

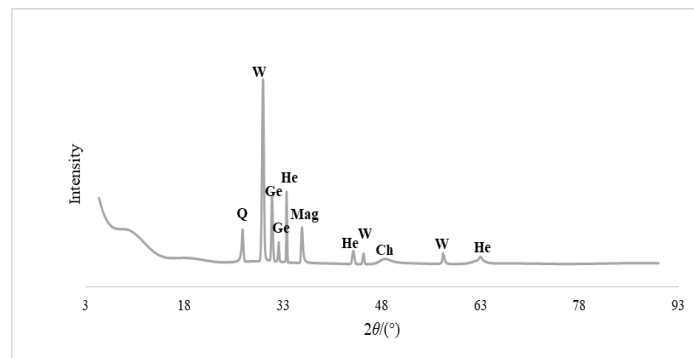
II. EXPERIMENTAL SETUP AND MODELLING

A. Materials

Similar tailings samples as was earlier characterized by Nyembwe et al [18] was used in this study. The samples were provided by the Phalaborwa Mining Company (PMC) and received from their Rio Tinto mine in Phalaborwa, RSA. Through XRF the chemical compositions of the major and trace minerals were exposed as available from Table I; the mineralogical content of the samples is presented in Fig. 1: Diffraction spectrum of tailings mineral

TABLE I: CHEMICAL/ELEMENTAL CHARACTERIZATION OF CARBONATITE TAILINGS MINERAL

| Bulk stream chemistry (XRF) | |
|-----------------------------|-----------------|
| Element | Composition (%) |
| Al | 1.63 |
| Ca | 47.5 |
| Cu | 0.47 |
| Fe | 32.6 |
| Mg | 6.38 |
| P | 2.47 |
| Si | 5.18 |
| Sr | 1.08 |



Ch: chalcopyrite (0.47wt %); Ge: Gehlenite (5.78wt %) H: hematite (10.07%); Mag: Magnetite; Q: quartz (12wt %); W: Calcite magnesium carbonate (73wt %)

Fig. 1: Diffraction spectrum of tailings mineral

B. Chemical leaching

For the purpose of leaching the carbonatite tailings mineral samples, an incubator with a built in orbital shaker was used. The incubator acted as a containment chamber used to prevent contamination of the solutions during experimentation as well as to keep both the temperature and rotational speed (200 rpm) stable. 500 mL volumetric flasks were used to prepare a 10% mass by volume solution; the liquid solution was prepared using distilled water, sulphuric acid and ferric sulphate to produce a ferric sulphate solution of 0.1 M [6]. Rotational speed for the orbital shaker was stable at 200 rpm whilst temperature was set to 25°C. Each of the solutions was prepared at a pH value of 0.5-1 after which pH evolution was allowed to occur over the course of the 12 hours leaching test. The dissolution kinetic information was obtained as 30 mL sample was withdrawn from the leaching vessel hourly and was analysed for its dissolved metal content using inductively coupled plasma optical emission spectroscopy (ICP-OES). Prior to that, the withdrawn

slurry was filtered using 150 mm filtration paper. Lastly the filtered residue was then dried, stored in a desiccator and were subjected to mineralogical and chemical characterization using X-ray diffraction (XRD) and X-ray fluorescence (XRF) as previously described [19-40].

C. Leachate analyses

Leachate samples obtained after leaching chalcopyrite solutions were characterized by measuring pH, oxidation redox potential (ORP) and temperature. For the measurements of pH, temperature and ORP (for each leachate solution) a portable pH meter with an analytical electrode HI8424 (Hanna Instruments Inc.) was used. Samples were also measured for acidity, alkalinity, chloride ion concentration, sulphate ion concentration. For sulphate ion measurements, a COD and Multiparameter Photometer HI 83099 was used.

D. Titration tests

The alkalinity was measured through titration method with 0.1N sulphuric acid (H_2SO_4) where the solution was titrated from pH values lower than 8.3 to 4.5 using an indicator for clear endpoint visibility. The acidity was measured through titration method with 0.02N sodium hydroxide (NaOH) where 0.02N sodium carbonate (Na_2CO_3) was used as standardization procedure. For chloride ion concentration, titration was conducted using silver nitrate ($AgNO_3$) and potassium dichromate (K_2CrO_4) as indicator [41].

E. Speciation modelling

To determine the aqueous speciation of the major metal ions in the leachate of the carbonatitic tailings, AQUACHEM software was used interfaced with PHREEQC (program version 3.3.12-12704.) modelling software [5][41]. The phreeqc database, Minteq.v4.dat was used for the purpose of this report. The ORP had to be adjusted with a correction factor before it could be used as input data. The correction factor was obtained from Field Measurements of Oxidation-Reduction Potential [42]. The corrected ORP value was then used to calculate the pe value using the following equation:

$$pe = E_h / (0.059) \quad (1)$$

pe donates the negative logarithm of the electron activity.

Eh donates the oxidation redox potential of the sample.

To predict the speciation of the major metals present within the leachate of the chalcopyrite bearing minerals the following input data was used within the phreeqc workbench interface: Acidity, alkalinity, pH, pe, temperature (°C), ICP data (metal ion concentrations), Cl^- and SO_4^{2-} .

III. RESULTS & DISCUSSION

A. pH variation

Fig. 2: pH behavior of tailings samples at varying time

displays the pH evolution of the carbonatite tailings samples at room temperature conditions:

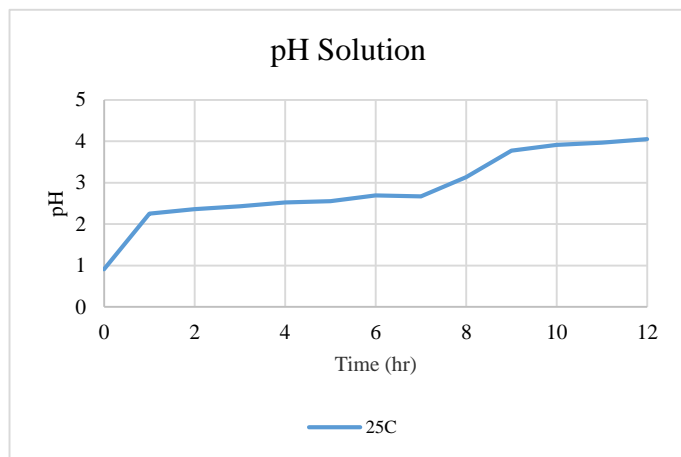


Fig. 2: pH behavior of tailings samples at varying time

The evolution during experimentation under room temperature conditions (25°C) was generally acidic but observed to gradually increase during the set leaching time as higher concentration of Ca is released in solution. The tailings is mainly constituted of calcite magnesium (Fig. 1: Diffraction spectrum of tailings mineral

); Ca is used to reduce soil acidity as Ca^{2+} ions reduce H^+ ions in solution which neutralized the solution pH [43]. The same effect are assumed to occur during mineral dissolution as the high Ca content (Table I) releases Ca^{2+} ions leading to the observed pH evolution phenomena. Acid attack plays a vital role during the early stages of leaching at room temperature conditions as the formation of calcium salt (CaSO_4) is believed to occur due to the high H_2SO_4 concentrations at these conditions [44]. Insoluble salt species of Ca is therefore likely the dominant mineral species at the early stages of leaching (first 4 hours) which aids in stabilizing acidic conditions.

B. Extraction behavior at room temperature

Fig. 3 displays the recovery rate of Cu and Fe during leaching in sulphate solution using ferric sulphate. After the set leaching time of 12 hours, extraction rate of 5.55% Cu from the mineral surface was obtained. Rapid Cu withdrawal was observed during the first 2 hours of leaching which can be attributed to the acidic pH conditions observed at this time, where the effects of acid attack on Ca in solution are the highest. The peak extraction rate of 16.58% was observed after 4 hours dissolution as the pH conditions were favorable at this time; this agrees with previous findings according to which the dissolution of CuFeS_2 is identified as an acid consuming reaction [45]. The recovery of Cu is reduced after 6 hours dissolution with increasing pH conditions likely due to higher concentration of Ca^{2+} ions cumulating in solution. From the graph no plateau stage is observed indicating that, although the rate of mineral dissolution displays retarding behavior, mineral passivation has not yet been reached.

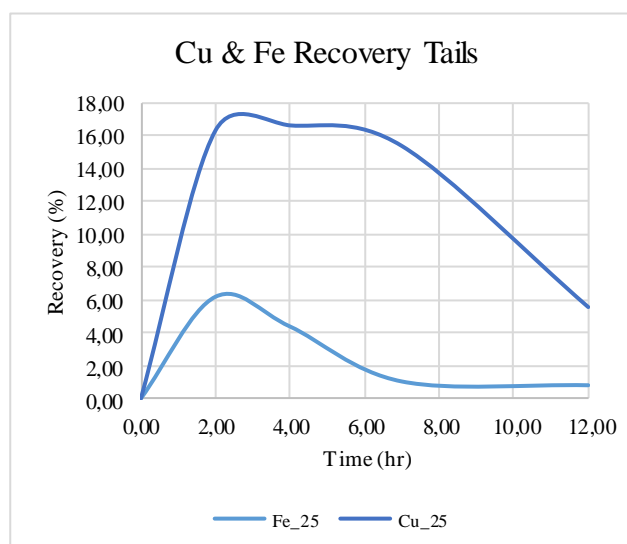


Fig. 3: Recovery of Cu & Fe during mineral dissolution

Fe extraction was also influenced by an increase in the pH conditions. Fe displays similar behavior to that of Cu indicating that during acid attack of hematite (the main constituent of Fe in the carbonatite tails solutions), Fe is more likely to form ferrous iron (Fe^{2+}). From previous studies it was observed that Fe is preferentially released in solution [46] before Cu as Fe^{2+} ions compete with Cu^{2+} ions; competition of Cu with Fe could reduce the concentration of soluble species in solution which contributes to the observed extraction behavior.

C. Speciation results

Table II displays the speciation results for the tailings samples obtained using phreeqc simulation software and were accurately predicted within a 10% error threshold:

TABLE II: CARBONATITE TAILINGS STREAM SPECIATION RESULTS

| Element | Species | Carbonate tailings (%) | | | |
|--------------|--------------------|------------------------|---------|---------|---------|
| | | 120 min | 240 min | 420 min | 720 min |
| Ca | CaSO_4 | 53.28 | 52.00 | 50.42 | 50.52 |
| | Ca^{2+} | 46.74 | 48.03 | 49.61 | 49.46 |
| | CaOH^+ | <1 | <1 | <1 | <1 |
| Cu(2) | CuSO_4 | 50.73 | 50.59 | 52.16 | 53.43 |
| | Cu^{2+} | 49.27 | 49.41 | 47.87 | 46.55 |
| | CuOH^+ | <1 | <1 | <1 | 1 |
| Fe(2) | Fe^{2+} | 70.34 | 69.43 | 68.23 | 67.61 |
| | FeSO_4 | 29.66 | 30.59 | 31.77 | 32.39 |
| | FeHCO_3^+ | <1 | <1 | <1 | <1 |
| | + | | | | |

As seen from Table II, a reduction in the formation of calcium salt species (CaSO_4) along with an increase in calcium ion (Ca^{2+}) occurs over the course of the leaching period (12 hours), evident from the pH evolution behavior (Fig. 2) as higher concentrations of Ca^{2+} free hydrated ionic species compete with hydrogen ion to stabilize solution pH [46]. The

speciation data for Cu species also agree with the observed recovery behavior (Fig. 3) where the highest concentration of soluble free hydrated cupric ions (Cu^{2+}) were the greatest after 4 hours of leaching and observed to reduce as leaching progressed; additionally an increase in insoluble Cu salt species (CuSO_4) were promoted as leaching progressed together with an increase in pH conditions. Higher concentrations of soluble ferrous ion (Fe^{2+}) species was available but identified as reducing in concentration over the set leaching time as higher concentrations of insoluble Fe salts (FeSO_4) formed

D. Mineralogical investigation of solid residue

The mineral content for the tailings residue samples for the complete leaching period at room temperature conditions is displayed in Fig. 4 with mineral content summarized in Table III:

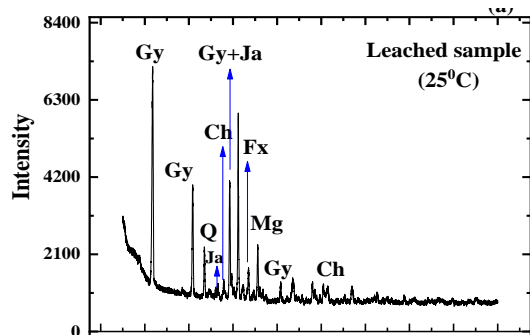


Fig. 4: Diffraction spectrum of tailings residue at 25°C

Progressive dissolution of the CuFeS_2 mineral from the carbonatite tailings host ore was observed for the measured temperature conditions as a decrease in major peak intensity was observed from the initial feed indicating that mineral dissolution had occurred [47][52]. Additionally, new mineral phase formation of Cu species was identified during the course of the leaching period; these intermediate phases being bornite, chalcocite and covelite. Iron mineral phases of hematite (He), magnetite (Mg) and jarosite (Ja), linked to the dissolution media, were also formed during chemical leaching of the tailings mineral; furthermore, precipitates of gypsum, associated with the carbonatite hosting ore, was also observed.

TABLE III: MINERAL COMPOSITION OF CARBONATITE TAILINGS RESIDUE SAMPLES

| Mineral phase | Chemical composition | Mineral Concentration (%) | |
|---------------|---|---------------------------|-------|
| | | 25°C | Feed |
| Bo | Cu_5FeS_4 | 0,09 | *** |
| Ch | CuFeS_2 | 0,58 | 0.88 |
| Cx | Cu_2S | 0,29 | *** |
| Co | CuS | 0,90 | *** |
| Gy | $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ | 63,30 | *** |
| He | Fe_2O_3 | 1,06 | 10.4 |
| Ja | $\text{XFe}^{3+}_3(\text{OH})_6(\text{SO}_4)_2$ | 4,96 | *** |
| Mg | Fe_3O_4 | 10,78 | *** |
| Q | SiO_2 | 16,99 | 12.00 |

IV. CONCLUSION

The purpose of this study was to observe the dissolution kinetics of the tailings stream minerals with particular focus on the effects of mineralogical composition of the new formed phases from concentration of the Rom material on the leaching kinetics. The major compositional mineral (calcite-magnesium [73wt%]) from the host ore had a big impact on the leaching kinetics as the speciation prediction showed an increase in free hydrated calcium ion (Ca^{2+}) which reduced the solution acidity as these ions compete with H^+ for dissolution. As concentration of Ca increases, the formation of gypsum at these conditions are further promoted. The reduction in potential and increase in pH also further promoted the formations of ferric salt species during the course of the set leaching period. At these conditions, the dissolution of Cu could be hindered as the surface of the mineral is enclosed by a matrix mixture of gypsum and jarosite that impedes the transfer of ions from the surface of the mineral.

ACKNOWLEDGEMENTS

The authors are thankful to the support from the North-West University, and the laboratory assistance of Mr N Lemmer from the North-West University as well as Ms N Baloyi from the University of Johannesburg.

REFERENCES

- J. Schaming, "An Investigation of Leaching Chalcopyrite Ores," Kingston, 2011.
- M. Sokic, B. Markovic and D. Zivkovic, "Kinetics of chalcopyrite leaching by sodium nitrat in sulphuric acid," *Hydrometallurgy*, no. 95, pp. 273-279, 2009.
<https://doi.org/10.1016/j.hydromet.2008.06.012>
- M. Khoshkhoo, "Chalcopyrite Disolution in Sulphate-Based Leaching and Bioleaching Systems," 2014.
- M. Stott, H. Watling and P. Franzmann, "The role of iron-hydroxy precipitates in the passivation of chalcopyrite during bioleaching," *Minerals Engineering*, vol. 13, no. 10, pp. 1117-1127, 2000.
[https://doi.org/10.1016/S0892-6875\(00\)00095-9](https://doi.org/10.1016/S0892-6875(00)00095-9)
- B. Barlow, K. Nyembwe, E. Fosso-Kankeu and F. Wanders, "Prediction of Dissolution of Copper from a Chalcopyrite Carbonatite Ore of South Africa," CapeTown, 2018.
- E. Cordoba, J. Munoz, M. Blazquez and A. Ballester, "Leaching of chalcopyrite with ferric opn Part I: General Aspects," *Hydrometallurgy*, no. 93, pp. 81-87, 2008.
<https://doi.org/10.1016/j.hydromet.2008.04.015>
- Y. Li, N. Kawashima, J. Li, A. Chandra and A. Gerson, "A Review of the Structure, Fundamental Mechanisms and Kinetics of the Leaching of Chalcopyrite," 2013.
<https://doi.org/10.1016/j.cis.2013.03.004>
- Biegler, I. & Swift, D., 1979. Anodic electrochemistry of chalcopyrite. *Journal of Applied Electrochemistry*, Volume 9, pp. 545-554.
<https://doi.org/10.1007/BF00610940>
- Peterson, J. & Dixon, D., 2006. Competitive bioleaching of pyrite and chalcopyrite. *Hydrometallurgy*, Issue 83, pp. 40-49.
<https://doi.org/10.1016/j.hydromet.2006.03.036>
- Gomez, C. et al., 1996. Electrochemistry of chalcopyrite. *Hydrometallurgy*, Volume 43, pp. 331-344.
[https://doi.org/10.1016/0304-386X\(96\)00010-2](https://doi.org/10.1016/0304-386X(96)00010-2)
- Tshilombo, A., 2004. Mechanism and kinetics of chalcopyrite passivation and depassivation during ferric and microbial leaching, s.l.: s.n.
- Hackl, R., Dreisinger, D., Peters, E. & King, J., 1995. Passivation of chalcopyrite during oxidative leaching in sulfate media. *Hydrometallurgy*, Issue 39, pp. 25-48.
[https://doi.org/10.1016/0304-386X\(95\)00023-A](https://doi.org/10.1016/0304-386X(95)00023-A)

- [13] Antonijevic, M. & Bogdanovic, G., 2004. Investigation of the leaching of chalcopyrite ore in acidic solutions. *Hydrometallurgy*, Volume 73, pp. 245-256.
<https://doi.org/10.1016/j.hydromet.2003.11.003>
- [14] Acero, P., J.Cama, Ayora, C. & Asta, M., 2009. Chalcopyrite dissolution rate law from pH 1 to 3. *Geologica Acta*, 7(3), pp. 389-397.
- [15] Simandl, G. & Paradis, S., 2018. Carbonatites: related ore deposits, resources, footprint, and exploration methods. *Applied Earth Science*, 127(4), pp. 123-152.
<https://doi.org/10.1080/25726838.2018.1516935>
- [16] Heinrich, E., 1970. The Phalaborwa Carbonatitic Complex: A Unique Copper Deposit, s.l.: s.n.
- [17] V. Gorbachev, V. Abzalov and B. Yur'ev, "Conversion of magnetite to hematite in iron-ore pellets," *Steel in Translation*, vol. 37, p. 27, 2007.
<https://doi.org/10.3103/S0967091207040031>
- [18] K. Nyembwe, E. Fosso-Kankeu, F. Waanders and K. Nyembwe, "Structural, composition and mineralogical characterization of carbonatitic copper sulfide: Run of mine, concentrate and tailings," *International Journal of Minerals, Metallurgy and Materials*, vol. 26, no. 2, pp. 143-151, 2019.
<https://doi.org/10.1007/s12613-019-1718-8>
- [19] Fosso-Kankeu E., Potgieter J. and Waanders F.B. 2019. Removal of malachite green and toluidine blue dyes from aqueous solution using a clay-biochar composite of bentonite and sweet sorghum bagasse. *International Journal of Applied Engineering Research*. 14(6): 1324-1333.
- [20] Johannes Cornelius van der Linde, Elvis Fosso-Kankeu, Gerhard Gericke, Frans Waanders, Louise Dreyer, Nico Lemmer. 2019. Flocculant types and operating conditions influencing particles settling rates in feed water used at a coal power plant. *Desalination and Water Treatment*. 150: 293-300.
<https://doi.org/10.5004/dwt.2019.23735>
- [21] Assumpta Chinwe Nwanya, Miranda M. Ndingwi, Noluthando Mayedwaa, LC Razanamahandry, Chinwe O Ikpo, Tesfaye Waryo, SKO Ntwampe, E Malenga, E Fosso-Kankeu, Fabian I Ezema, Emmanuel I Iwuoha, Malik Maaza. 2019. Maize (*Zea mays* L.) fresh husk mediated biosynthesis of copper oxides: Potentials for pseudo capacitive energy storage. *Electrochimica Acta*. 301: 436-448.
<https://doi.org/10.1016/j.electacta.2019.01.186>
- [22] LC Razanamahandry, CT Onwordi, W Saban, AKH Bashir, L Mekuto, E Malenga, E Manikandan, E Fosso-Kankeu, M Maaza, SKO Ntwampe. 2019. Performance of various cyanide degrading bacteria on the biodegradation of free cyanide in water. *Journal of Hazardous Materials*. 380: 1-6.
<https://doi.org/10.1016/j.jhazmat.2019.120900>
- [23] E. Fosso-Kankeu, A. Mulaba-Bafubiandi, B.B. Mamba, T.G. Barnard, Assessing the effectiveness of a biological recovery of nickel from tailings dumps. *Journal of Minerals Engineering*. Vol. 24, pp. 470-472, 2011.
<https://doi.org/10.1016/j.mineng.2010.11.007>
- [24] E. Fosso-Kankeu, T.L. Netshitanini, A.L.K. Abia, E. Ubomba-Jaswa, F.B. Waanders, Application of solar treatment for the disinfection of geophagic clays from markets and mining sites. *African Journal of Biotechnology*. Vol. 14, no. 50, pp. 3313-3324, 2015.
<https://doi.org/10.5897/AJB2015.14971>
- [25] E. Fosso-Kankeu, F. Waanders, C.L. Fourie, Adsorption of Congo Red by surfactant-impregnated bentonite clay. *Desalination and Water Treatment*. doi: 10.1080/19443994.2016.1177599: pp. 1-9, 2016.
- [26] A.H. Munyai, E. Fosso-Kankeu, F. Waanders, Biological influence on the mobility of metals from mine tailing dump located in Krugersdorp area. *International Journal of Science and Research*. ISSN: 2319-7064. Vol. 5, no. 4, pp. 1396-1403, 2016.
<https://doi.org/10.21275/v5i4.NOV162808>
- [27] T.L. Netshitanini, E. Fosso-Kankeu, F. Waanders, E. Ubomba-Joswa, A.L.K. Abia, Co-effect of leached metals and pH of simulated gastric fluid on the survival of microorganisms in geophagic clays. *International Journal of Science and Research*. ISSN: 2319-7064. Vol. 5, no. 4, pp. 1107-1116, 2016.
<https://doi.org/10.21275/v5i4.NOV162696>
- [28] E. Fosso-Kankeu, F. Waanders, M. Geldenhuys, Impact of nanoparticles shape and dye property on the photocatalytic degradation activity of TiO₂. *International Journal of Science and Research*. Vol. 5, no. 11, pp. 528 – 535, 2016.
- [29] A.H. Munyai, E. Fosso-Kankeu, F. Waanders, Mobility of metals from mine tailings using different types of organic acids: Batch leaching experiment. *International Journal of Science and Research*. Vol. 5, pp. 520-527, 2016.
- [30] E. Fosso-Kankeu, A. Manyatshe, F. Waanders, Mobility potential of metals in acid mine drainage occurring in the Highveld area of Mpumalanga Province in South Africa: Implication of sediments and efflorescent crusts. *International Biodeterioration and Biodegradation*. Vol. 119, pp. 661-670, 2017.
<https://doi.org/10.1016/j.ibiod.2016.09.018>
- [31] E. Fosso-Kankeu, F.B. Waanders, F.W. Steyn, Removal of Cr(VI) and Zn(II) from an aqueous solution using an organic-inorganic composite of bentonite-biochar-hematite. *Desalination and Water Treatment*. Vol. 59, pp. 144-153, 2017.
<https://doi.org/10.5004/dwt.2017.0059>
- [32] E. Fosso-Kankeu, F. Waanders, A.F. Mulaba-Bafubiandi and S. Sidu, Leachability of suspended particles in mine water and risk of water contamination. 10th ICARD/IMWA 2015; 10th International Conference on Acid Rock Drainage & IMWA Annual Conference. 21-24 April 2015 Santiago-Chile. Editors: Adrian Brown, Charles Bucknam, Joanna Burgess, Manuel Carballo, Devin Castendyk, Linda Figueroa, Lisa Kirk, Virginia McLemore, James McPhee, Mike O'Kane, Robert Seal, Jacques Wiertz, David Williams, Ward Wilson, Christian Wolkersdorfer. ISBN: 978-956-9393-28-0. Chap 4. Pp 1-9. 2015.
- [33] E. Fosso-Kankeu, F.B. Waanders, and A.H. Munyai, Susceptibility of Metals Release from Tailings Dumps Located in the Krugersdorp Area. 7th International Conference on Latest Trends in Engineering and Technology (ICLTET' 2015), November 26-27, 2015 Irene, Pretoria (South Africa). Editors: E. Muzenda and T Yingthawornsuk. ISBN: 978-93-84422-58-5. 2015.
- [34] E. Fosso-Kankeu, F. Waanders, and C. Laurette Fourie, Surfactant Impregnated Bentonite Clay for the Adsorption of Anionic Dyes. 7th International Conference on Latest Trends in Engineering and Technology (ICLTET' 2015), November 26-27, 2015 Irene, Pretoria (South Africa). Editors: E. Muzenda and T Yingthawornsuk. ISBN: 978-93-84422-58-5. 2015.
- [35] E. Fosso-Kankeu, F.B. Waanders, F.W. Steyn, The Preparation and Characterization of Clay-Biochar Composites for the Removal of Metal Pollutants. 7th International Conference on Latest Trends in Engineering and Technology (ICLTET' 2015), November 26-27, 2015 Irene, Pretoria (South Africa). Editors: E. Muzenda and T Yingthawornsuk. ISBN: 978-93-84422-58-5. 2015.
- [36] E. Fosso-Kankeu, F. Waanders, and M. Geldenhuys, Photocatalytic Degradation of Dyes using TiO₂ Nanoparticles of Different Shapes. 7th International Conference on Latest Trends in Engineering and Technology (ICLTET' 2015), November 26-27, 2015 Irene, Pretoria (South Africa). **Award Winning Paper**. Editors: E. Muzenda and T Yingthawornsuk. ISBN: 978-93-84422-58-5. 2015.
- [37] E. Fosso-Kankeu, F. Waanders, T.L. Netshitanini, E. Ubomba-Jaswa, and K. Abia, Identification of Metals in Geophagic Clays: Investigation of their Behaviour in Simulated Gastric Fluid. 7th International Conference on Latest Trends in Engineering and Technology (ICLTET' 2015), November 26-27, 2015 Irene, Pretoria (South Africa). Editors: E. Muzenda and T Yingthawornsuk. ISBN: 978-93-84422-58-5. 2015.
- [38] E. Fosso-Kankeu, F. Waanders, and W. Botes, Recovery of Base Metals from Mine Tailings Dumps collected in the Vicinity of Potchefstroom: Leaching assisted by Complexing Agent. 7th International Conference on Latest Trends in Engineering and Technology (ICLTET' 2015), November 26-27, 2015 Irene, Pretoria (South Africa). Editors: E. Muzenda and T Yingthawornsuk. ISBN: 978-93-84422-58-5. 2015.
- [39] Elvis Fosso-Kankeu, Charl Olivier, Dumisane Moyakhe, Brad Barlow, Quentin Campbell and Frans Waanders. 2018. Effect of fine coal tailing porosity on the mobility and speciation of heavy metals in the leachates. Editors: Elvis Fosso-Kankeu, Frans Waanders, Michel Plaisent. 10th Int'l Conference on Advances in Science, Engineering, Technology & Healthcare (ASETH-18) Nov. 19-20, 2018 Cape Town (South Africa). ISBN: 978-81-938365-2-1. Vol I. Pp 101-105.
- [40] Fosso-Kankeu Elvis and Redelinghuys Johannes. 2018. Bacterial ecology of biofilms sustaining pollution by acid mine drainage near mining areas in Mpumalanga Province – South Africa. 11th ICARD/IMWA/MWD

- Conference "Risk to Opportunity". 10-14 September 2018 Pretoria, South Africa. C. Wolkersdorfer, L. Sartz, A. Weber, J. Burgess, G. Tremblay. ISBN: 978-0-620-80650-3 Vol 1 (2 volumes).
- [41] B. Barlow, E. Fosso-Kankeu, N. Lemmer and F. Waanders, "Geochemical Speciation of Metal ions in the Leachate of Tailings Treated with Synthetic Rain Water," Parys, 2017
- [42] B. Stiggov, "Field Measurements of Oxidation-Reduction Potential (ORP)," 2013.
- [43] J. E. Lamar, "Uses of Limestone and Dolomite," Urbana, 1961.
- [44] K. Scrivener, "Calcium Aluminate Cements," in *Lea's Chemistry of Cement and Concrete*, 1998, pp. 713-782.
<https://doi.org/10.1016/B978-075066256-7/50025-4>
- [45] P. Acero, J. Cama, C. Ayora and M. Asta, "Chalcopyrite dissolution rate law from pH 1 to 3," *Geologica Acta*, vol. 7, no. 3, pp. 389-397, 2009.
- [46] D. Lu, W. Wang, Y. Chang, F. Xie and K. Jiang, "Thermodynamic Analysis of Possible Chalcopyrite Dissolution Mechanism in Sulphuric Acidic Aqueous Solution," *Metals*, vol. 6, p. 303, 2016
<https://doi.org/10.3390/met6120303>
- [47] A. Santos, F. Arena, A. Benedetti and D. Bevilacqua, "Effect of redox potential on chalcopyrite dissolution imposed by addition of ferrous ions," *Eletica Quimica Journal*, vol. 42, pp. 40-50, 2017.
<https://doi.org/10.26850/1678-4618eqj.v42.1.2017.p40-50>
- [48] A. Manyatshe, E. Fosso-Kankeu, D. van der Berg, N. Lemmer, F. Waanders, H. Tutu, Metal retention potential of sediment and water quality in the Mooi River, South Africa. *Desalination and Water Treatment*. doi: 10.5004/dwt2017.20222. 2017.
- [49] A. Manyatshe, E. Fosso-Kankeu, D. van der Berg, N. Lemmer, F. Waanders, H. Tutu, Dispersion of inorganic contaminants in surface water in the vicinity of Potchefstroom. *Physics and Chemistry of the Earth*. Vol. 100, pp. 86-93, 2017.
<https://doi.org/10.1016/j.pce.2017.04.008>
- [50] A. Manyatshe, E. Fosso-Kankeu, D. van der Berg, N. Lemmer, F. Waanders, H. Tutu, Metal speciation in the rivers around Potchefstroom based on seasonality. *Water Environment Research*. Vol. 90, no. 1, pp. 84-95, 2018.
<https://doi.org/10.2175/106143017X15054988926587>
- [51] A. Manyatshe, E. Fosso-Kankeu, D. Van Der Berg, N. Lemmer, F. Waanders, H. Tutu, Assessment of seasonal variation in surface water quality of the Mooi and Vaal Rivers network, South Africa. *International Conference on Advances in Science, Engineering, Technology and Natural Resources (ICASETNR-16)* Nov. 24-25, 2016, Parys – South Africa. ISBN: 978-93-84468-79-8. 2016.
- [52] K. Nyembwe, E. Fosso-Kankeu, F. Wanders and E. Malenga, "Mineralogical observation made during the kinetic dissolution study of chalcopyrite mineral in sulphate media under free pH at room temperature," Cape Town, 2018.