Int. J. Environ. Sci. Technol. (2015) 12:173–182
DOI 10.1007/s13762-013-0417-7

ORIGINAL PAPER

Jet loop reactor application for mine water treatment using fly ash, lime and aluminium hydroxide

G. Madzivire · W. M. Gitari ·
V. R. K. Vadapalli · L. F. Petrik

Received: 7 August 2012 / Revised: 19 July 2013 / Accepted: 3 November 2013 / Published online: 27 November 2013

Abstract Recent studies have shown that a combination of coal fly ash (FA) and $Al(OH)_3$ can be used to treat neutral mine drainage (NMD) and reduce sulphate concentration to within South African drinking water quality levels, Class II (400–600 mg/L). The shortcomings of this method were the large amounts of FA required to raise the pH to greater than 11 (3:1 liquid-to-solid ratio) so that $Al(OH)_3$ can be added to facilitate removal of sulphate ions through ettringite precipitation. This requires large silos to store FA, making up-scaling of this treatment technology using normal mixing methods to be unrealistic. In the current study, a jet loop reactor was used to reduce the amount of FA needed to increase the pH to greater than 11. The pH was raised to greater than 11 by mixing 0.25 % of lime (w/v ratio) and 13 kg of coal FA with 80 L of NMD in a jet loop reactor. After the pH of the mixture was above 11, amorphous $Al(OH)_3$ (83.2 g) was added to the mixture. This resulted in the sulphate concentration decreasing to less than 500 mg/L. Bench-scale studies using 0.25 % (w/v) of lime and 6:1 coal mine water to FA ratio could not reduce the sulphate concentration to below 500 mg/L. Therefore, the impingement and cavitation mixing techniques that happen in a jet loop reactor played an important role in enhancing sulphate removal.

Keywords Sulphate · Neutral mine drainage · Ettringite · Impingement · Cavitation

Introduction

Mining activities in South Africa have left underground voids and mine tailings containing pyrite (FeS_2) mineral exposed to O_2 and H_2O. Exposing FeS_2 to H_2O and O_2 produces acidity as shown in Eq. 1. The acidity generated enhances chemical weathering of the surrounding rock. This causes leaching of potential toxic elements such as Al, Mn, As and Cr into the water producing highly contaminated water termed acid mine drainage (AMD) (Lottermoser 2007).

$$FeS_2 + \frac{7}{2}O_2 + H_2O \xrightarrow{\text{bacteria}} Fe^{2+} + 2H^+ + 2SO_4^{2-} \quad (1)$$

The mine water can be acidic or alkaline depending on the type of geology that was disturbed during mining. If the surrounding rock contains alkaline minerals such as limestone, sodium hydroxide or dolomite, the resultant water can be circumneutral due to in situ neutralization of the acidity from FeS_2 oxidation as shown in Eqs. 2–4 (Banks et al. 1997; Younger et al. 2002; Lottermoser 2007).

$$FeS_2 + CaMg(CO_3)_2 + \frac{3}{2}H_2O + \frac{15}{4}O_2 \rightarrow Fe(OH)_3 + Ca^{2+} + Mg^{2+} + 2CO_2 + 2SO_4^{2-} \quad (2)$$

G. Madzivire (✉) · L. F. Petrik
Environmental and Nano Science Group, Chemistry Department,
University of the Western Cape, Modderdam Road,
Private Bag X17, Bellville, Cape Town 7535, South Africa
e-mail: gmadzivire@uwc.ac.za

W. M. Gitari
Department of Ecology and Resources Management,
School of Environmental Studies, University of Venda,
Private Bag X5050, Thohoyandou 0950, South Africa

V. R. K. Vadapalli
Environmental Geosciences, Council for Geoscience,
Private Bag X112, Silverton, Pretoria 0001, South Africa

$$\mathrm{FeS_2 + 2CaCO_3 + \frac{3}{2}H_2O + \frac{15}{4}O_2 \rightarrow Fe(OH)_3 + 2Ca^{2+} + 2CO_2 + 2SO_4^{2-}} \quad (3)$$

$$\mathrm{4FeS_2 + 16NaOH + 15O_2 \rightarrow 4Fe(OH)_3 + 16Na^{+} + 8SO_4^{2-}} \quad (4)$$

Chemical treatment of mine water is a costly process (Potgieter-Vermaak et al. 2006; Labastida-Núñez et al. 2013). Previous studies have shown that the concentrations of Fe, Al, Mn and sulphate in AMD were significantly decreased during the treatment of mine water with coal FA (Gitari et al. 2006; Petrik et al. 2003; Vadapalli et al. 2008). Removal of sulphate ions from neutral mine drainage (NMD) with coal fly ash (FA) was found to be pH-dependent. Significant removal of sulphate ions was noticed after precipitating out Mg^{2+} ions from the system at pH greater than 11 (Madzivire et al. 2011). It was also discovered that addition of $Al(OH)_3$ at pH greater than 11 resulted in sulphate concentration decreasing to below the WHO guidelines for drinking water through ettringite precipitation (Madzivire et al. 2010).

$$\mathrm{6Ca^{2+} + 3SO_4^{2-} + 2Al(OH)_3 + 32H_2O \leftrightarrow 3CaO \cdot 3CaSO_4 \cdot Al_2O_3 \cdot 32H_2O + 6H^{+}} \quad (5)$$

The challenge experienced with this treatment approach was the high amount of coal FA that was needed. This means that large silos were required to store the coal FA at the treatment plant. Also, the optimum liquid-to-solid ratio of 3:1 needed using an overhead stirrer mixing technique produced a thick slurry that cannot be easily handled by normal pumps making up-scaling of this process difficult and reduced the amount of recovered treated water.

Superior mixing with a jet loop reactor can be used as one way to reduce the amount of coal FA that can be utilized in the treatment of mine water. The jet loop reactor has been used in the selective hydrogenation of palm olein (Sin 2005). It promotes a faster reaction rate by exerting a higher mass transfer rate and mixing intensity compared to continuous stirred tank reactor (Sin 2005). Intense mixing in a jet loop occurs due to hydrodynamic cavitation and impingement processes that occur inside the reactor (Gavi et al. 2007; Mason 2007; Kumar et al. 2000). Hydrodynamic cavitation is produced by pressure variations due to the changes in the geometry of the system in which the solution is flowing through. This happens when a solution flows through a small orifice, thereby causing the pressure and kinetic energy to drop (Mason 2007; Kumar et al. 2000). The turbulence produces an area of greatly reduced fluid pressure causing vaporization of the liquid, forming a cavity. Hydrodynamic cavitation can be controlled by adjusting flow rate, pressure and orifice size. Intense mixing of the reactants results in the formation of metastable phases causing the kinetics to be increased. A very important aspect of this type of processing is that it can be scaled up easily. In this study, the use of the jet loop reactor was investigated in order to reduce the amount of coal FA required for the treatment of mine water. This work was conducted in the Environmental and Nano Sciences Research Group laboratory (Chemistry Department) at the University of the Western Cape, Cape Town, South Africa. This work was finished in January 2011.

Materials and methods

The mine water used in this study was collected from a coal mine in Mpumalanga Province, South Africa. The mine water was analysed using inductively coupled plasma optical emission spectroscopy (ICP-OES) and ion chromatography (IC). Fly ash was collected from electrostatic precipitators of a nearby coal power station and sealed in plastic bags devoid of air. The FA was analysed using X-ray fluorescence spectroscopy (XRF) and X-ray diffraction spectroscopy (XRD) for the elemental and mineralogy composition, respectively.

Optimization of the amount fly ash and lime required

The following experiments were conducted in order to find the optimum conditions (jet sizes, amount of FA and minimum amount of lime) required to increase the pH of the mine water to pH greater than 11 in order to precipitate sulphate in the form of ettringite.

A. Mine water (80 L) and coal FA (13 kg) were mixed together using a jet loop reactor with jet nozzle sizes set at 8 mm. The mixture of mine water and coal FA was mixed by a combination of impingement and cavitation in the reactor. The pH and EC were measured after every 15 min, and samples were collected after every 30 min. The samples were filtered using a 0.45 µm filter paper and analysed using ICP-OES and IC.

B. Mine water (80 L) was mixed with 16 kg FA using a jet loop reactor with jet nozzle sizes set at 8 mm. The mixture was mixed by a combination of impingement and cavitation in the reactor measuring pH and EC after every 15 min. Aliquot samples were collected after 30 min, filtered using a 0.45 µm filter paper and analysed using ICP-OES and IC.

C. The jet nozzle sizes were changed from 8 to 6 mm. Then, mine water (80 L) and 16 kg coal FA were reacted in a jet loop reactor, measuring pH and EC after every 15 min. Aliquot samples were collected for analysis using ICP-OES and IC after every 30 min.

D. Mine water (500 mL) was mixed with coal FA (83 g) using an overhead stirrer. Different amounts of lime were added to the mixture (w/v % of lime to the mine water). The various amounts of lime added were 0.25, 0.5, 0.75 and 1 %. For each mixture, 0.52 g of $Al(OH)_3$ was added after 15 min. The reaction was carried on after adding $Al(OH)_3$, measuring pH and EC after 15 min and collecting samples after every 30 min. The samples were filtered through 0.45 μm filter paper and analysed using ICP-OES and IC.

Optimization of the jet loop reactions

Experiments were further carried out using a combination coal FA and 0.25 % of lime (w/v) at liquid-to-solid ratio of 6:1 in a jet loop reactor. The first set of three experiments was done to investigate the effect of jet size on sulphate removal. The jet nozzle sizes were varied from 6, 8, 10 and 12 mm. Mine water (80 L) was reacted with coal FA (13 kg) and 0.25 % lime (w/v %). After 15 min, 83.2 g of $Al(OH)_3$ was added. The reaction was allowed to proceed for 150 min measuring pH and EC after every 15 min. Samples were collected after every 30 min, filtered through a 0.45 μm filter paper and analysed using ICP-OES and IC.

Results and discussion

The mine water used in this study was neutral mine drainage (NMD) with a pH of 8.0 (Lottermoser 2007). The water contained high concentration of Na and sulphate, with very low concentration of Fe, Al, Mn, Ca and Mg as shown in Table 1. This was because of the in situ neutralization acidity produced from FeS_2 oxidation by NaOH according to Eq. 4.

The percentage composition of coal FA was determined using XRF. The results obtained showed that the coal FA was made of mainly SiO_2 (48.27 %), Al_2O_3 (30.89 %), CaO (6.71 %), Fe_2O_3 (2.81 %), MgO (2.12 %), TiO_2 (1.26 %), P_2O_5 (0.89 %), K_2O (0.84 %), Na_2O (0.55 %), SO_3 (0.19 %) and MnO (0.02 %). The coal FA used was Class F because the percentage sum of Fe_2O_3, SiO_2 and Al_2O_3 was greater than 70 % (ASTM 1994; McCarthy 1988).

Table 1 The composition of the mine water used in this study

Parameter (units)	Mean ± standard deviation
pH	8.0
Alkalinity (mg/L of $CaCO_3$)	554
Sulphate (mg/L)	1,475.25 ± 15.23
Cl (mg/L)	24 ± 0
Na (mg/L)	886.58 ± 36.77
Ca (mg/L)	70.35 ± 7.93
Mg (mg/L)	39.54 ± 1.87
K (mg/L)	9.94 ± 2.37
B (mg/L)	2.61 ± 1.34
Hg (mg/L)	2.43 ± 1.92
Sr (mg/L)	2.05 ± 0.09
Si (mg/L)	1.28 ± 0.78
Se (mg/L)	1.12 ± 1.65
P (mg/L)	1.03 ± 1.55
Al (mg/L)	0.55 ± 0.42
Zn (mg/L)	0.41 ± 0.72
Ba (mg/L)	0.20 ± 0.04
Cu (mg/L)	0.19 ± 0.05
Li (mg/L)	0.18 ± 0.02
Fe (mg/L)	0.06 ± 0.14
Ni (mg/L)	0.02 ± 0.15
Ti (mg/L)	0.017 ± 0.021
Be (mg/L)	0.017 ± 0.012
Mn (mg/L)	0.0094 ± 0.025
As (mg/L)	0.0014 ± 0.002
Cd (mg/L)	0.005 ± 1.07
Cr (mg/L)	BDL
V (mg/L)	BDL
Co (mg/L)	BDL
Pb (mg/L)	BDL
Mo (mg/L)	BDL

BDL means below detection limit

Optimization of the amount fly ash and lime required

Coal FA and NMD were reacted together using a liquid-to-solid ratio 6:1 and 5:1 in a jet loop reactor with jet sizes set at 8 mm. The 5:1 and 6:1 liquid-to-solid ratios could not overcome the pH barrier to achieve a pH greater than 11 after mixing for up to 120 min as shown in Fig. 1. The pH in NMD and FA mixture increased due to the dissolution of lime in FA.

$$CaO(s) + H_2O \rightarrow Ca^{2+} + 2OH^- \quad (6)$$

The pH above 11 was required so that $Al(OH)_3$ could be added to precipitate out sulphate as ettringite. Ettringite is more stable at pH 11.5–12.5; therefore, no $Al(OH)_3$ was added at this stage (Myneni et al. 1998).

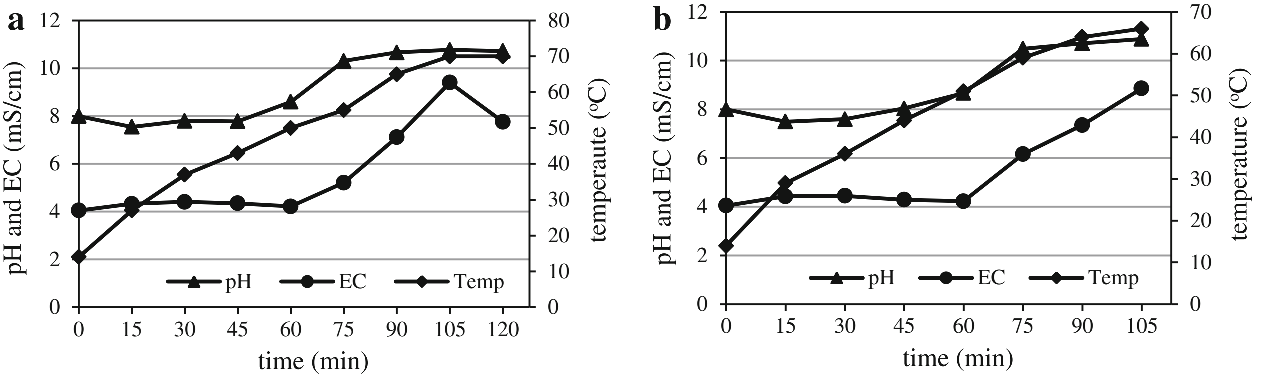


Fig. 1 The pH, electrical conductivity (EC) and temperature profile during the treatment of NMD (80 L) with FA in a jet loop reactor with jet sizes set at 8 mm [13 kg of FA (**a**) and 16 kg of FA (**b**)]

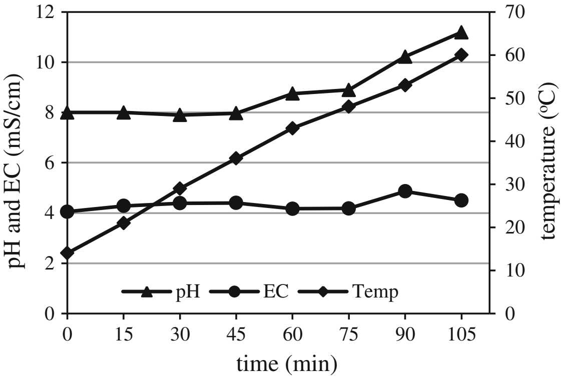


Fig. 2 The pH, electrical conductivity (EC) and temperature profile during the treatment of NMD (80 L) with 16 kg of FA in a jet reactor with jet sizes set at 6 mm

The jet nozzle sizes were changed from 8 mm to 6 mm in an attempt to increase the mixing intensity of coal FA and mine water through the increase in cavitation. This did not achieve a pH of greater than 11.5 as shown in Fig. 2.

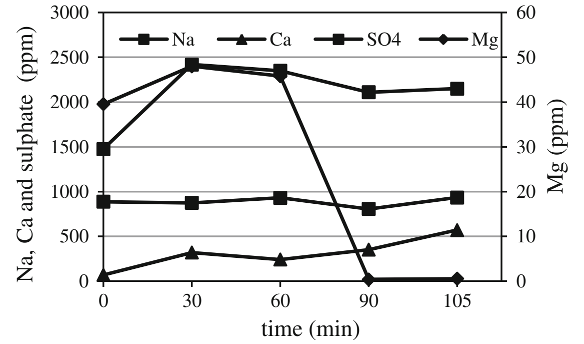


Fig. 4 Na, Ca, Mg and sulphate concentration during the treatment of NMD (80 L) with 16 kg of FA in a jet loop reactor with jet sizes set at 6 mm

The treatment of the mine water with coal FA in a jet loop reactor, with jet sizes set at 8 mm, is shown in Fig. 3. Results indicated that increasing the amount of FA from 13 to 16 kg did not show any increased performance in the cleanup of the mine water. Na concentration remained constant; Ca and sulphate

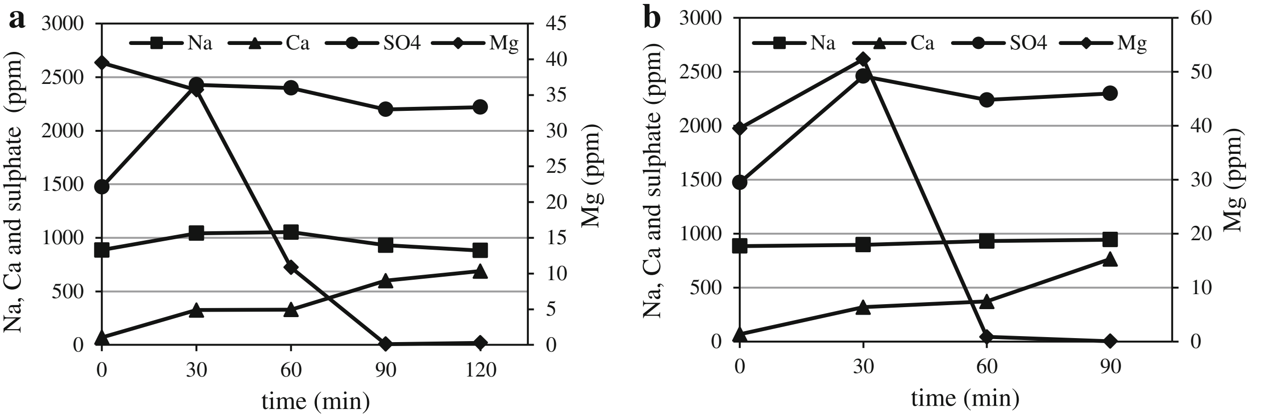


Fig. 3 Na, Ca, Mg and sulphate concentration during the treatment of NMD (80 L) with FA in a jet loop reactor with jet sizes set at 8 mm [13 kg of FA (**a**) and 16 kg of FA (**b**)]

concentration increased due to leaching from coal FA into the mine water. The concentration of Mg was decreased by almost 100 % when the pH of the mine water was increased to above 10. Magnesium is known to precipitate out as $Mg(OH)_2$ at pH greater than 11 according to Eq. 7 (Madzivire et al. 2011). The increase in the concentration of Ca and sulphate resulted in the increase in EC according to Eq. 6 (Fig. 1).

$$Mg^{2+} + 2OH^- \leftrightarrow Mg(OH)_2(s) \tag{7}$$

Changing the jet nozzle size to 6 mm and maintaining the amount of FA at 16 kg did not result in the significant difference from the results obtained using a jet size of 8 mm (Figs. 3b, 4). The Na concentration remained the same, while Ca and sulphate leached from FA into the water. The Mg concentration decreased by almost 100 % after the pH increased above than 10 after 60 min.

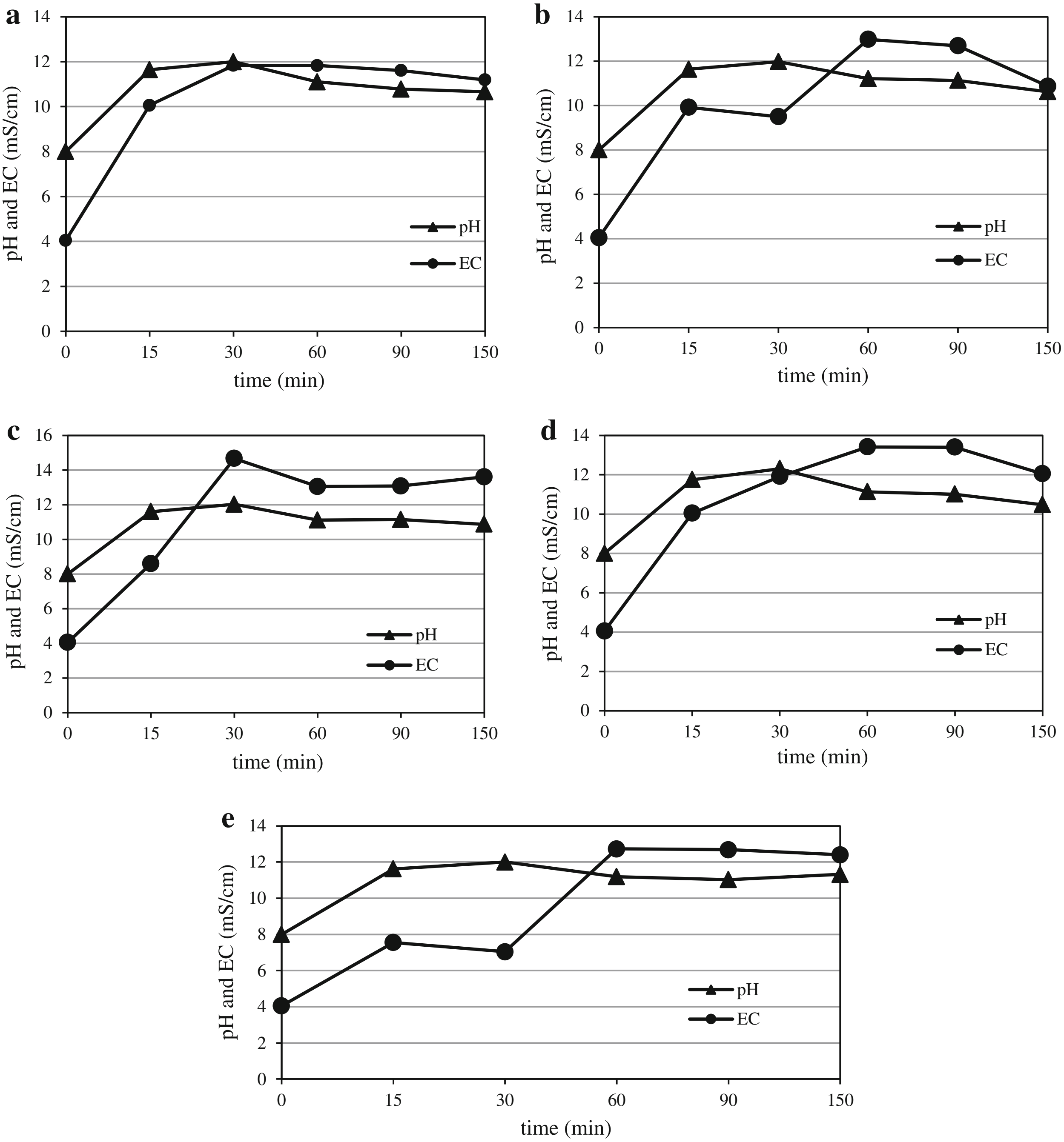


Fig. 5 pH and EC profiles during the treatment 500 mL of NMD with different amounts of 83 g of FA and 0.25 % lime (**a**), 0.5 % lime (**b**), 0.75 % lime (**c**), 1 % lime (**d**) or 1 % lime only (**e**) using an overhead stirrer

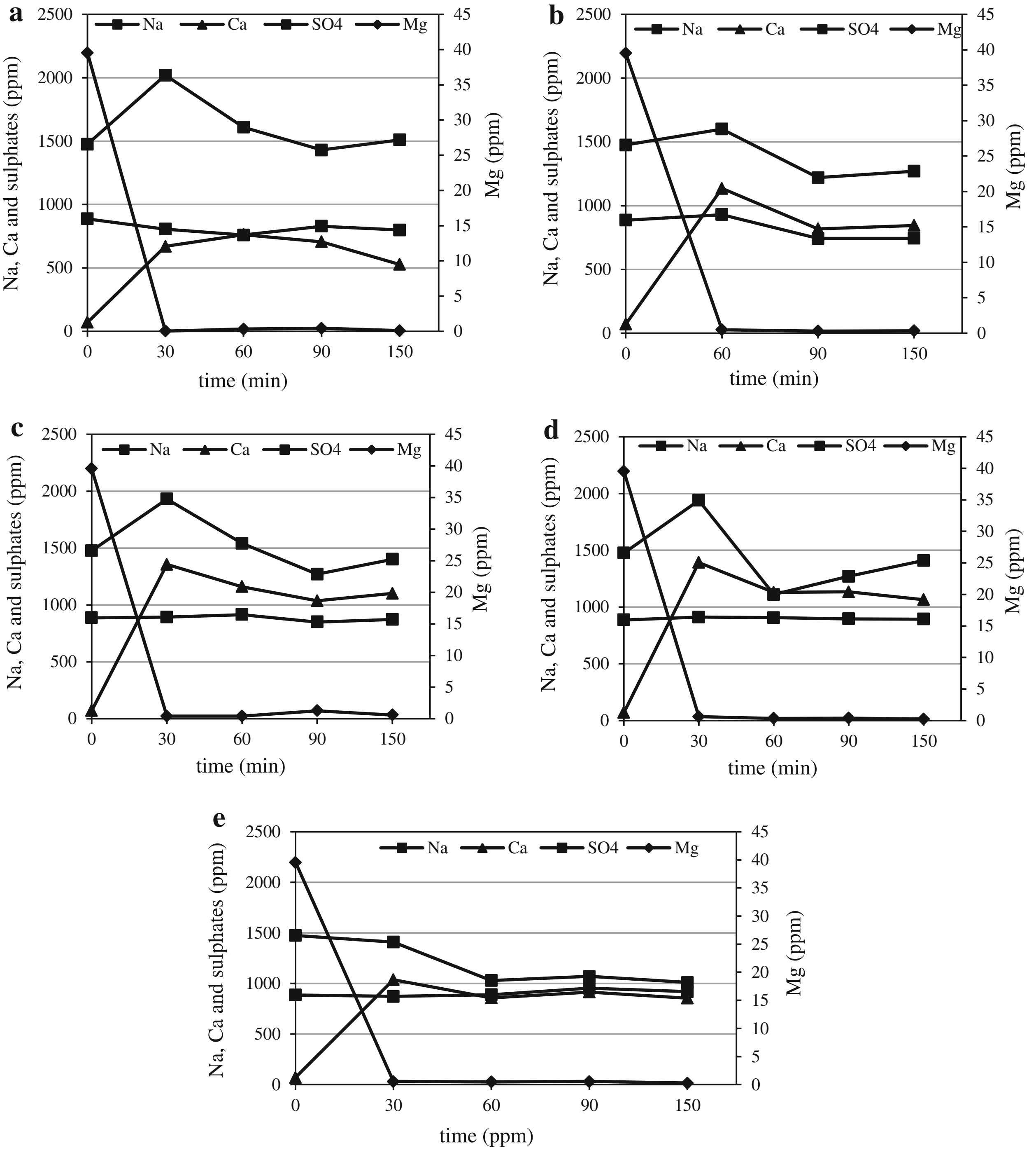


Fig. 6 Na, Ca and SO_4^{2-} concentrations during 500 mL of NMD treatment with different 83 g of FA and 0.25 % lime (**a**), 0.5 % lime (**b**), 0.75 % lime (**c**), 1 % lime (**d**) or 1 % lime only (**e**) using an overhead stirrer

$Al(OH)_3$ could not been added to precipitate sulphate as ettringite (Eq. 5), since the pH could not be taken up to greater than 11. Ettringite is more stable at pH 11.5–12.5 (Myneni et al. 1998). This prompted a series of bench-scale experiments to evaluate the minimum amount of lime together with coal FA that could be added in order to increase the pH to greater than 11.

Mine water (500 mL) was reacted with a combination of FA (83 g) and various amounts of lime. The amount of

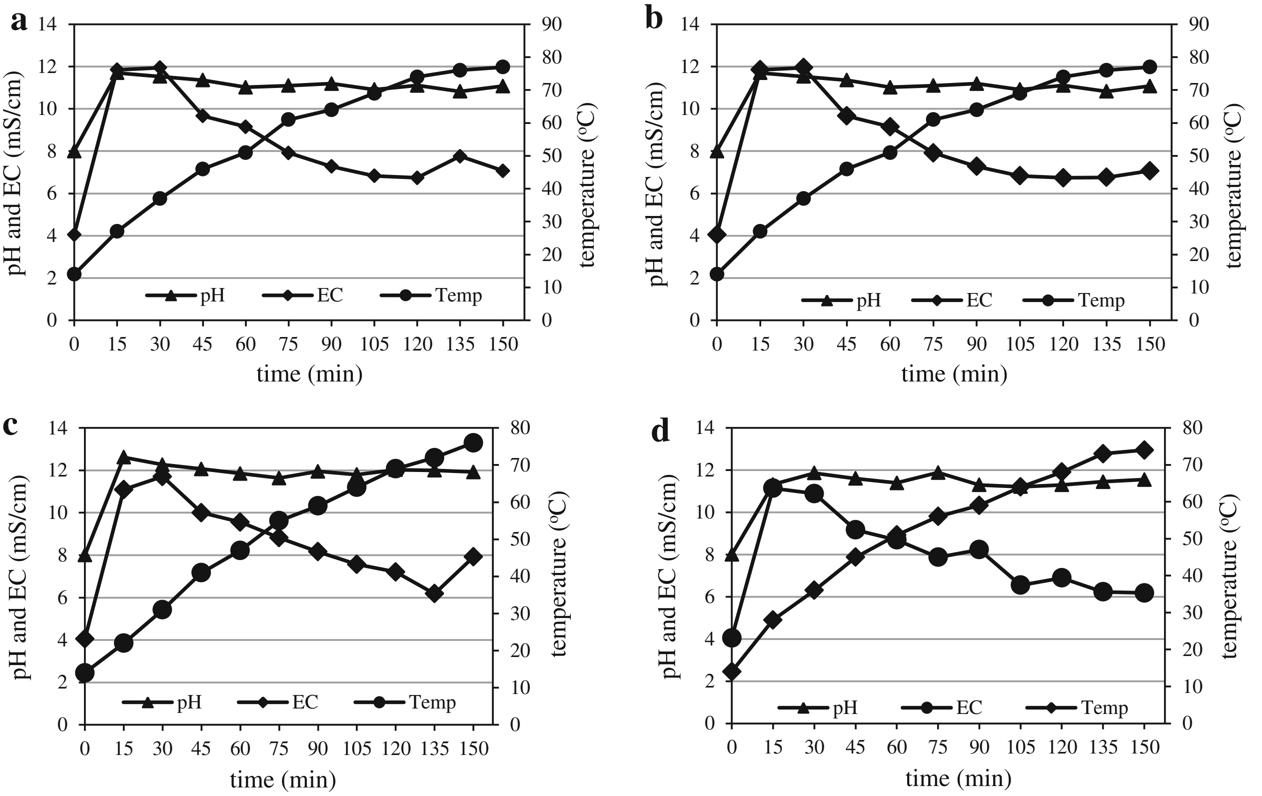


Fig. 7 pH, EC and temperature profiles during the treatment of NMD (80 L) with 13 kg of FA, 0.25 % (w/v) of lime and 83.2 g of $Al(OH)_3$ in a jet loop reactor with 6 mm (**a**), 8 mm (**b**), 10 mm (**c**) or 12 mm (**d**) jet sizes

lime was varied between 0.25 and 1 % lime (w/v), and the results obtained are shown in Fig. 5.

From the results shown in Fig. 5, pH greater than 11 for all the mixtures was attained after 15 min at which 0.52 g of $Al(OH)_3$ was then added to the mixture. After the addition of $Al(OH)_3$, the pH and EC showed a gradual increase.

Results obtained from the analysis of the product water (Fig. 6) showed that the Na concentration remained constant, and the sulphate and Ca ions concentration decreased slightly after addition of $Al(OH)_3$. Magnesium was removed in the first 30 min due to the formation of $Mg(OH)_2$ according to Eq. 7.

From the results of the bench-scale experiments (Fig. 6), the highest sulphate removal was noted in the case where 1 % lime only was used. This is because there were no sulphate ions that initially leached into the water from FA. In experiments where a combination of lime and FA was used, sulphate ions initially leached into the water from FA and then started precipitating after addition of $Al(OH)_3$ through the ettringite formation according to Eq. 5.

Optimization of the jet loop reactions

From the bench-scale experiments, it was found out that the combination of 0.25 % of lime and 83 g of coal FA can achieve a pH of greater than 11. The same experiments (using the same proportions of lime and FA to 80 L of mine water) were repeated using a jet loop reactor. The results obtained using a jet loop reactor with jet sizes 6, 8, 10 or 12 mm showed that pH increased to greater than 11 after mixing mine water with 13 kg of coal FA and 0.25 % of lime for 15 min as shown in Fig. 7. The temperature of the mixture increased gradually during mixing mine water with coal FA and lime in the jet loop reactor (Fig. 7a, b). The EC (Fig. 7) increased after addition of coal FA and lime due to the dissolution of CaO according to Eq. 6 and started to decrease after addition of $Al(OH)_3$ because of the precipitation of SO_4^{2-} as ettringite (Eq. 5).

The composition of the water recovered after treatment of NMD (80 L) with 13 kg FA and 0.25 % lime for 15 min followed by addition of 83.2 g of $Al(OH)_3$ is shown in Fig. 8. Sulphate concentration decreased from 1,465 mg/L to 400–500 mg/L due to the formation of ettringite (Eq. 5) after 120 min. The final concentration of SO_4^{2-} was within the limits set for Class II drinking water guidelines (DWAF 1996). The Na concentration remained constant, implying that there was no mineral phase that could precipitate and remove Na from the solution. Magnesium concentration decreased by almost 100 % after the first 15 min. Magnesium is known to be

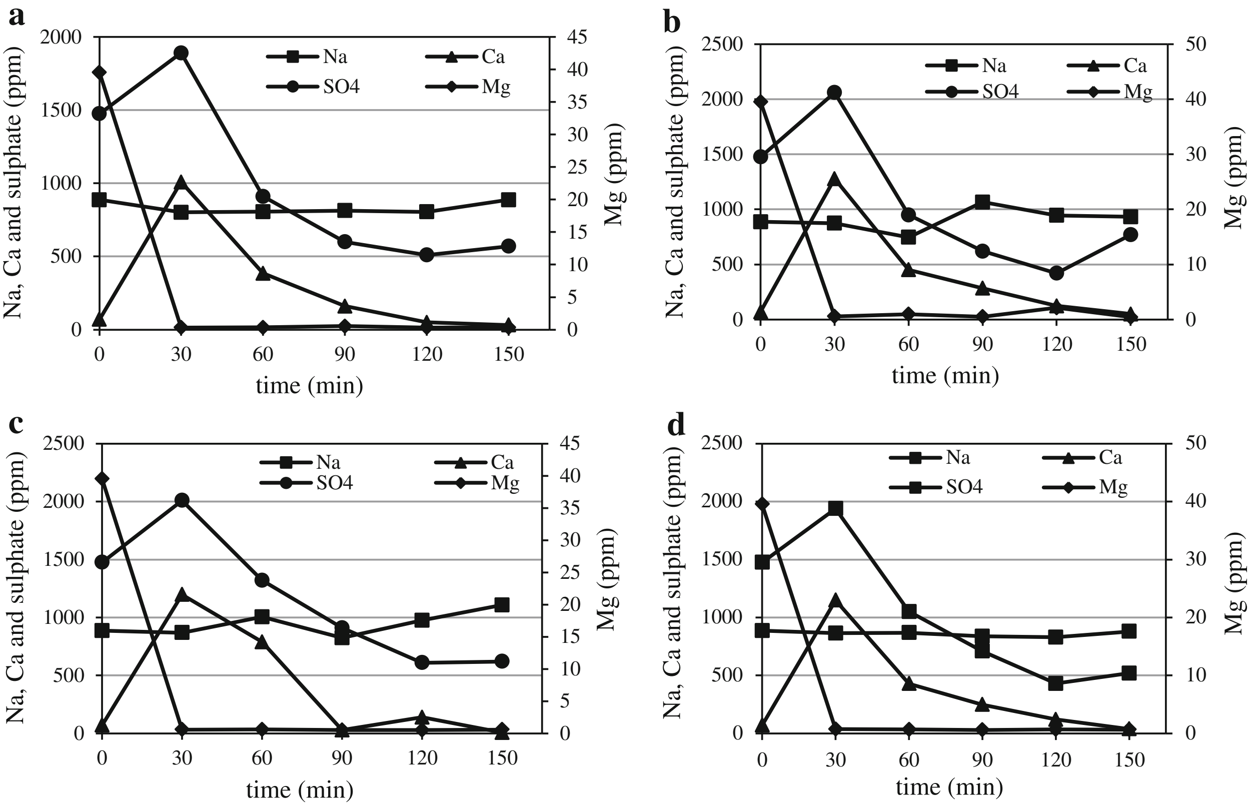
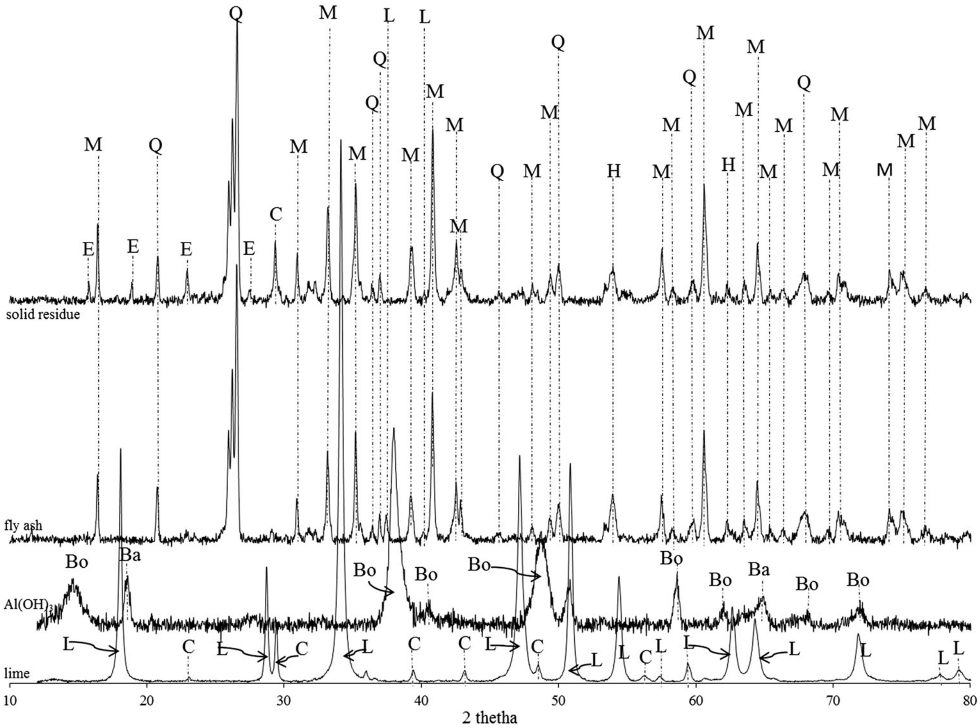


Fig. 8 Na, Ca and SO_4^{2-} concentrations during the treatment of NMD (80 L) with 13 kg of FA, 0.25 % (w/v) of lime and 83.2 g of $Al(OH)_3$ in a jet loop reactor with at 6 mm (**a**), 8 mm (**b**), 10 mm (**c**) or 12 mm (**d**) jet sizes

Fig. 9 XRD spectra of FA, $Al(OH)_3$, lime and residues after the treatment of NMD in a jet loop rector for 120 min (E, ettringite; L, lime; M, mullite; G, gypsum; Bo, boehmite; Ba, bayarite; C, $CaCO_3$, H, hematite; Q, quartz)



precipitated in the form of brucite, $Mg(OH)_2$ at pH greater than 11 according to Eq. 7.

As depicted in Fig. 8 above the concentration of Ca and sulphate increased during the initial 30 min. This was due to leaching of Ca and sulphate ions into water from the FA. After addition of $Al(OH)_3$, the Ca and sulphate concentration started decreasing due to the formation of ettringite according to Eq. 5. The kinetics of the removal of sulphate ions from mine water through the formation of ettringite was enhanced as compared to using an overhead stirrer. In the jet loop reactor, the reaction occurred faster due to the efficient mixing caused by hydrodynamic cavitation inside the reactor. Cavitation enhances rate of reaction due to intense micro-mixing of the reactants (Mason 2007).

XRD analysis of the solid residues recovered after treating NMD showed the disappearance of the lime and boehmite and bayerite peaks in the FA, lime and $Al(OH)_3$ spectra and the appearance of ettringite peaks in the solid residue collected after 120 min as shown in Fig. 9 below. The appearance of ettringite peaks in the XRD spectrum of FA after treating NMD proved that indeed sulphate and Ca concentration dropped due the formation of ettringite crystals according to Eq. 5.

Conclusion

From the results obtained, sulphate and Ca initially leached into the mine water from coal FA. After addition of $Al(OH)_3$ to the mixture, the concentration of sulphate and Ca started to decrease due to the precipitation of ettringite. Na remained almost constant during the treatment of mine water with fly ash, while the concentration of Mg decreased to approximately zero when pH was increased to greater than 10. Experiments conducted using an overhead stirrer has shown low sulphate removal compared to jet loop experiments. This is due to the increased rate of formation of ettringite caused by the superior mixing in a jet loop reactor compared to an overhead stirrer. Jet sizes did not have any effect on sulphate removal. Cavitation and impingement mixing of NMD and FA that occurred in the jet loop reactor resulted in a gradual increase in temperature of the mixture. These findings proved that the treatment of mine water with FA can be up-scaled from bench scale to 80 L pilot plant capacity using a jet loop reactor.

Acknowledgments This research was conducted as part of Ph.D. study in Chemistry at the University of the Western Cape and was funded by Water Research Commission and ESKOM (Grant Number: K5/2129). The jet loop reactor was designed by Georg Nieuwoudt of Biofuels in Stellenbosch University (www.biofuelson.co.za).

References

American Society for Testing and Materials (1994) Standard specification for fly ash and raw or calcined natural pozzolan for use as mineral admixture in Portland cement concrete. American Society for Testing and Materials, Pennsylvania

Banks D, Yonger PL, Arnesen RL, Egil R, Iversen ER, Banks SB (1997) Mine-water chemistry: the good, the bad and the ugly. Environ Geol 32(3):157–174

Department of Water Affairs and Forestry (1996) South African water quality, guidelines, 2nd edn. Volume 1: domestic use. CSIR Environmental Services, Pretoria

Gavi E, Marchisio DL, Barressi AL (2007) CFD modelling and scale-up of confined impinging jet reactors. Chem Eng Sci 62:2228–2241

Gitari MW, Petrik LF, Etchebers O, Key DL, Iwuoha E, Okujeni C (2006) Treatment of acid mine drainage with fly ash: removal of major contaminants and trace elements. J Environ Sci Health Part A Toxic/Hazard Subst Environ Eng 41:1729–1747

Kumar SP, Kumar MS, Pandit AB (2000) Experimental quantification of chemical effects of hydrodynamic cavitation. Chem Eng Sci 55:1633–1639

Labastida-Núñez I, Lázaro I, Celis LB, Razo-Flores E, Cruz R, Briones-Gallardo R (2013) Kinetic of biogenic sulfide production for microbial consortia isolated from soils with different bioaccessible concentrations of lead. Int J Environ Sci Tech 10(4):827–836

Lottermoser B (2007) Mine waters; characterization, treatment and environmental impacts, 2nd edn. Springer, New York, pp 83–100

Madzivire G, Petrik LF, Gitari WM, Ojumu TV, Balfour G (2010) Application of coal fly ash to circumneutral mine waters for the removal of sulphates as gypsum and ettringite. Miner Eng 23(3):252–257

Madzivire G, Gitari WM, Vadapalli VRK, Ojumu TV, Petrik LF (2011) Fate of sulphate removed during the treatment of circumneutral mine water and acid mine drainage with coal fly ash: modelling and experimental approach. Miner Eng 24(13):1467–1477

Mason TJ (2007) Review developments in ultrasound—non-medical. Prog Biophys Mol Biol 93:166–175

McCarthy GJ (1988) X-ray powder diffraction for studying the mineralogy of fly ash, In: Fly ash and coal conversion by-products: characterization, utilization and disposal IV. Mater Res Soc Symp Proc 75

Myneni SCB, Samuel J, Traina SJ, Logan TJ (1998) Ettringite solubility and geochemistry of the $Ca(OH)_2$–$Al_2(SO_4)_3$–H_2O system at 1 atm pressure and 298 K. Chem Geol 148:1–19

Petrik LF, White RA, Klink MJ, Somerset VS, Burgers CL, Fey M (2003) Utilization of South African fly ash to treat acid coal mine drainage, and production of high quality zeolites from the residual solids. In: Proceedings of the international ash utilization symposium. University of Kentucky, Centre of Applied Energy Research, pp 1–26

Potgieter-Vermaak SS, Potgieter JH, Monama P, Van Grieken R (2006) Comparison of limestone, dolomite and fly ash as pre-treatment agents for acid mine drainage. Miner Eng 19(5):454–462

Sin TS (2005) A comparative study on the jet loop reactor and continuos stirred tank reactor in the selective hydrogenation of palm olein. MSc. Dissertation, Faculty of Chemical and Natural Resources Engineering, Universiti Teknologi Malaysia

Vadapalli VRK, Klink MJ, Etchebers O, Petrik L, Gitari W, White RA, Key D, Iwuoha E (2008) Neutralization of acid mine drainage using fly ash, and strength development of the resulting solid residues. S Afr J Sci 104(7/8):317–322

Younger PL, Banwart SA, Hedin RS (2002) Mine water: hydrology, pollution. Dordrecht Kluwer Academic Publishers, Remediation