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# Influence of binder composition on hematite-rich mixed minerals agglomeration behaviour and product properties

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## ABSTRACT

Physicochemical interactions between the mineral particles and liquid binder play a pivotal role in controlling the agglomeration behaviour and defining the agglomerate attributes. In this study, the effect of tap water, saline water (2M NaCl) and 30% and 44% w/w H<sub>2</sub>SO<sub>4</sub> solutions as binders on agglomeration behaviour and product attributes (compressive strength, re-wetting stability and microstructure) of a hematite-rich mixed minerals was investigated. The results revealed that at equivalent binder mass dosage of 13 wt.%, albeit different binder volume dosages, the agglomeration with tap and saline water displayed markedly faster nucleation and coalescence-controlled agglomerate growth behaviour. The acidic solutions led to slower nucleation followed by pseudo-layering agglomerate growth behaviour, the extent of which was greater at 44% than at 30% w/w H<sub>2</sub>SO<sub>4</sub> binder addition. Generally greater compressive strength and re-wetting stability were displayed by the acid-bound agglomerates compared with tap water and saline water-bound ones. The internal microstructural analysis revealed that the pore volume fractions of the wet agglomerates were almost independent of the binder type. In the dry state, however, the pore volume fractions of the water-bound agglomerates were slightly lower than that of acid-bound ones, both were, however, markedly higher than those observed for wet agglomerates. The increase is believed to be due to particles' shrinkage resulting from interfacial stresses and strains following moisture loss during drying. The observed outcomes highlight the importance of binder type and their impact on agglomeration behaviour and product characteristics.

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## 1. Introduction

Heap leaching (HL) is a process used to extract value metals (e.g., gold (Au), copper (Cu) and nickel (Ni)) from their low grade ores at lower capital and operating costs than the other hydrometallurgical methods (Bouffard, 2005; Dhawan et al., 2012a,b, 2013; Lewandowski and Kawatra, 2009a). It generally involves long-term (e.g., 200–300 days) lixiviant (e.g., H<sub>2</sub>SO<sub>4</sub> solution) percolation through crushed

mineral ores stacked in large heaps of ~4–10m height (Bouffard, 2005; Dhawan et al., 2012a,b, 2013; Lewandowski and Kawatra, 2009a). The resulting pregnant leach solution (PLS) is treated to recover the valuable metals of interest. For the HL process to be effective and economically profitable, the ore heap must be porous, stable and permeable to permit the efficient and uniform flow of the lixiviant/leach solution (Readett and Fox, 2011; Steemson and Smith, 2009).

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Run-of-mine (ROM) lateritic ores are characteristically polydispersed comprising a large fraction (e.g., >30 wt.%) of fine (e.g., <100  $\mu\text{m}$ ) particles (Bouffard, 2005; Dhawan et al., 2013; Nosrati et al., 2012a; Quast et al., 2013). When stacked in a heap, the migration of fine particles with lixiviant during irrigation reduces heap permeability through blocking and clogging the flow channels and pores. Consequently, non-uniform lixiviant distribution and percolation/flux problems result, leading to inefficient HL and low metal recovery (Bouffard, 2005; Dhawan et al., 2012a,b, 2013; Lewandowski and Kawatra, 2009a; Readett and Fox, 2011). Hence, agglomeration of the ROM or crushed ores is warranted as an effective solution to minimize or eliminate the fine particles-mediated, poor heap permeability issues (Bouffard, 2005; Kodali et al., 2011; Nosrati et al., 2012a).

Depending on the ore mineralogy and chemical composition and the operating HL conditions, raffinate-based lixiviant (e.g.,  $\text{H}_2\text{SO}_4$  rich solution) is often used as agglomeration medium (binder) alone or in conjunction with other additives (e.g., Portland cement, bentonite, geo-polymers) (Bouffard, 2005; Lewandowski and Kawatra, 2009a; Readett and Fox, 2011). The major role of a binder is to foster the formation of robust agglomerates with desirable strength and stability under HL conditions. Unlike Au and iron ores where Portland cement and bentonite are used as agglomeration binders, respectively,  $\text{H}_2\text{SO}_4$  solution is generally considered and used as efficient agglomeration binder for Ni laterite ores (Oxley et al., 2007; Readett and Fox, 2011; Steemson and Smith, 2009). This is due to the fact that other additives (e.g., Portland cement, geopolymers) easily lose their binding effectiveness upon contact with acidic lixiviant used in Ni laterites heap leaching (Oxley et al., 2007; Readett and Fox, 2011; Steemson and Smith, 2009).

During acid agglomeration, the wetted mineral particles generally bind together via (i) liquid bridges, (ii) liquid films and (iii) solid bridges from re-crystallization/solidification of solubilized species (Bika et al., 2005; Bouffard, 2005; Lewandowski and Kawatra, 2009b; Pietsch, 2003; Rumpf, 1990). Particularly, the wet agglomerates undergo a certain degree of curing prior to stacking in a heap the extent dependent upon the exposed environmental conditions. When a binder solution chemically reacts with and partially solubilizes the solid particles during agglomeration, the dry agglomerate strength which is enhanced by re-crystallization or solidification of solubilized species can be estimated using Eq. (1) (Bika et al., 2005). In case of non-reactive binder solution with no interfacial chemical reactions, Eq. (2) is used to determine the dry agglomerate strength (Kendal, 1987).

$$\delta_c = \pi b^2 \frac{1 - \varepsilon}{\varepsilon} \left[ \frac{4\pi s_b r_{\text{liq}}}{3} \right]^{2c} \sigma_{sb} \quad (1)$$

$$\delta_c = 24.7 z(\varepsilon) \frac{\gamma_p}{d_p} \quad (2)$$

where  $\delta_c$  is dry agglomerate compressive strength (Pa),  $z(\varepsilon) = 13.3(1 - \varepsilon)^4$ ,  $\varepsilon$  is agglomerate porosity,  $\gamma_p$  is the interfacial energy between particles,  $d_p$  is the average feed particle size,  $s_b$  is the solubilized solid concentration in binder solution, expressed as g/g (which is the solubility of solids in the binder solution),  $r_{\text{liq}}$  is the liquid/solid mass ratio and  $\sigma_{sb}$  is solid bridge strength.  $b$  and  $c$  are dimensionless parameters of typical values 0.288–1.17 and 0.21–0.68, respectively, which are related to the separation distance between primary particles

and dependent upon the agglomerates' consolidation status (Bika et al., 2005; Pierrat and Caram, 1997; Pietsch, 2003).

The binder solution properties (e.g., viscosity, density, acidity, interfacial tension) and percent mass or volume dosage not only influence the particles' wetting behaviour, saturation level, nucleation and growth processes during agglomeration but also the final product characteristics (e.g., strength, microstructure, re-wetting stability, porosity) (Adetayo et al., 1993; Iveson and Litster, 1998a,b; Iveson and Page, 2001; Kawatra and Halt, 2011; Nosrati et al., 2012a; Xu et al., 2013b). Eqs. (1) and (2) indicate that changes which occur in solid-liquid interface during and post agglomeration directly affect the final agglomerate quality and robustness and hence, stability during HL (Bouffard, 2005). Studies of  $\text{H}_2\text{SO}_4$  acid agglomeration of copper ores revealed the formation of leached species-mediated solid bridges (e.g., gypsum), which enhanced the resulting agglomerates strength (Efthymiou et al., 1998). Bika et al. (2005) also reported that aqueous binder leaching of feed particles during granulation of pharmaceutical powders affected the inter-particle bonding mechanisms and the resulting dry granule properties. Re-crystallization or solidification of the solubilized species upon granule drying was noted as the main mechanism for formation of solid bridges. Agglomeration studies of real Ni laterite have also shown that parameters such as ore mineralogy and particle size, binder acid strength and mass content or volume dosage impact on the agglomeration behaviour and product properties (Nosrati et al., 2012a, 2013; Oxley et al., 2007; Readett and Fox, 2011; Steemson and Smith, 2009; Xu et al., 2012, 2013a,b). For example, decreasing binder content from 42 to 36 vol.% (including the ore's inherent moisture) dramatically reduced the wetting propensity, nucleation and agglomerate growth rates of siliceous goethitic ore (Nosrati et al., 2012a). On the other hand, binder content >46 vol.% led to ineffective agglomeration due to over saturation of feed powder, leading to balling and formation of sticky paste which strongly adhered to the drum wall (Nosrati et al., 2012a). This indicates the key role added binder volume plays in the agglomeration process and its links to mineral ore characteristics and other operating variables.

Notably, whilst various facets of goethite-rich limonitic Ni laterite ores have been extensively studied including agglomeration behaviour (Elliot et al., 2009; Guo et al., 2011; Moroney et al., 2008; Nosrati et al., 2014; Tang and Valix, 2006; Watling et al., 2010; Xu et al., 2012, 2013a,b), only limited studies on the agglomeration and leaching behaviour of hematitic Ni laterites have been reported (Panagiotopoulos and Kontopoulos, 1988; Tzeferis, 1994). Hence, further fundamental studies are warranted to foster our understanding of the agglomeration behaviour and product characteristics of the latter.

Water is a critical resource for Australian mineral processing operations and its accessibility and quality can impact on the economic viability of the business. Most groundwater available for mining operations in arid and semi-arid regions are characteristically saline (including sea water) or hypersaline. To date, no study has been reported on the effect of binder salinity on agglomeration behaviour and agglomerate properties. In this paper, the effect of water-based binder composition on agglomeration behaviour and product attributes of a hematite-rich mixed mineral feed, which mimics complex, low grade limonitic Ni laterite ore, is investigated. Specifically, the influence of binder acidity and salinity on powder wetting, agglomeration behaviour and

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