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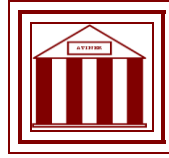# ATINER

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Effect of Epoxy Depolymerisation in the Leaching of Copper from Electronic Waste

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An Introduction to
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Abstract

The aim of this study was to examine the role of epoxy in the bioleaching of copper from electronic wastes. Metal dissolution tests were performed by chemical leaching using fungi generated citric acid mimicking the spent medium based leaching. Copper dissolution from electronic waste was found to be inhibited by the decomposition of its epoxy component during the leaching process. Citric acid attack and partial depolymerisation of epoxy resulted in amine group cleavage and release raising the solution pH from an initial of 1.8 up to 6.1 and with resulting epoxy surface modification promoted the removal of dissolved copper by adsorption and precipitation as di-copper citrate. Independent measurement of epoxy induced copper loss was used to reconcile the true copper recovery from citric acid at pH from 1.8-3.0, temperatures from 30-90°C, pulp densities of 5-100 g/L and 24 hours. Copper loss of up to 30% of the total copper in the waste or 83% of the dissolved metal was observed. Inhibition of copper dissolution with increasing waste pulp density was largely attributed to the epoxy induced copper removal. In addition these secondary reactions masked the self catalysis of copper dissolution by Cu^{2+}. Minimal effect of epoxy induced copper removal and optimal copper recoveries were observed at the lowest pH of 1.8, lowest pulp density 5 g/L and highest temperature 90°C. These results demonstrated the importance of overcoming the effects of epoxy depolymerisation and the potential merit of applying spent medium leaching in overcoming these effects and in optimising the recovery of copper from e-wastes.

Keywords: Copper, Epoxy E-waste, Citric acid, Adsorption, Precipitation

Introduction

The rapid advance in information technology and the relentless desire of consumers for the "state of the art" products have led to an accelerated obsolescence of electronic goods. Without the systems and the technology in place to effectively capture and manage these wastes, the accumulation of e-wastes has become a pervasive problem at a local, regional and national level. The problem with waste electrical and electronic equipment (WEEE) is not just its growing volume but also its toxicity, and its content of valuable resources (e.g., gold, copper) which are lost when e-waste is disposed (Barba-Gutierrez et al., 2008; Chancerel & Rotter, 2009; Oleszek et al., 2013; Tuncuk et al., 2012; Zheng et al., 2013). The challenge is to develop sustainable recycling technologies to address the volume and complexity of this waste using cost-effective and ecologically sensitive methods (Dalrymple et al., 2007).

Bioleaching offers a promising technology as this technology uses naturally occurring biological micro-organisms and their metabolic products in extracting valuable metals from the waste such as spent catalyst and electronic waste (Brandl et al., 2008; Ivanus, 2010; Valix et al., 2001). Three groups of micro-organisms are currently used in bioleaching: *chemolithoautotrophs* bacteria that derive their energy from the biooxidation of inorganic compounds containing reduced S and Fe^{2+}, heterotrophic bacteria and fungi, both of which require carbon source for growth and energy (Brandl et al., 2001; Brown, 2010; Ilyas et al., 2010; Ivanus & Ivanus, 2009; Xiang et al., 2010). Whilst studies involving heterotrophic fungi including *Aspergillus niger*, *Penicillium simplicissimum* and *Penicillium chrysogenum* (Brandl et al., 2001; Brown, 2010; Ilyas & Lee, 2013) have been limited. Fungi however offers numerous advantages including their ability to dissolve metals under alkaline conditions by complexing the metallic fractions with organic acid metabolites and the lower toxicity of the complexed metals (Burgstaller & Schinner, 1993; Ilyas & Lee, 2013). These organisms affect the solubilisation of metals from metal-rich materials via a series of reactions, including oxidation, reduction, and complexation by the generation of organic-acid leachates (e.g., citric acid). The dissolution of any metallic fractions, however, is also subject to other side reactions referred to as secondary reactions. These are reactions other than leaching that could promote or alternatively hamper the dissolution and recovery of the metallic fractions by leaching (Valix et al., 2001; Viramontes-Gamboa, 2007). These reactions could include adsorption, precipitation and co-precipitation, passivation and galvanic coupling. Optimising the recovery of the metallic fractions from e-waste will require confirmation of the occurrence of these reactions and identification of the windows of conditions under which these reactions could be minimised or avoided. Electronic wastes consist of complex mixtures of plastics, glass and metals. Approximate analysis presents 60-70% of general electronic scrap as non-metals and 30-40% as metals (Brandl et al., 2001; Brandl et al., 2008). Intricate designs of electronic wastes often make it difficult and costly to separate the non-metallic and metallic fractions. Despite fine milling and separation by heavy medium methods such

as saline solution total metal concentrations of the final concentrated wastes has been reported to be only 20-30 % (Ilyas & Lee, 2014; Ilyas et al., 2013). This study investigated the role of the non-metallic fractions, in particular epoxy, in promoting secondary reactions in the bioleaching of copper as a test case metal. To perform this investigation, citric acid was chosen to mimic the spent medium leaching achieved by fungi metabolic acids.

Materials and Methods

Copper Rich E-Waste and FR4 Epoxy

Ground electronic wastes (copper-rich) were obtained from Total Union PCB Recycle in Hong Kong. Metallic components of the printed circuit boards, PCB, were separated by crushing, milling and magnetic separation. This waste was used as received with minor size separation. After undergoing sieving, waste fraction with a mean particle size range of 104 µm was collected and used throughout all experiments. The composition of this waste is summarised in Table 1.

Table 1. *Elemental Composition of the Cu-rich Waste*

Metallic components (wt%)							Non-metallic components (wt%)
Al	Cu	Fe	Mg	Pb	Sn	Zn	44.8
0.14	47.82	0.03	0.02	0.01	0.02	0.09	

Shredded epoxy with no metallic components was a flame retardant epoxy supplied by All Engineering Australia.

Leaching and Precipitation Tests

The chemical leaching tests were performed using reagent grade citric and sulphuric acids to reflect the chemical leaching that would be achieved by spent medium leaching with fungi and acidophilic sulphur oxidising bacteria. Leaching tests were carried out in a series of temperature controlled 50 ml Variomag batch reactors at temperature from 30- 90°C with a pulp density of 10 to 100 g/L for periods of 0.5-24 hours and stirred at 1000 rpm. Metal recoveries were estimated from the ratio of dissolved metals to the original metal content of the waste. Because of the heterogeneity of the waste, the original metal content of the waste was determined by summing the dissolved metal and metal present from the leaching residue. The metal content in the residues were determined by aqua regia digestion of the waste (Meng & Zhang, 2012); the dissolved metals were analysed by Varian Vista AX CCD Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES) using standard procedures. The pH and oxygen reduction potential of the solutions were monitored during leaching with a dedicated pH-mV-temp meter (TPS WP-80D). To examine copper loss by adsorption and precipitation, epoxy were immersed in 4800 ppm of Cu and subjected to similar conditions used for

leaching. The remaining copper left in solution was estimated by ICP-AES. Analysis of the precipitates harvested was conducted by FTIR and scanning electron microscopy. FTIR analysis was performed using Thermo Scientific Nicolet 6700 FTIR Spectrometer. The precipitate was compressed with KBr in 0.2 wt% concentration and an absorbance spectrum (4000–500 cm^{-1}) was measured with a resolution of 0.1 cm^{-1} and subtracted against a blank background. A Phillips XL 30CP scanning electron microscope with automated specimen stage, ultra-thin window EDS microanalysis and X-ray mapping was used to confirm the elemental composition of the precipitates.

Results and Discussion

Effect of Secondary Reactions on the Leaching Efficiency

The effect of secondary reactions is manifested by inhibition of metal dissolution in terms of slower rate of reaction or lower metal recovery. A key issue, for example, that continues to hamper the practical implementation of the bioleaching technology in processing electronic waste is the low metal recovery achieved with increasing high pulp densities (Brandl et al., 2001; Liang et al., 2010; Xiang et al., 2010; Zhu et al., 2011). This effect has often been attributed to the increasing toxic effect of the waste on the bioleaching organisms (Bas et al., 2013; Brandl et al., 2001; Ilyas et al., 2013; Ilyas et al., 2010; Pradhan, 2010). This is true to some respect and as shown in Figure 1a, increasing the pulp density in direct leaching reduced copper recovery. The spent medium results, which were conducted by harvesting the biogenic acid and used in leaching in the absence of microorganisms, however showed similar trends. This would suggest that effects observed are abiotic in nature. This is further reinforced by the results in Figure 1b involving the chemical leaching with sulphuric acid at pH 1.0 and citric acid at pH 1.7 which showed similar decline in copper leaching with increasing pulp density.

Figure 1. *Recovery of Copper from: a) Direct and Spent Medium Bioleaching of PCB with Acidophilic S/Fe Oxidising Bacteria and b) Chemical Leaching at 90 °C as Function of Pulp Density*
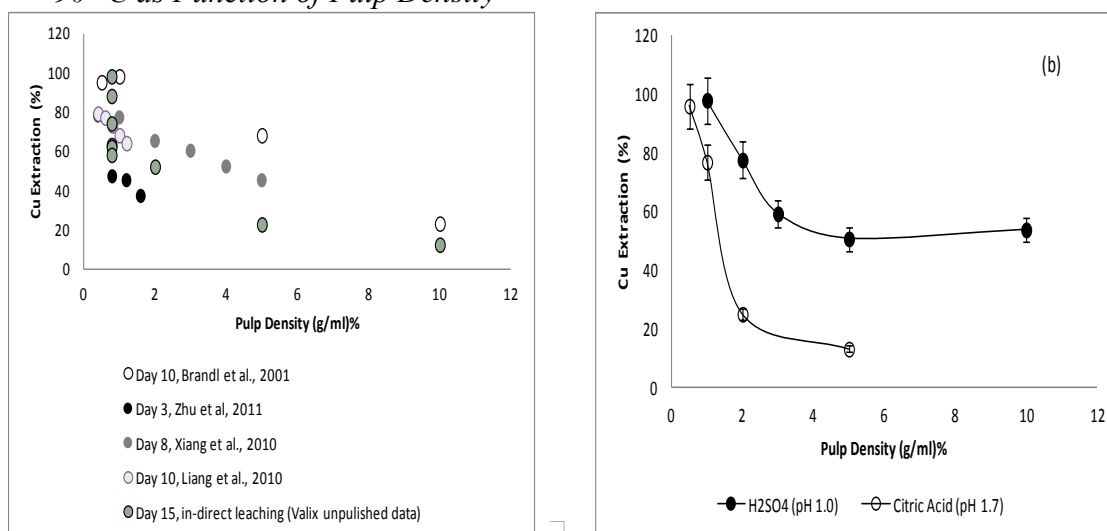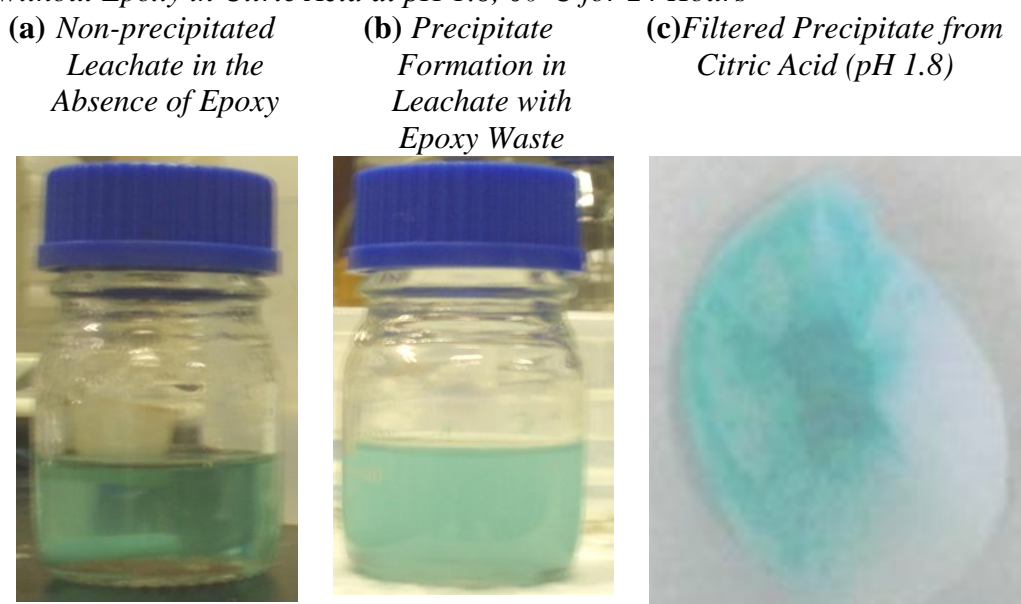

Epoxy Induced Precipitation during Bioleaching

Precipitation, the transformation of dissolved metals to less soluble solids could reduce metal recovery significantly during leaching and could partially hamper leaching kinetics by fouling metallic surfaces. Precipitation in hydrometallurgical processing could be promoted by saturation of dissolved metals in solution (Park & Fray, 2009) and the presence of precipitating agents such as hydroxides, sulfides, sulfate and oxalates and exopolymeric substances (EPS) secreted by microbes (Li & Yu, 2014). Precipitation in bioleaching of e-wastes that have been reported have focused principally in hydrolysed ferric precipitates (Lewis et al., 2011; Wang et al., 2009; Xiang et al., 2010; Zhu et al., 2011). Precipitation in lithotrophic leaching of e-wastes appears to be predominated by the formation of hydrolysed iron precipitates (Lewis et al., 2011; Wang et al., 2009; Xiang et al., 2010; Zhu et al., 2011). This is largely because ferric ions are present in substantial quantities in bacterial leaching because it is present in the waste and as it is often used as Fe^{2+}/Fe^{3+} redox couple to support the biooxidation and dissolution of copper. The occurrence of precipitation in leaching with fungi and their metabolic products, organic acids does not appear to be as well documented (Bucknell, 2010).

In this study, the role of the epoxy in promoting precipitation was examined by conducting two separate leaching tests that involved leaching of 5g/L pure copper metal and the second of 5g/L pure copper metal and 5g/L shredded AF4 epoxy in citric acid at pH 1.8, 60°C and 1000 rpm for 24 hours. The results are shown in Figure 2. Figure 2a shows that in the absence of epoxy no precipitates formed while in the presence of epoxy precipitates formed with distinct blue-green colour (see Figure 2b and 2c). The formation of precipitates under the acidic leaching conditions (pH 1.8) is inconsistent with thermodynamic stability of copper-citrate complexes. Copper ions are

considered to be stable in a copper- water system up to pH 3.3. The solubility of copper is further extended to approximately pH 11.0 when copper is complexed with citrate (Wu & Tsai, 2007). Figure 2 shows however the precipitation is induced by the presence of epoxy or more particularly flame retardant (FR4) epoxy. FR4 is a glass fibre reinforced laminate that employs epoxide resin based on diglycidyl ether of bisphenol A used extensively in printed circuit boards, a key component of the copper rich waste used in this study.

Figure 2. *Precipitate Formation after 24 Hour Leaching of Cu with the without Epoxy in Citric Acid at pH 1.8, 60°C for 24 Hours*

(a) *Non-precipitated Leachate in the Absence of Epoxy*   **(b)** *Precipitate Formation in Leachate with Epoxy Waste*   **(c)** *Filtered Precipitate from Citric Acid (pH 1.8)*


Analysis of the precipitate generated in citric acid was performed by FTIR and SEM-EDS (see Figure 3). The FTIR spectra of the precipitate revealed strong peaks including 1640, 1558, 1354, 1080 and 740 cm^{-1} consistent with di-copper citrate precipitate $Cu_2C_6H_4O_7H_2O_2$ (Eremin et al., 2008; Zhang et al., 2006). The SEM-EDS reveal precipitates containing elemental C and Cu in a ratio of 3-4 that is also consistent with the structure of hydrated copper (II) citrate as established from the FTIR analysis.

Mechanism of Adsorption and Precipitation

The maximum concentration of copper that would dissolve from 5g/L of Cu granules would be 5000 ppm, which is significantly lower than the solubility limit (250 g/L in 10% HCl) of di-copper citrate precipitate in acidic solution (Codex, 2013). This suggests precipitation, as observed in Figure 2, occurred in an unsaturated solution and supports the role of the epoxy n this process. Previous results has shown that binding of metal on surfaces such as silica, goethite minerals and clays acts as the pre-cursor for the formation of metal cluster in under-saturated solutions (Charlet & Manceau, 1992; Duggan & Roberts, 2014; Kumar et al., 2012; Lim et al., 2011; Sheha, 2012). When a

high level of metal sorption is achieved, polymerisation into clusters was proposed to occur followed by the growth and/or coalescence of the clusters to the point where distinct precipitate phase forms. Both epoxy and silica that are present in the e-waste epoxy residue have carboxyl and hydroxyl functional groups that exhibits strong binding affinities for cations and would support the sorption of copper ions.

Figure 3. *Characterisation of Copper Precipitate formed from Leaching of 5g/L Cu with 5g/L of Epoxy in Citric Acid at 60°C, pH 1.8, and 1000 rpm for 24 Hours: a) FTIR; b) SEM-EDS Micrograph and d) EDS Spectrum 1 Analysis*
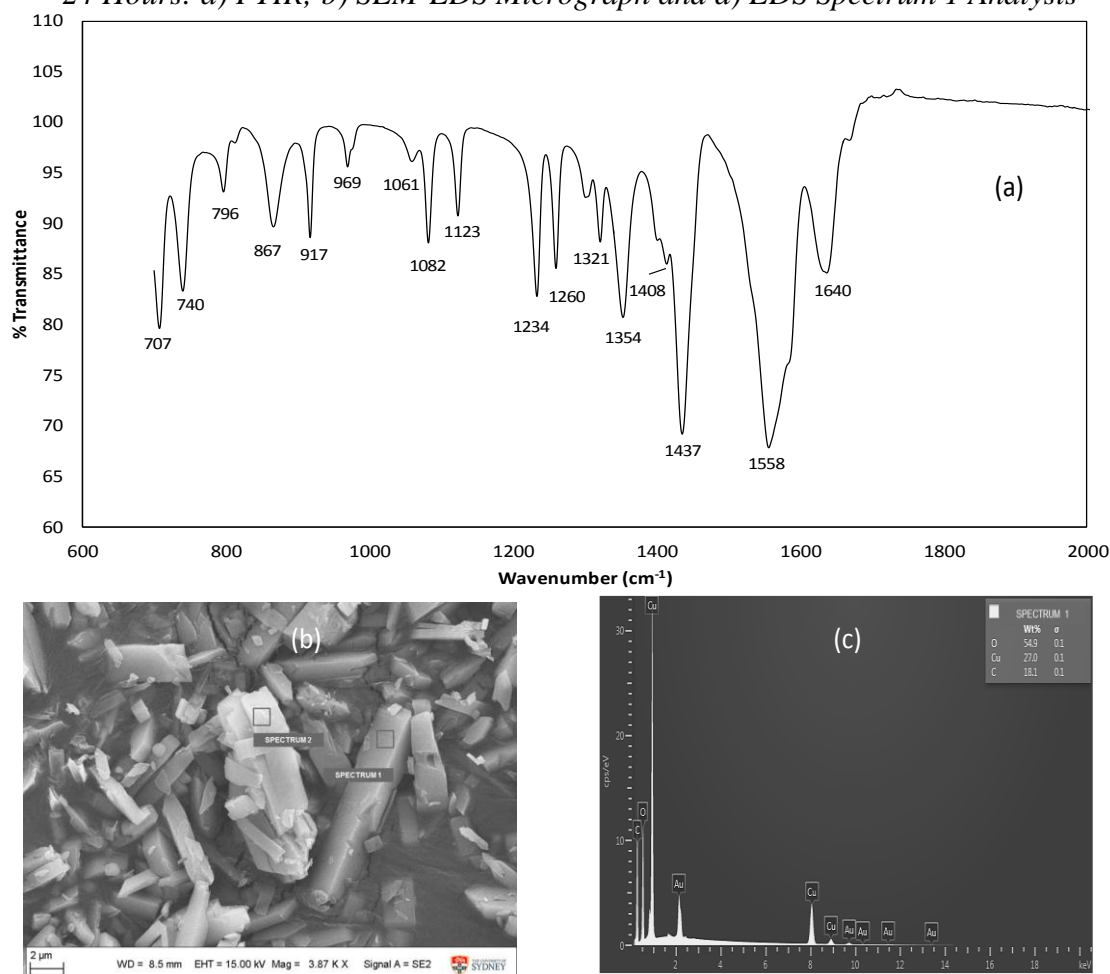
The mechanism by which precipitation occurred was further investigated by examining the changes in the surface chemistry of the epoxy during leaching by FTIR and zeta potential measurement. Figures 4a and 4b compare the FTIR spectra of the neat epoxy before and after leaching with citric acid at 60°C. Obvious changes occurred as a result of the leaching. This included weakening of the intensities in the regions of 831 cm^{-1}, 1604 cm^{-1}, and 2870-2964 cm^{-1} associated with C-H substituted group in phenyl ring, phenyl ring and alkyl groups. In addition, the intensity around 3400 cm^{-1} associated with

the absorption of hydroxyl group was also weakened by leaching. The low intensity at 912 cm^{-1} of the epoxide ring in the raw waste reflects the curing of the epoxy. After leaching, this peak disappeared suggesting progression of curing during the leaching process. The intensity around 1105 cm^{-1} associated with C-O-C increased with leaching. The increase in the absorption at 1105 cm^{-1}, typically assigned to the etherification of epoxy with formation of aliphatic ethers as curing progresses (Liu et al., 2006), which is consistent with the loss of epoxide absorption with leaching. A comparison of the surface functional groups of the leached epoxy and neat citric acid were compared in Figures 4b and 4c, respectively. As shown, characteristic peak at 1715 cm^{-1} assigned to C=O vibration of the citrate group is not present in the leached epoxy. This suggests that citrate anion does not adsorb on the epoxy during leaching and is not responsible for the changes in the epoxy surface chemistry during leaching. That is the changes in the surface functionalities in Figure 4 appears to result primarily from the degradation of the epoxy. Degradation of epoxy to its monomeric or lower molecular weight components is achieved by epoxy solvolysis. Solvolysis involves the chemical depolymerisation of epoxy consisting of the breaking of cleavable bonds present in the backbone of step-growth polymers by processes of alcoholysis, glycolysis, hydrolysis and aminolysis by solvolytic agents including water, alcohol, acids, alkali or amine (Destais-Orvoen et al., 2004; Eddingsaas et al., 2010; El Gersifi et al., 2003; El Gersifi et al., 2006; Liu et al., 2004). In this leaching process, partial solvolysis was achieved with citric acid leading to the partial cleavage of both alkyl group, and conversion of aromatic rings.

Figure 4. *The FTIR Spectra of a) Neat Epoxy, b) Epoxy Residue after Citric Acid Attack at 60°C, pH 1.8, Pulp Density of 10g/L and 1000 rpm for 24 Hours and c) Neat Citric Acid*
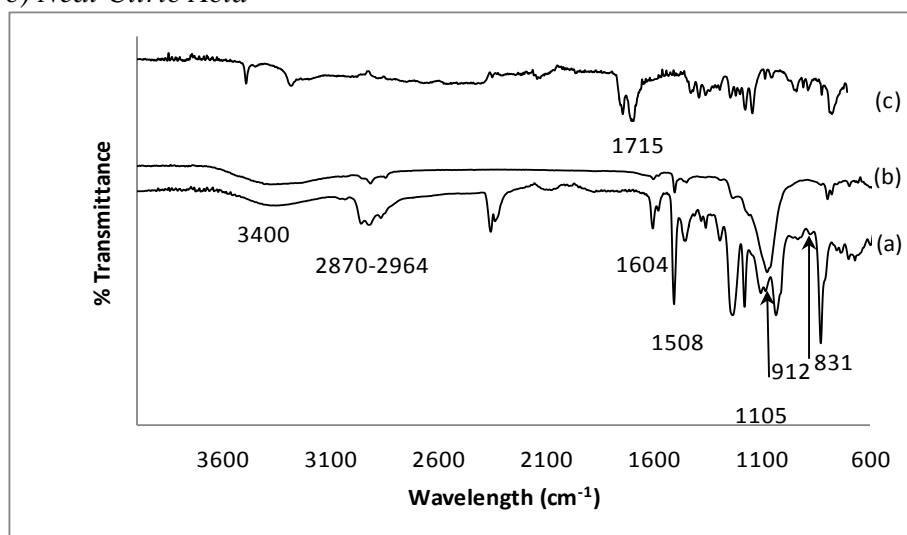
The corresponding epoxy surface modification resulting from the citric acid attack is shown in Figure 5. Surface charge was measured by zeta potential measurement as a function of pH. The point zero charge (pzc)

represents the pH at which the electrical density charge of zeta potential on the surface is zero. Above the pzc the surface charge is considered to have net positive charge and below the pzc the surface charge would be net negative. As shown the pzc of the epoxy prior to leaching was 5.7. This decreased to approximately 1.8 as a result of leaching in citric acid. Leaching performed at pH greater than pH 1.8 should result in net negative surface that would promote the sorption of positively charged copper ions and complexes. It is proposed that the partial degradation of the epoxy, evident in the FTIR analysis of the epoxy in Figure 4, led to the formation of net negative charge. This promoted copper adsorption acting as a precursor for the observed precipitation of copper citrate from under saturated solution. To examine the changes of the epoxy only in the solution pH, 5g/L of shredded epoxy was added to 5000 ppm of copper prepared in citric acid at various pH.
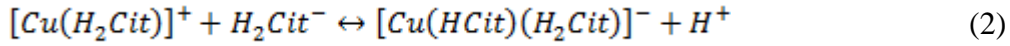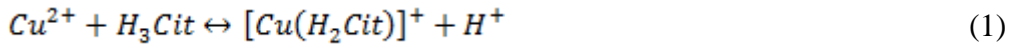
Figure 5. *Zeta Potential of: a) Neat Epoxy and b) Epoxy after Citric Acid Attack at 60°C, pH 1.8, Epoxy Pulp Density of 5g/L and 1000 rpm for 24 Hours*
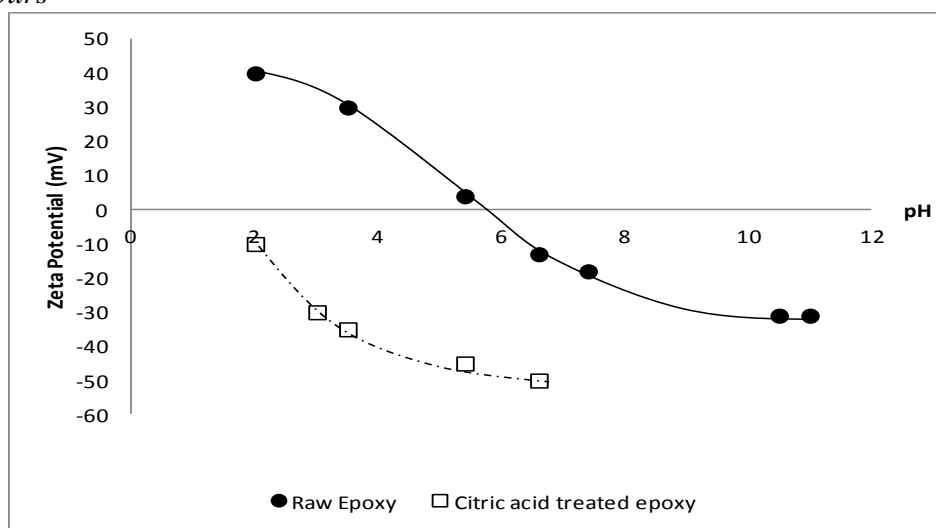

The changes in the solution pH of copper citrate solution with the addition of epoxy further reflect the depolymerisation of epoxy and precipitation of copper. Figure 6 shows the addition of epoxy in copper citrate solution with initial pH of 1.81, 2.05, 2.48 and 3.01 all resulted in the rise of pH at the early phase followed by decline with time. The depolymerisation of epoxy is known to results in the cleavage of its bisphenol monomer and amine curing reagents by solvolysis (El Gersifi et al., 2006). While bisphenol itself is a very weak organic acid (pKa 9.6-10.2) and would dissociate either as an anionic or neutral moiety, the amine curing agent is alkaline. The initial rise in the alkalinity of the solution was therefore proposed to be associated to the cleaved amine compounds in citric acid.

The reduction in pH with time appears to be associated with the release of protons as copper precipitated. The precipitation of di-copper citrate is

proposed to occur as a result of reaction of copper with di-hydrogen citrate, where Cit is ($C_5H_4O_7$) (Parry & Dubois, 1952):

$$Cu^{2+} + H_3Cit \leftrightarrow [Cu(H_2Cit)]^+ + H^+ \qquad (1)$$

$$[Cu(H_2Cit)]^+ + H_2Cit^- \leftrightarrow [Cu(HCit)(H_2Cit)]^- + H^+ \qquad (2)$$

This is followed by the separation of the di-copper precipitates:

$$2[Cu(HCit)(H_2Cit)]^- \leftrightarrow Cu_2(C_6H_4O_7) + 3H_2Cit^- + H^+ \qquad (3)$$
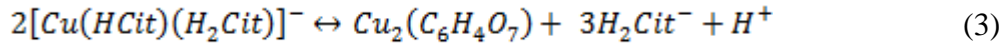
The di-hydrogen citrate from equation (3) would continue to complex with other copper ions, whilst the gradual accumulation of protons released accompanying the di-copper citrate precipitation would result in the reduction in pH. Thus, the early phase rise in pH is proposed to reflect epoxy depolymerisation whilst the subsequent reduction in pH was attributed to the accumulation of H^+ with di-copper citrate precipitation.

Effect of Epoxy Depolymerisation on Copper Loss and Copper Leaching
<u>Waste Pulp Density</u>
To examine the effect of increasing epoxy pulp density in copper removal from citric acid solution, 10, 20, 50 and 100 g/L of shredded epoxy were added to 5000 ppm of Cu prepared with citric acid with an initial pH 1.8, heated to 60°C and stirred at 1000 rpm for up to 24 hours. Copper loss was calculated from:

$$Cu_{loss}(\%) = \frac{Cu_o - Cu_f}{Cu_o} x100 \qquad (4)$$

where Cu_o and Cu_f are the initial and final mass of copper at specific points of time respectively. The effect of epoxy addition on solution pH is shown in Figure 7a. As shown addition of 10 and 20 g/L of epoxy have little effect on the pH. However increasing the epoxy addition to 50 and 100 g/L resulted in significant rise in pH from 1.8 up to 4.88 within 24 hours, which is consistent with greater epoxy depolymerisation. The effect of epoxy density on copper loss is shown in Figure 7b. As shown increasing the pulp density to 50 g/L resulted in progressively higher copper loss of up to 40.3% then declined at 100 g/L. The rise in the copper loss with epoxy, the precursor for copper removal, would be as expected. However, the eventual reduction loss at 100 g/L appears to be due to the rise in pH with pulp density (see Figure 7a). The rise in pH may have hampered the acid attack of the epoxy and its degradation. It is also apparent that the copper loss is reversible as shown in Figure 7b after 16 hours.

Figure 6. *Effect of Addition of 10g/L of Epoxy on Various Initial Solution pH of 4800 ppm Cu Dissolved in Citric Acid at 60°C for 24 Hours*
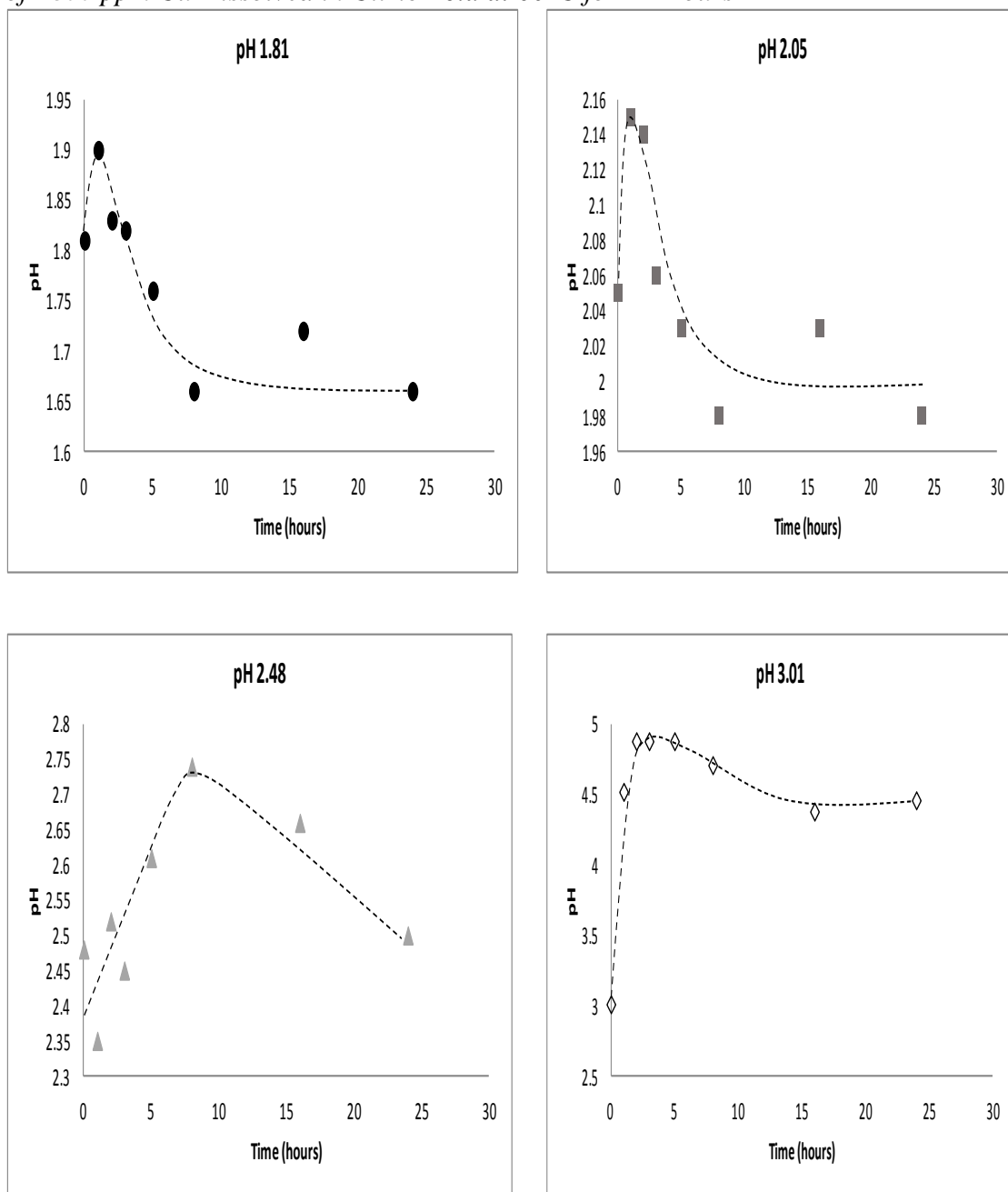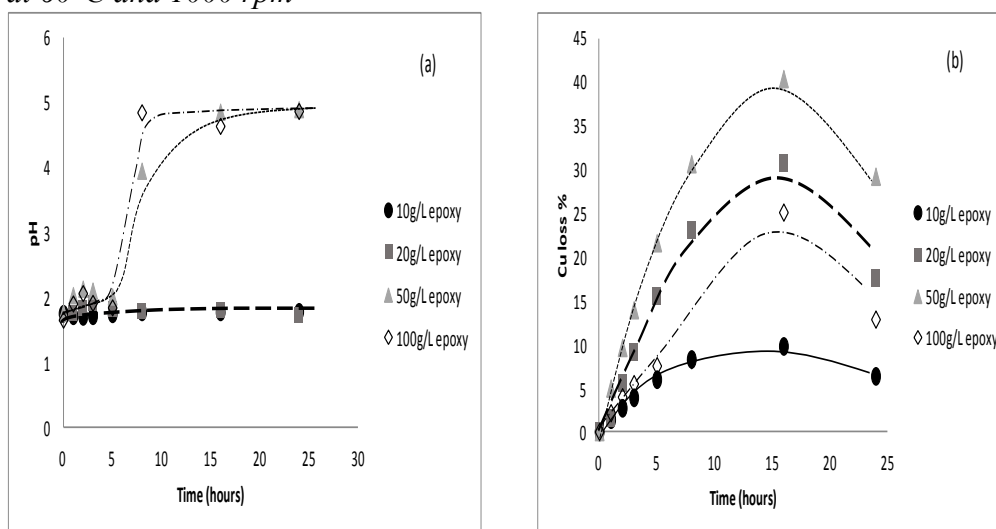
Figure 7. *Effect of Epoxy Pulp Density on: a) Solution pH and b) (%) Copper Loss as a Function of Time from 5000 ppm Cu in Citric Acid at pH 1.8 Heated at 60°C and 1000 rpm*

Various pulp densities of PCB were leached in citric acid at 60°C for 24 hours. The copper recovered are plotted as a function of time in Figure 8a. These copper recoveries were corrected for copper loss, independently established by separate adsorption and precipitation tests. For example the copper recovery at 10g/L at 24 hours was corrected for copper loss estimated by adding 5g/L of epoxy in 4.8g/L of copper in citric acid adjusted to pH 1.8 and heated to 60°C for 24 hours. This was repeated for the other pulp densities. The corrected copper recoveries are only estimates as adsorption were performed in copper concentrations that assumed full copper dissolution. These corrected copper recoveries are compared with the actual copper recoveries obtained at 16 and 24 hours of leaching in Figure 8b and 8c. The distinct inhibition of copper leaching with increasing PCB pulp density is obvious in Figure 8. Whilst the copper dissolution corrected for copper loss was quite stable after 24 hours up to 100 g/L, however at 16 hours, there was a rise in copper dissolution with pulp density, which appears to be self-catalysed copper dissolution. This is consistent with previous reports that suggests the accumulation of Cu^{2+} catalyses the dissolution of copper through the $Cu + 2Cu^{2+} = 2Cu^{+}$ reaction (El Din et al., 2000). The eventual fall of copper recovery from 16 to 14 hours could be attributed the equilibration shift in equation (2) with accumulation of H^{+}. These comparative copper recoveries shows the significant role polymeric decomposition in epoxy containing e-waste pulp density in promoting inhibition of copper dissolution during bioleaching.

Figure 8. *Effect of PCB Pulp Density on: a) Cu Leaching with Citric Acid at 60°C, pH 1.8, 24 Hours and 1000 rpm, b) Actual and Corrected Cu Recovery after 16 Hours of Leaching and b) Actual and Corrected Cu Recovery after 24 Hours of Leaching.*
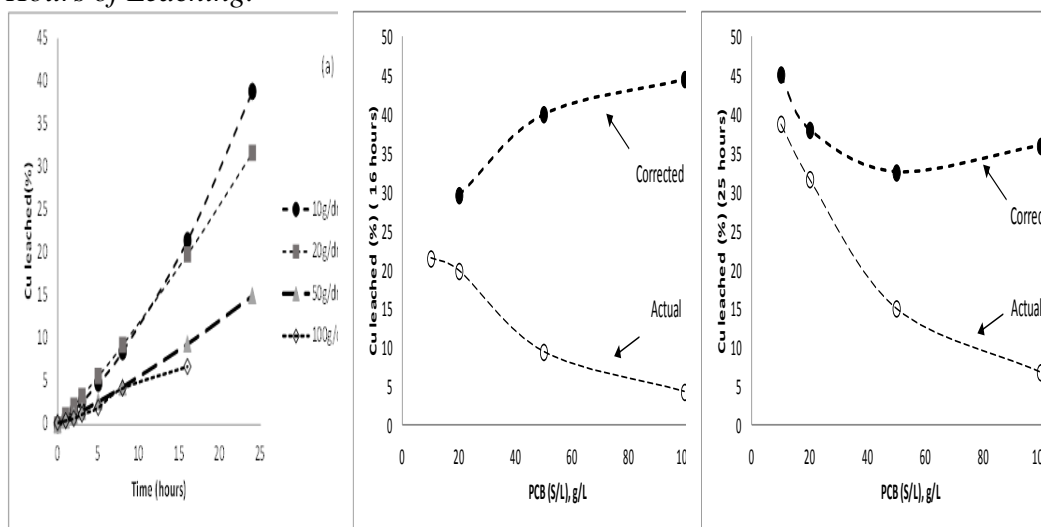
Effects of Temperature and pH

The effects of temperature and pH on the epoxy induced removal of copper from solution are shown in Figures 9 and 10. In general changing the temperature did not appear to have a significant effect on copper removal, however it appears the copper removal is least at the higher temperature. This suggests the certain advantage of spent medium method over direct method of leaching in overcoming this particular secondary reaction. Copper removal increased from solution pH of 1.8 to 2.48 but was reduced at pH 3.0. The rise in pH above 1.8 would create greater net negative charge, which should promote greater adsorption and is consistent with the higher removal of copper from solution. The lower copper loss at an initial pH 3.01 could be attributed to the limited copper complexation at pH greater than 3.0. The final pH achieved with an initial pH of 3.0 is 6.1. Citrate anions will coordinate with cupric ions only at pH below 3.0 (Parry & Dubois, 1952). The inability of copper ions to complex with citrate anion and the generally lower dissolved copper at these pHs would have hampered precipitation.

Figure 9. *Effect of Temperature on: a) Cu Loss with Addition of 5g/L of Epoxy in 4800 ppm Copper Citrate Leaching with Citric Acid at pH 1.8 and 1000 rpm, b) Actual and Corrected Cu Recovery from Leaching 10g/L of PCB in Citric Acid at pH 1.8, 1000 rpm*
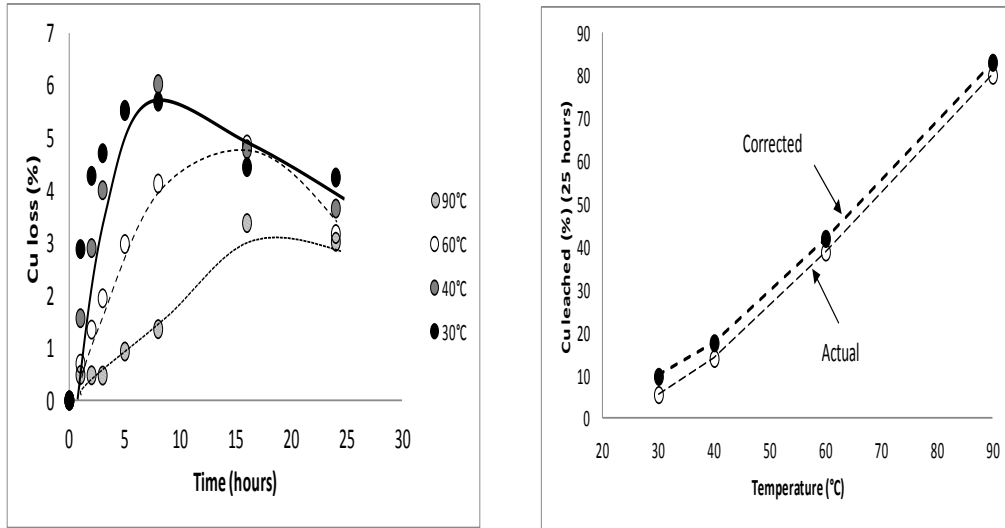

Figure 10. *Effect of pH on: a) Cu Loss with Addition of 5g/L of Epoxy in 4800 ppm Copper Citrate Leaching with Citric Acid at 90°C and 1000 rpm, b) Actual and Corrected Cu Recovery from Leaching 10g/L of PCB in Citric Acid at 90°C and 1000 rpm.*
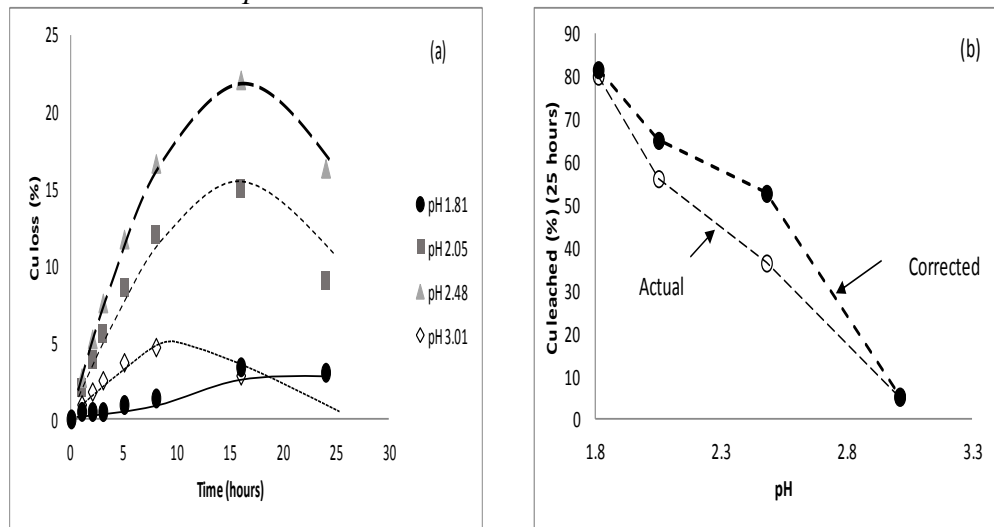
Conclusions

This study revealed the role of epoxy decomposition in the inhibition of copper dissolution in citric acid. The mechanism for the epoxy induced removal of dissolved copper from solution appears to involve epoxy depolymerisation,   copper   adsorption   and   precipitation.   Epoxy

depolymerisation releases amine groups in solution that raises the solution and epoxy surface conversion that shifted the epoxy isoelectric point from 5.7 to 1.8. The combined effect increased the net negative surface change of the epoxy promoting sorption of copper ions and complexes on the epoxy surface. This adsorption was proposed to act as the pre-cursor for the formation of metal cluster in under-saturated solutions which at the high level metal sorption promoted polymerisation into clusters and growth to the point where distinct precipitate phase formed. The process of copper loss by adsorption and precipitation appears reversible with time.

Correction of copper recovery for independently measured epoxy induced copper loss revealed that as much 30% of copper can be lost from solution. In addition the copper loss appears to have masked potential benefits of self-catalysis of copper dissolution by dissolved copper ions. Removal of copper from solution is minimised at the lower pH and higher temperature, conditions that also promote greater leaching of copper. These results demonstrate the importance of overcoming the effects of epoxy depolymerisation and the potential merit of applying spent medium leaching in the recovery of copper from e-wastes.

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