is suitable to be used in Layer B and in the bulk earthworks.

Table 3. Material properties of Kriel and Camden ash

Property	Kriel	Camden	
	Coarse Ash	Fine Ash	Coarse Ash
SAR Index	57	67	61
Grading Modulus	1.5	0.9	1.6
Plasticity Index	np	np	np
CBR Swell	-0.09	-0.03	0.01
CBR (100% MOD AASHTO)	45	47	23
CBR (98% MOD AASHTO)	40	43	20
CBR (95% MOD AASHTO)	32	37	16

In this paper, three bottom ash samples from Kriel and Camden power stations were tested against the national specification for railway earthworks. The ash samples were all found to meet the technical requirements for use as a selected structural layer (Layers A and B) as well as the bulk earthworks with the exception of the Camden fine ash which does not meet the grading requirements for Layer A.

6 RECOMMENDATIONS

The investigation reported in this paper serves as a preliminary investigation towards the use of ash in railway track construction or maintenance.

It is recommended that a more extensive research programme be carried out at each power station to determine the suitability of the coal ash for use in the railway substructure. This would also involve an environmental impact assessment to determine effects such as leaching. The determination of a maximum LOI value is also recommended given its effect on compressive strength and reported incidents relating to the potential effects of high amounts of unburned coal in rail embankments.

7 ACKNOWLEDGMENTS

The authors would like to acknowledge and thank the CSIR who funded the research project as well as Ulula Ash for their donation of ash samples from Kriel power station.

8 REFERENCES

Campbell, A.E. 1999. Chemical, physical and mineralogical properties associated with the hardening of some South African fly ashes. *Dissertation for Master of Science in Environmental Geochemistry*, Cape Town: University of Cape Town.

COLTO, 1998. Standard specifications for road and bridge works. South African Institution of Civil Engineering: Halfway House.

Department of Energy: Republic of South Africa. Coal Resources. [ONLINE] Available at: http://www.energy.gov.za/files/coal_frame.html. [Accessed 30 January 2019].

Fernandes, G., Palmeira, E.M. & Gomes, R.C. 2008. Performance of geosynthetic-reinforced alternative sub-ballast material in a railway track. *Geosynthetics International*, (5) Vol. 15: 311-321.

George, T.B., Mokoena, R. & Rust, F.C. 2018. A review on the current condition of rail infrastructure in South Africa. *Proceedings of 37th Annual Southern African Transport Conference, Pretoria, 9-12 July 2018.*

Grabe, P.J., Ebersohn, W., Lombard, P.C. & Lombard P.J. 2012. *Introduction to Railway Engineering*, Pretoria: University of Pretoria.

Lewis, T.S. 1976. Construction of fly ash roadway embankment in Illinois. *Transportation Research Record* (593): 20-23.

Li, D., Hyslip, J., Sussmann, T., Chrismer, S. 2016. *Railway Geotechnics*, Boca Raton:Taylor & Francis Group.

Heyns, M.W. 2016. Fly ash as an alternative stabiliser for road pavement materials: a case study in South Africa. *Dissertation for Master of Engineering*, Bloemfontein: Central University of Technology of the Free State.

Indraratna, B. & Salim, W. 2003. Deformation and degradation mechanics of recycled ballast stabilised with geosynthetics, *Soils and Foundations* (4) Vol. 43: 35-46.

Krezel, Z.A., McManus, K.J., Harding, G.E. 2004. The use of layered recycled aggregate concrete barriers in targeting urban noise. *Proceedings of 3rd International Conference on Urban Regeneration and Sustainability*. Siena.

Minerals Council South Africa Pocketbook. 2018. Facts and figures. Johannesburg: Minerals Council South Africa.

Mgangira, M.B., George, T., Mokoena, R. 2015. Fit-for-purpose laboratory assessment of lightly stabilised fly ash material for road construction. *Proceedings of 34th Annual Southern African Transport Conference, Pretoria, 6-9 July 2015.*

Piehler, G., El-Baroudi, H., Brellenthin, J. & Goss, L.B., 1982. Environmental evaluation of coal combustion by-product utilizations. *Resources and Conservation* (9): 323-331.

Prasad, D.S.V., Prasada Raju, G.V.R. & Anjan Kumar, M., 2009. Utilization of industrial waste in flexible pavement construction. *Electronic Journal of Geotechnical Engineering* (Bund. D) Vol. 13: 1-12.

Reynolds-Clausen, K., Singh, N. 2016. Eskom's revised coal ash strategy and implementation progress. *Proceedings of the Test and Measurement Conference, Centurion, 26-28 September 2016.*

Selig, W. & Waters, J.M. 1994. *Track geotechnology and substructure management*. Thomas Telford Publishing

Sol-Sanchez, M., Thom, N.H., Moreno-Navarro, F., Rubio-Gamez, M.C. & Airey, G.D. 2014. Performance of geosynthetic-reinforced alternative sub-ballast material in a railway track. *Construction and Building Materials, (75):* 19-24.

Spoornet. 2016. Technical Specification for Railway Earthworks S410. Transnet Ltd.

TMH1. 1986. Technical Methods for Highways. Standard Methods of Testing Road Materials (2nd Ed.) Pretoria: 103-112.

Transnet SOC Ltd. 2016. *30-Year Long-term Planning Framework*. Johannesburg: Transnet Group Capital.

Viswanadham, B.V.S. & Mathur, V.K., 2014. Performance of rail embankments constructed with coal ash as a structural fill material: Centrifuge study. *Geotechnical engineering*, (3) Vol. 45: 40-48.

Vukićević, M., Popović, Z., Despotović, J. & Lazarević, L. 2018. Fly ash and slag utilization for the Serbian railway substructure. *Transportation Research Board* (2) Vol. 33:389-396.