

Effect of Fly Ash particle size on its capacity to neutralize Acid Mine Drainage and influence on the rheological behaviour of residual solids

VR Kumar Vadapalli^{1*}, Leslie Petrik¹, Veruscha Fester², Paul Slatter² and Gervais Sery²

¹Environmental & Nano Sciences Group, Department of Chemistry, University of the Western Cape, Bellville-7535

rvadapalli@uwc.ac.za, Ph No: +27-21-9593878, Fax: +27-21-9593878 and
lpetrik@uwc.ac.za, Ph No: +27-21-9593304, Fax: +27-21-9593878

² Flow Process Research Center, Department of Civil Engineering, Cape Peninsula University of Technology, Cape Town

FesterV@cput.ac.za, Ph No: +27-21-4603760, Fax: +27-21-4603710,
SlatterP@cput.ac.za, Ph No: +27-21-4603077, Fax: +27-21-4603710 and
SeryG@cput.ac.za, Ph No: +27-21-4603759, Fax: +27-21-4603710

* Author for Correspondence

Abstract

Fly Ash (FA) from South African power stations was successfully used to treat Acid Mine Drainage (AMD) and the insoluble residual solids that were obtained as a result of the reaction between FA and AMD proved suitable as a backfill material for mine stabilization. Particle Size Distribution (PSD) of FA varies from time to time depending on the coal burning conditions in the power station. Such variability in PSD of FA could influence its capability to neutralize AMD as well as the flow behaviour of residual solids that have to be transported hydraulically to the backfill site. The objective of this paper is to study the influence of variability of PSD on the above mentioned properties.

The FA from Arnot power station in South Africa was used for this study. PSD analysis showed that the FA particle size distribution was <25 μm (38%), 25-75 μm (42%) and 75-150 μm (14%). The % of fine and coarse particles (in the context of this study) could influence the neutralization capacity of FA and also influence the rheological behaviour of residual solids. Therefore the original FA was compared to samples that were prepared by fine or coarse particle addition to have double the quantity (in mass %) with respect to either the <25 μm or the 75-150 μm fractions. AMD from Landau mine was reacted with un-altered (original) FA and two altered FA samples with doubled amounts of their fine or coarse fractions respectively.

It was found that pH and EC trends that were monitored every 30 minutes differed significantly for each size fraction. The time that was taken to achieve neutral pH, as well as major and trace element and sulphate removal efficiencies of each reaction was

compared. It was observed that the reaction was more rapid (to achieve neutral pH) for the sample containing a higher % of fines compared to the standard or Normal FA sample and the coarse particle size enriched FA sample. It was also observed that the FA that was enriched with fines was more efficient in removing the toxic metals from AMD. The residual solids that were recovered from the reactions were tested for their flow behaviour using an MC1 rheometer. In general it was observed that the higher the solids to liquid ratio the greater the viscosity for all the solids recovered from reactions. The rheological behaviour of residual solids obtained from the reactions using unaltered and altered FA was compared and it was found that the sample enriched with fine particles showed the highest slurry viscosity and that inconsistent rheological behavior was observed for the slurry enriched with coarse particles. Thus particle size is shown to have a significant effect upon the neutralization capacity and the flow properties of FA.

KEYWORDS: fly ash, acid mine drainage, residual solids, particle size distribution, rheology

INTRODUCTION

Acid Mine Drainage (AMD) is a consequence of oxidation of sulfide bearing minerals which are exposed to the environment, mainly by mining and smelting activities. AMD is highly acidic (pH 2-4) and carries a high load of heavy metals and sulphates with it (Razo et al., 2004). Fly Ash (FA) is a coal combustion by-product from power stations. It is highly alkaline in nature and is another environmental hazard relating to energy generation which has been receiving much attention of late. Only 5% of the FA that is produced in South Africa is properly utilized, and the rest is dumped in ash dams and landfills (Eskom, 2001). Poor management of FA causes various environmental problems such as loss of usable land, as well as detrimental effects on plants, soil, air pollution and aesthetics (Carlson and Adriano, 1993). There is mounting pressure on power stations to manage the FA in an effective manner so that it could be beneficial to the environment.

Fly Ash from South African power stations was successfully used to treat/neutralize AMD (Gitari et al., 2006). The insoluble Solid Residues (SR) that were obtained as a result of the reaction between FA and AMD proved suitable as a backfill material to stabilize mines (Petrik et al., 2006a). Moreover, it was shown that the SR can be synthesized to high quality zeolites using high (Zeolite Y) and low (Zeolite P) temperature methods (Somerset et al., 2005a; Petrik et al., 2006b). The zeolites thus synthesized were successfully employed to treat post-neutralization waters (Somerset et al., 2005b; Petrik et al., 2006c). An integrated AMD management scheme using FA was proposed recently (Petrik et al., 2006a).

The Particle Size Distribution (PSD) of FA varies from time to time depending on the coal burning conditions in the power stations. Such variability in the PSD of FA could influence its capability to neutralize AMD and remove toxic metals. Moreover, it could also influence the rheological properties of SR. Rheology is the study of flow and

deformation of matter. Rheological investigation of SR will elucidate certain critical parameters such as optimum solids to liquid ratio, yield stress, hydraulic gradient etc to transport SR to the backfilling site. Understanding the rheology of SR is critical to the design and optimization of the hydraulic transportation system.

Neutralization experiments were carried out using standard FA and FA altered with respect to its fine and coarse particle content, to understand the effect of PSD on the neutralization kinetics. The SR recovered after these experiments were investigated for their rheological behaviour and also to understand the influence of the PSD of FA on the rheology of SR, and the results are presented and discussed in this paper.

MATERIALS AND METHODS

The FA from Arnot power station in South Africa was used for this study. PSD analysis showed that the FA particle size distribution was <25 μm (38%), 25-75 μm (42%) and 75-150 μm (14%). The percentage of fine and coarse particles (in the context of this study) could influence the neutralization capacity of FA. Therefore the original FA was compared to samples that were prepared by fine or coarse particle addition to double the <25 μm or the 75-150 μm fractions. AMD from Landau mine was reacted with unaltered (original) FA and two altered FA that were doubled with respect to the mass % of their fine and coarse fractions. The pH and EC of each reaction was monitored every half an hour until the reaction reached a pH of 7 or greater. The original AMD and process waters recovered from different reactions were analyzed for metal and sulphate concentrations using ICP-MS and IC respectively. The original FA, two altered FA and solid residues recovered from the reactions were examined for major oxides using XRF. After the neutralisation process, the slurry was allowed to settle. All the supernatant water was decanted after 90 minutes, 180 minutes, and then every 24 hours, to obtain different concentrations of the remaining settled solids slurry. The dewatering behaviour is important for final deposition and mine backfilling (Ilgner, 2003). A Paar-Physica MC1 rheometer was used to conduct the rheological investigation of the residual fly ash tests over a range of shear rates using the controlled rate mode of operation with a vane-in-cup geometry. For high solids concentrations it is recommended that a vane be used to eliminate slip. The shear rate range of the rheometer is $0.5 - 10^3 \text{ s}^{-1}$. During the tests, turbulence was induced at shear rates higher than 500 s^{-1} . The rheological parameters were therefore obtained over a shear rate range below this value.

RESULTS AND DISCUSSION

Effect of particle size distribution on the neutralization characteristics of FA

Figure 1 shows the particle size distribution obtained using a Malvern 2000 particle sizer and the results are tabulated in Table 1 showing the percentage of fine and coarse particles in each of the FA mixtures prepared. The density of the fly ash particles was 2200 kg/m^3 . The samples are described in terms of the volume percentage of fines as shown in Figure 1.

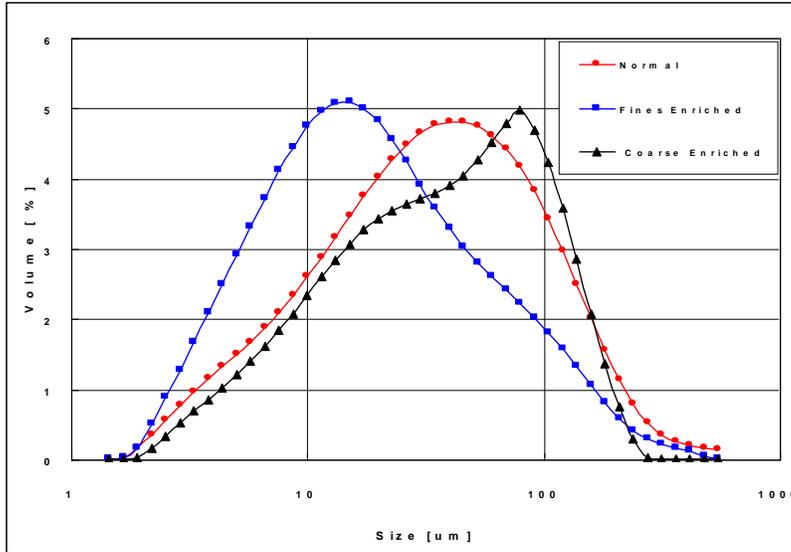


Figure 1: Volume % particle size distribution plot of standard and modified ash

Table 1: Table showing % of fine and % coarse particles in different FA

FA	% Fine and % Coarse
Normal	38% and 14%
FA enriched with Fines	76% and 5.4%
FA enriched with Coarse	31.8% and 28%

pH and EC trends

The Arnot FA and Landau AMD were used for the neutralization experiments and were mixed in 1:3 ratio (FA: AMD) for all the reactions. Figure 2 shows the pH and EC trends for the reaction that used normal (unaltered FA) to neutralize Landau AMD. It can be seen from Fig 2 that there was an immediate increase in the pH of the solution as soon as the FA was added to the solution. This can be attributed to the dissolution of readily soluble species that were present in the FA. This increasing trend continued for one and half hour and afterwards there was a long plateau observed at a pH of 6 for about 5 hours. According to Robbins et al. (1999) and Webster et al. (1998), most of the metals precipitate out of the solution between pH 4 to 6.5. It was observed that during the precipitation of metals the pH of the reaction mixture remains same. The same principle can be applied to the above mentioned plateau. It can be also observed that there was a rapid decrease in the EC values during the first one and half hours of reaction which corresponds very well with the pH trend. But, unlike the pH, the EC values gradually decreased as the reaction proceeded. It took approximately 7.5 hrs for the reaction to reach an alkaline pH under the conditions applied.

Figure 3 shows the pH and EC trends of the neutralization reaction in which the FA enriched with fines was applied for neutralization of AMD. The pH and EC trends were

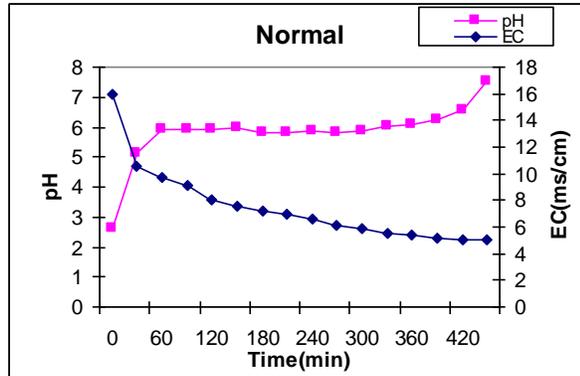


Figure 2: pH and EC trends of the neutralization reaction for normal FA

similar to the trends that were observed during the reaction for normal FA. The only distinguishable feature was the time taken for the reaction to reach alkaline pH. The reaction was much faster in comparison to the previous reaction, taking approximately 5.30 hrs to reach a pH of 8.45.

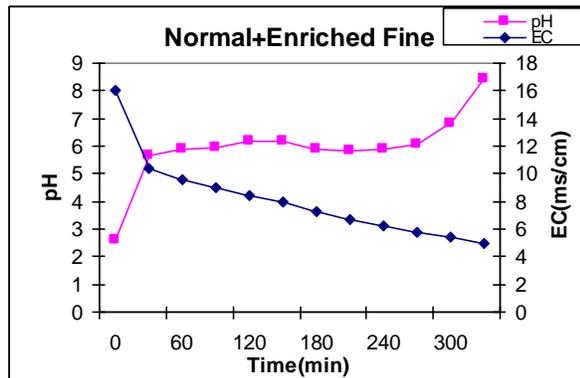


Figure 3: pH and EC trends of the neutralization reaction for FA with enriched fine particles

The neutralization reaction using FA that was enriched with coarse particles took a longer time to reach a pH of 8.45 than other two reactions. Figure 4 shows the pH and EC trends of the reaction showing that 11.5 hrs were required to reach a neutral pH.

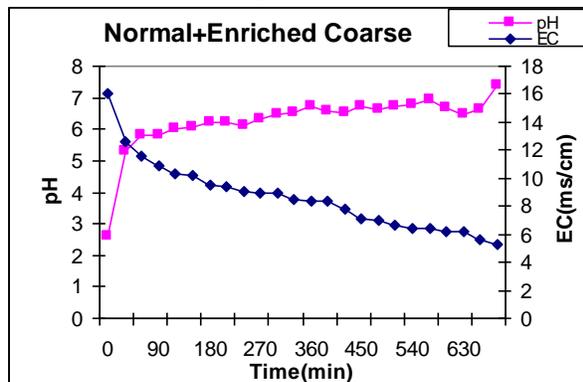


Figure 4: pH and EC trends of the neutralization reaction for FA with enriched coarse particles

Figure 5 gives a clear indication of pH and EC trends of different neutralization reactions. Although no significant difference is observed in the EC values between the three reactions, it is quite apparent from Fig 5 that the time of reaction to reach alkaline pH was the fastest when using FA enriched with fines, followed by the reactions that used normal FA and coarse FA.

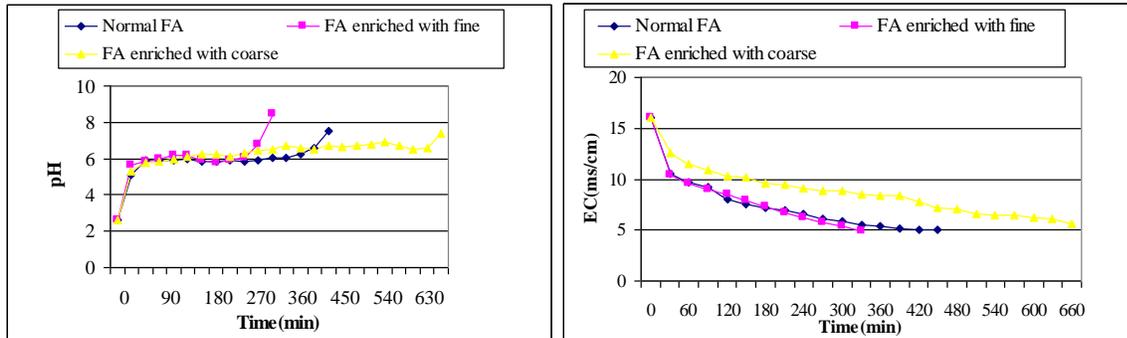


Figure 5: pH and EC trends of different neutralization reactions that used different FA

ICP-MS and XRF results

Table 2 shows the XRF analysis of the unaltered Arnot FA; altered Arnot FA enriched with respect to fine or coarse particles and solid residues recovered from the different neutralization reactions that used the above mentioned FA.

Table 2: XRF analysis for different FA and SR recovered from different reactions

Oxide (w/w %)	Arnot FA	SR-Arnot FA	Arnot FA+EF	SR-EF	Arnot FA+EC	SR-EC
SiO ₂	53.69	49.792	53.811	49.123	53.861	51.254
Al ₂ O ₃	25.55	24.298	27.193	25.18	25.093	24.486
CaO	6.641	6.047	6.682	5.969	6.502	6.197
Cr ₂ O ₃	0.053	0.048	0.063	0.061	0.046	0.045
Fe ₂ O ₃	3.837	5.324	3.947	5.153	3.751	5.252
K ₂ O	0.587	0.559	0.615	0.555	0.603	0.565
MgO	2.6	2.201	2.668	2.421	2.565	2.271
MnO	0.055	0.11	0.05	0.129	0.057	0.114
NiO	0.01	0.009	0.011	0.012	0.008	0.009
P ₂ O ₅	0.302	0.274	0.36	0.328	0.28	0.281
TiO ₂	1.61	1.468	1.742	1.547	1.577	1.506

- SR-Arnot FA: Solid residues obtained from the reaction between un-altered FA and AMD
- SR-EF: Solid residues obtained from the reaction between FA enriched with fines and AMD
- SR-EC: Solid residues obtained from the reaction between FA enriched with Coarse and AMD

Although the differences are generally low, it is evident from the above table that the mass percentage of the most of the major oxides such as Al_2O_3 , CaO , Cr_2O_3 , Fe_2O_3 , K_2O , MgO and TiO_2 is more in the FA that is enriched with fine particles when compared to the normal FA and FA enriched with coarse particles. The enrichment of Fe in all the solid residues indicates their efficiency to remove iron from the AMD. It can be also noticed that minor amounts of major oxides such as SiO_2 , Al_2O_3 and CaO were also utilized during the neutralization reactions. The results also indicate that the main mechanisms that control the removal of metals from AMD are ion adsorption, precipitation and co-precipitation. Similar conclusions were made by Gitari, 2006 while neutralizing AMD with FA and Komnitas et al., 2004 while cleaning acidic leachates using FA barriers. Table 3 gives a clear picture of the efficiency of each FA to remove toxic elements from AMD. Figure 6 graphically represents and compares the efficiency of different FA to remove toxic elements and sulphate from AMD.

Table 3: ICP analysis of raw AMD and process waters recovered from different reactions (in mg/L)

Element	Landau AMD	Process Water-NF	Process Water-EF	Process Water-EC
Zn	2.100	0.008	0.000	0.007
Pb	0.211	<0.010	<0.010	<0.010
Ni	0.373	0.173	0.002	0.060
Mn	238.788	127.850	14.828	98.742
Fe	6540.295	0.594	0.092	0.127
Co	0.637	0.324	0.008	0.106
Cd	0.001	0.001	0.001	0.001
As	0.006	0.006	0.006	0.006
Ag	0.005	0.005	0.005	0.005
Al	693.934	0.100	0.693	0.031
SO_4^{2-}	16452.000	5158.000	4401.000	5244.000

- Process Water-EF: Water recovered from the neutralization Reaction with FA enriched with fines
- Process Water-EC: Water recovered from the neutralization Reaction with FA enriched with coarse
- Process Water-NF: Water recovered from the neutralization Reaction with unaltered FA

The reaction that used FA that was enriched with fines was more efficient in removing toxic elements and sulphate concentrations from AMD. Elements such as Ni, Mn, Fe and Co were greatly removed when compared to the water quality obtained by applying FA enriched with the coarse size fractions. This can be attributed to the higher surface area of fine particles which has a greater reactive surface. Interestingly, the reaction that used FA that was doubled with respect to the mass % of coarse particles achieved a better removal efficiency compared to the neutralization reaction that used normal FA. This is probably due to the longer time taken by the reaction that used FA enriched with coarse particles to reach alkaline pH. This would have allowed more time for the adsorption and precipitation reactions involved in the removal of the metals than in the case of the unaltered FA. This indicates that the removal efficiency of toxic elements by FA not only depends on the surface area but also depends on other factors such as

contact time and mineralogy. Similar conclusions were made by Hakan et al., 2006 while studying the factors that influence the adsorption capacity of metals on zeolites.

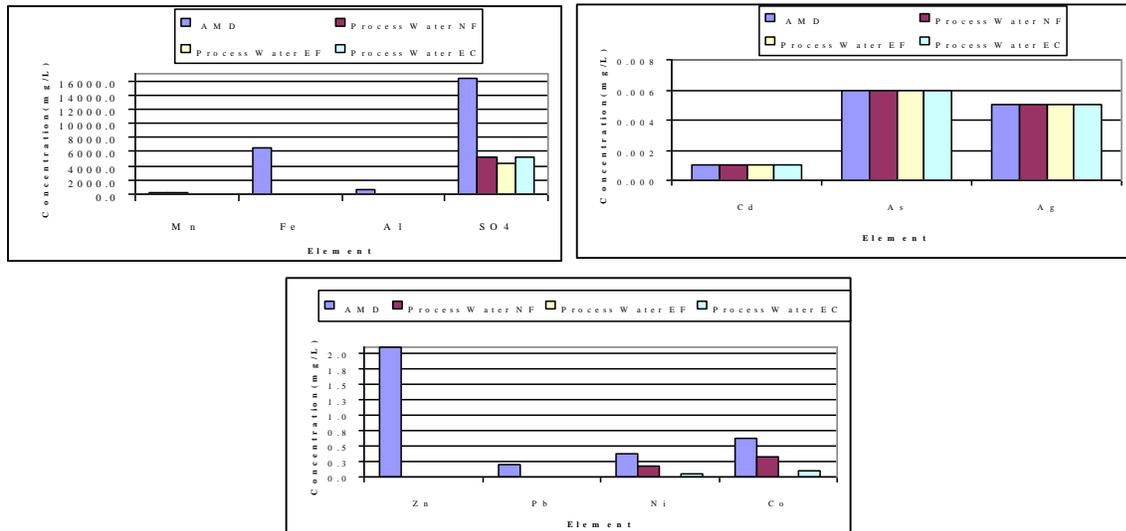


Figure 6: Toxic element removal efficiencies of different size fractions of FA

The rheological behaviour of residual solids from AMD neutralization process

Although some work has been done on the rheology of fly ash elsewhere (Cyr et al. 2000; Iyer and Stanmore, 1999;2000; Heywood et al. 1993; Bournonville and Nzihou, 2002;), the rheology of the residual solids obtained from the neutralization process has not been reported yet. The rheological behaviour of suspensions is susceptible to small changes in particle size, particle size distribution, pH and concentration amongst other factors. However, in South Africa when the fly ash is used to treat AMD, the resulting residual solids particle shape and distribution is significantly altered due to the neutralisation process (Petrik et al., 2006d). It is therefore important to study the effect of the neutralisation process on the rheological behaviour of the residual FA sludge in order to establish the design criteria for transport and backfilling. The particle distribution of the fly ash can vary from batch to batch and its effect on the rheology and hence the pressure gradient during pipeline transport has to be established.

Preliminary Rheological Investigation on FA

The fly ash behaved as quick settling slurries at volumetric concentrations below 30%. As the concentration of solids to liquids increased, inter-particle interactions became stronger, resulting in non-Newtonian behaviour. The fly ash suspensions displayed typical shear-thinning behaviour, i.e. the viscosity decreased with increasing shear rate. There were some time effects present when the fluid was tested first in the increasing shear rate and then the decreasing shear rate range. However, such transient structure is broken down after high shear rates and a constant curve could be obtained. This is shown in Figure 7. For comparative purposes, all tests were carried out starting from high to low shear rate to achieve the equilibrium curve of a fully sheared sample.

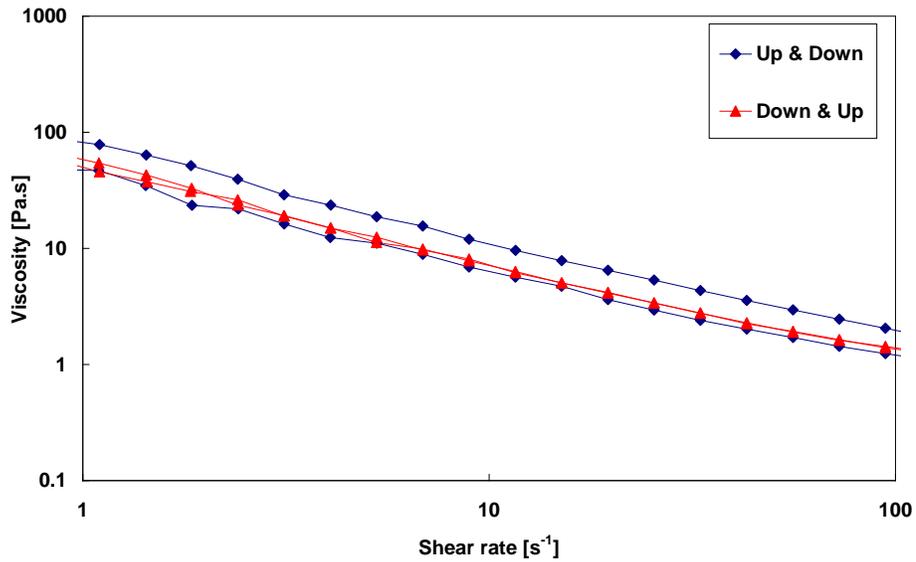


Figure 7: Time dependant behaviour of fly ash

Rheological behaviour of SR

All the slurries recovered from the different neutralization reactions showed shear-thinning behaviour. At least four concentrations were obtained for each SR suspension. The viscosity increased with increasing concentration as given in Figure 8 for Normal/Standard suspension. Suspensions of all the solids with volumetric fraction of less than 0.36 were too dilute to be tested in the rheometer. In the case of the coarse enriched suspension with a volume fraction of 0.36, results could not be obtained with the rheometer because the sample was too dilute.

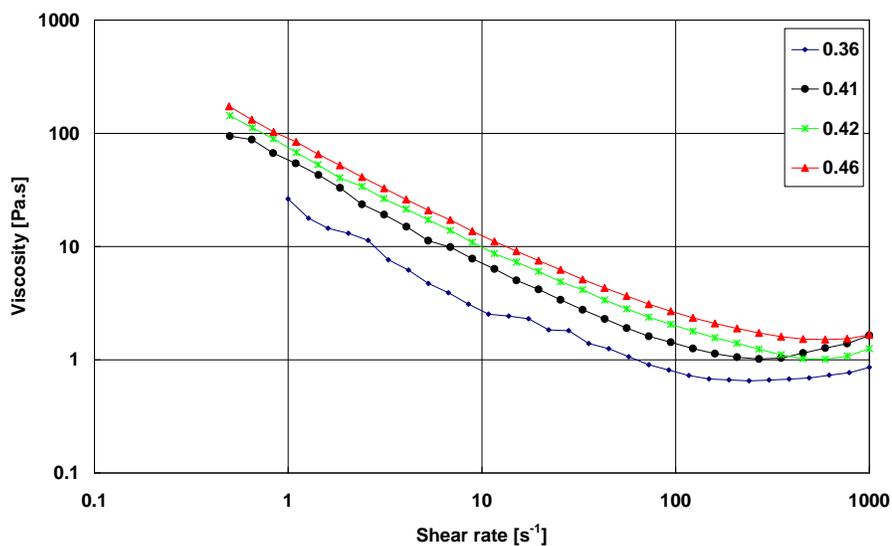


Figure 8: Effect of concentration on the viscosity for standard suspension

Maximum packing fraction

The maximum packing fraction is also referred to as the fluidity limit, implying that the suspension cannot be packed more densely and still remains fluid-like (Iyer and Stanmore, 2000) and it affects the rheological behaviour of the fluid, especially the yield stress. The yield stress is defined as the minimum stress that needs to be applied in order for a visco-plastic fluid to flow (Chhabra & Richardson, 1999). The yield stress increases with increasing volume fraction. There is a critical volume fraction after which the yield stress will increase exponentially and this is shown in Figure 9. The yield stresses were obtained from the flow curves by fitting the Herschel-Bulkley model to the experimental data. The fines enriched FA sample showed higher yield stresses than the normal and coarse enriched FA samples, as expected. The higher yield stress obtained for the coarse enriched sample over that of the normal FA at a volume fraction of 0.46 is clearly shown in Figure 9. Figure 9 also shows that the maximum volume fraction is below 0.5. It was indeed very difficult to obtain concentrations higher than 0.46 as it appears as if thereafter very little process water was available for mobilization.

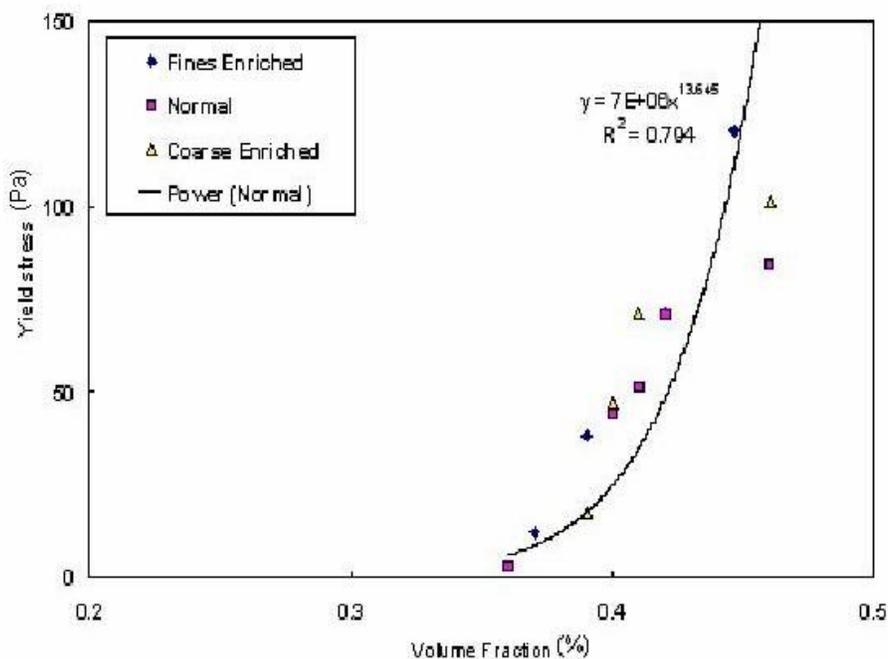


Figure 9: Yield stress dependence on concentration

The maximum packing fraction can also be obtained from a plot of $1-\mu^{1/2} = a\phi+b$ (Fig 10) (Luckham and Ukeje, 1999). The viscosity was taken at a shear rate of 10 s^{-1} and 100 s^{-1} for each suspension.

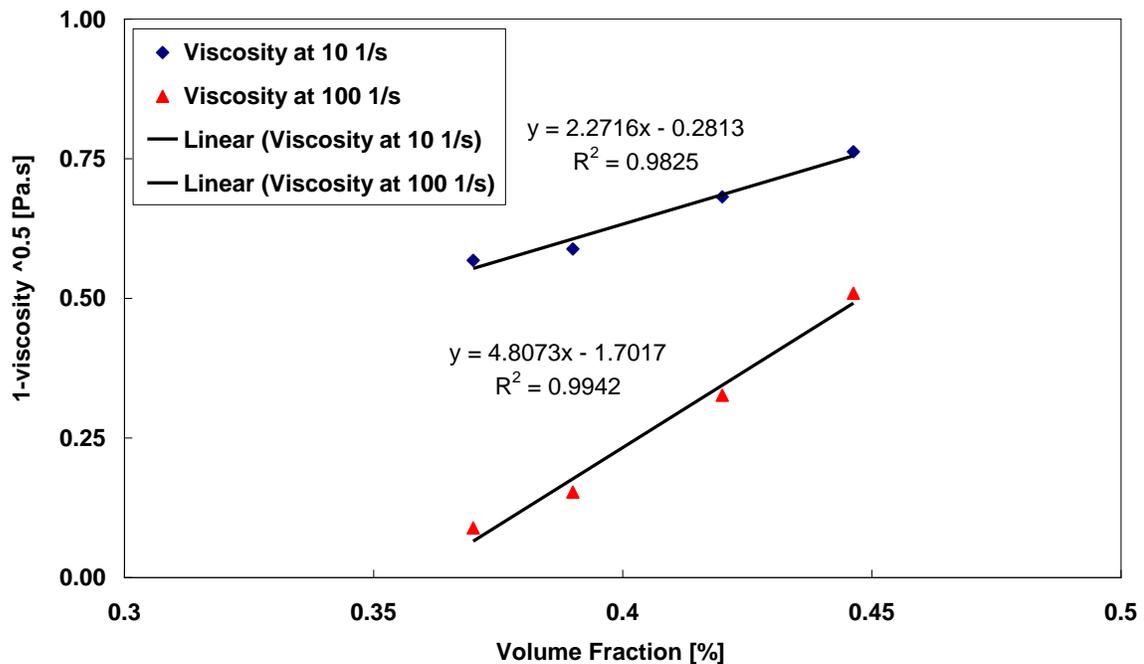


Figure 10: The $1-\mu_r^{1/2} - \phi$ relationship at shear rates of 10 and 100 s^{-1} for fines enriched sample

For the fines enriched suspension, a similar result for the maximum packing fraction of 0.51 was obtained when calculated at shear rates of 10 and 100 s^{-1} . For the standard sample, quite different results were obtained, i.e. a $\phi_m = 0.48$ at 10 s^{-1} and $\phi_m = 0.57$ at 100 s^{-1} . For the coarse enriched suspension values of $\phi_m = 0.53$ and 0.54 were obtained at 10 and 100 s^{-1} . However, all these values obtained are lower than 0.63, the value that is usually obtained for spherical particles. But this is in agreement with Iyer & Stanmore (2000), who stated that suspensions with non-spherical particles will result in lower obtainable volume fractions. The non-sphericity is a result of fly ash particles taking part in the neutralization reaction. Based on Scanning Electron Microscopic studies that were carried out previously, it was observed that the FA particles were eroded due to dissolution of its composite mineral phases and coated to a certain extent by deposits of heavy metals that precipitate out of AMD as insoluble mineral phases (Petrik et al., 2006d)

Effect of rheology on pumping head

It is general knowledge that an increased particle size distribution range will result in lower viscosities and that an addition of fines will result in higher viscosities (Boylu et al., 2004). However, in these tests, it was not the case (Figure 11). The sample with a fines fraction of 31.8 % resulted in higher shear stresses than that of the fines fraction of 38% as given in Figure 11. This result was also observed for a volume fraction of $\phi = 0.46$.

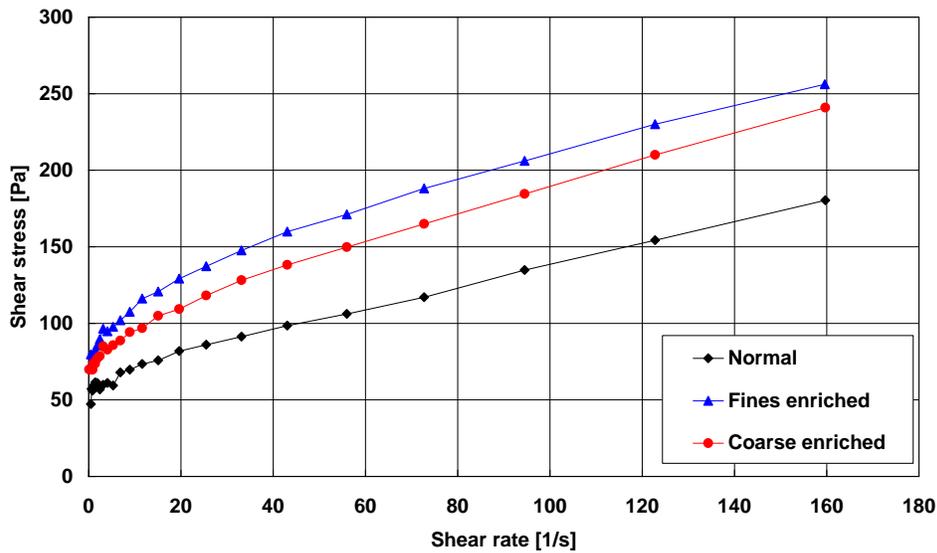


Figure 11: Effect of fines at a volume fraction $\phi = 0.41$

There was a significant effect of particle size distribution on the hydraulic gradient. When the fines fraction was doubled, it resulted in increased shear stresses of 38 %. Figure 12 shows the resulting increase in the hydraulic gradient in a 150 mm pipeline. Also demonstrated is that if the assumption of decreased viscosity with addition of coarse particles is adopted, it would be assumed that using the pumping conditions for the standard sample would be sufficient, if not conservative, which is clearly not the case.

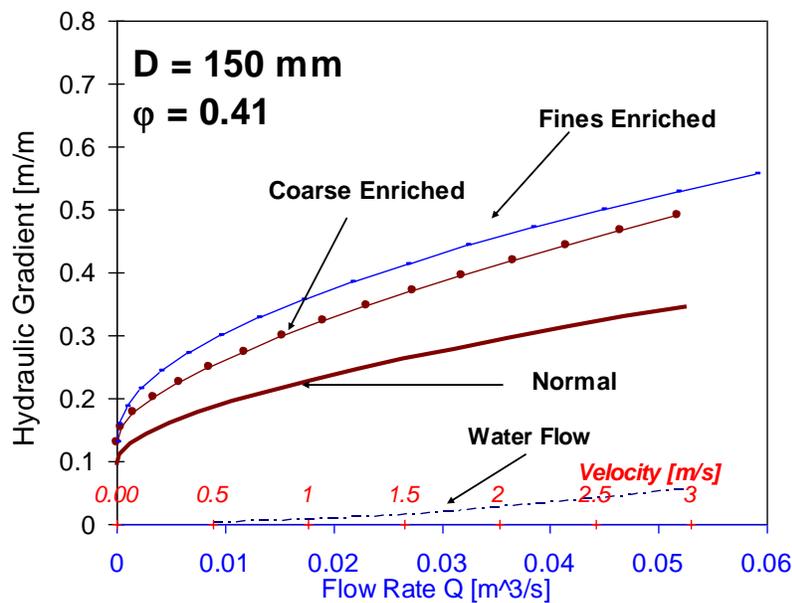


Figure 12: Hydraulic gradient for various particle sizes

Discussion of rheological behaviour

The rheology of fly ash is not a trivial matter to measure or to understand. The preliminary study shows that the particles size distribution has a significant effect on the rheology and the hydraulic gradient. The critical volume fraction obtained was 0.4 for all FA samples prepared, after which the yield stress increases exponentially with increasing volume fraction. From the samples prepared, it was shown that the maximum packing fraction was 0.46 at which pumping will be very difficult. The results obtained show that it is not just the effect of fines, but possibly an interaction or combination of fine and coarse particles. In this case, the addition of coarse particles did not decrease the viscosity as anticipated, but increased the viscosity, shear stresses and pumping head at concentrations greater than 0.42%. It appears from the results that there is a cross over point at $\phi = 0.41$, where the coarse enriched suspension changes from being less viscous to more viscous than the standard sample. Heywood et al. (1993) reported a similar case but contributed it to the difference in pH. In this case, the pH was 7.54 and 7.87 for the standard and coarse enriched suspension. So it can be assumed that the coarser particles have an adverse effect on the viscosity and this anomaly should be investigated further (Ohlero & Ferreira, 2004). According to Cyr et al. (2000), any suspension can show shear thickening behaviour if the volume fraction is high and the suspension is non-flocculated. The other parameters that mostly contribute to shear thickening behaviour are particle shape, size and distribution.

Conclusions

This work has shown the importance of the effect of particle size distribution on the neutralization capacity and rheology of fly ash suspensions. It was shown that the particle size distribution of FA has an influence on the neutralization reaction time and also on the removal efficiency of toxic elements and sulphate concentrations. The smaller particle size fraction enhanced neutralization kinetics due to the higher reactive surface area but concomitantly increased the slurry viscosity. Anomalous behaviour was observed for samples enriched with respect to coarse particles. Therefore the degree of dewatering necessary for obtaining the desired flow characteristics of the slurry composed of the residual solids would be dependent upon the particle size of the FA utilized during neutralization.

Acknowledgments

The authors are grateful to Coaltech 2020, ESKOM, WRC and Claude Leon Foundation for their financial and technical support to carry out the research.

References

1. Bournonville B and Nzihou A. (2002). Rheology of non-Newtonian suspensions of fly ash: effect of concentration, yield stress and hydrodynamic interactions. Powder Technology 128. 148 – 158.

2. Boylu F, Dinçer H and Ateşok G. (2004). Effect of coal particle size distribution, volume fraction and rank on the rheology of coal-water slurries. *Fuel Processing Technology*. 85. 241 – 250.
3. Carlson C.L., and Adriano D.C. (1993). Environmental Impacts of Coal Combustion Residues. *J. Environ. Qual.* 22. 227-247.
4. Chhabra, R. & Richardson, J.F. (1999). *Non-Newtonian flow in the process industries*. Oxford: Butterworth-Heinemann.
5. Cyr M, Legrand C and Mouret M. (2000). Study of shear thickening effect of superplasticizers on the rheological behaviour of cement pastes containing or not mineral additives. *Cement and Concrete Research*. 30. 1477 – 1483.
6. Eskom Annual Report (2001), South Africa.
7. Gitari M.W., Petrik L.F., Etchebers O., Key D.L., Iwuoha E. and Okujeni C. (2006) Treatment of acid mine drainage with fly ash: removal of major contaminants and trace elements. *J Environ Sci Health A Tox Hazard Subst Environ Eng*. 41(8).1729-47.
8. Hakan A., Oren A.H., Kaya A.(2006). Factors effecting adsorption characteristics of Zn^{+2} on two natural zeolites. *Journal of Hazardous Materials*. 131. 59-65.
9. Heywood N I, Mehta K B and Poplar D. (1993). Assessment of flow properties of pulverized fuel ash slurries at high concentration. *Proc of 12th International Conference on Slurry Handling and Pipeline Transport: Hydrotransport 12*, 28-30 September 1993, Brugge, Belgium, edited by C.A. Shook. London: Mechanical Engineering Publications.
10. Ilgner H J. (2003). Hydraulic fill or paste? How to make the right decision. 4th one-day seminar on hydraulic transport in the mining industry, 7 April 2003, Indaba Conference Center.
11. Iyer R S and Stanmore B. (1999). The effect of water absorption and the role of fines on the yield stress of dense fly ash slurries. *Cement and Concrete Research*. 29. 765 – 767.
12. Iyer R S and Stanmore B. (2000). The distortion of the diffuse double layer and its effects on flow properties of dense flyash slurries. *Colloids and Surfaces A: Physiochemical and Engineering Aspects*. 166. 133 – 144.
13. Komnitsas K., Bartzas G., and Paspaliaris, I. (2004). Clean up of acidic leachates using fly ash barriers: Laboratory column studies. *Global Nest: The International Journal*, 6(1), 81-89.

14. Luckham P F. and Ukeje M A. (1999). Effect of particle size distribution on the rheology of dispersed systems. *Journal of Colloid Interface Science*. 220(2). 347-356.
15. Olhero S M and Ferreira J M. (2004). Influence of particle size distribution on rheology and particle packing of silica-based suspensions. *Powder Technology* 139. 69 – 75.
16. Petrik L, Gitari M.W., Vadapalli V.R.K. Etchebers O., Ellendt A., Reynolds K., Surender D., Hendricks N., Klink M.J., Somerset V.S., White R.A., Burgers C., Key D.L. and Iwuoha E.I. (2006a). Applications of ash and its derivatives: water treatment, mine backfilling, lining and walling. 13th International Conference Ashes from Power Generation, 6-8 November, Krakow, Poland.
17. Petrik L., Ellendt A., Hendricks N. and Etchebers O. (2006b). Synthesis of zeolite at low and high temperature using solid residues resulting from the neutralization of acid mine drainage with fly ash. Submitted to the International Symposium on Zeolites and Microporous Crystals (ZMPC2006), [Yonago](#), [Tottori Prefecture](#), Japan, 30 July – 2 August 2006.
18. Petrik L., Ellendt A. and Etchebers O. (2006c). Treatment of mine effluent with zeolite synthesised from solid residues resulting from the neutralization of acid mine drainage with fly ash. Submitted to the International Symposium on Zeolites and Microporous Crystals (ZMPC2006), [Yonago](#), [Tottori Prefecture](#), Japan, 30 July – 2 August 2006.
19. Petrik L, Burgers C, Gitari W, Surender D, Reynolds K, Ellendt A., Etchebers, O, Vadapalli VRK, Key D and Iwuoha E. (2006d). Stability and Neutralization capacity of Potential Mine Backfill Material Formed by Neutralization of Fly Ash and Acid Mine Drainage. Final Report submitted to Water Research Commission, K5/1458, South Africa
20. Razo I., Carrizales L., Castro J., Diaz-Barriga F. and Monroy M (2004). Arsenic and Heavy Metal Pollution of Soil, Water and Sediments in a Semi-Arid Climate Mining Area in Mexico. *Water, Soil and Air Pollution*. 152.129-152.
21. Robbins, E.I., Cravotta, C.A., Savella, C.E., and Nord, Jr. G.L., (1999). Hydrobiogeochemical Interactions in Anoxic Limestone Drains for Neutralization of Acid Mine Drainage. *Fuel*. 78(2). 259-270.
22. Somerset V.S., Petrik L.F., White R.A., Klink M.J., Key D. and Iwuoha E.I. (2005a). Alkaline hydrothermal zeolites synthesized from high SiO₂ and Al₂O₃ co-disposal fly ash filtrates. *Fuel*. 84. 2324–2329.

23. Somerset V.S., Petrik, L. and Iwuoha, E. (2005b). Alkaline Hydrothermal Conversion of Fly Ash Filtrates Into Zeolites 2: Utilization in Wastewater Treatment. *Journal of Environmental Science and Health*. 40 (8). 1627-1636.
24. Webster JG, Swedlund PJ and Webster KS (1998) Trace Metal Adsorption onto Acid Mine Drainage Iron (III) Oxy Hydroxy Sulphate. *Environ. Sci. Technol.* 32 (10).1361-1368.