Rapid beneficiation of fine coal tailings using a novel agglomeration technology

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ABSTRACT

Froth flotation has been used successfully over the last century for the beneficiation of coal and mineral particles. However, the process has been affected by certain restrictions relating to the rate at which the bubble/particle concentrate segregates from the aqueous tailings and to the recovery of ultrafine particles. An alternative separation technique, which appears to have the potential to remove these limitations, is selective agglomeration using a high internal phase emulsion binder. Presented in this paper are the findings from an investigation into the continuous steady state processing of fine coal tailings using the emulsion binder. This coal was sourced from a hydrocyclone overflow and had an ash% of 42%. The results from the experiments are compared to the results obtained from a batch system. It was found that both systems achieved a high combustible recovery of 70–80% and low product ash of 15–17%, however, the continuous process needed at least 15% less organic liquid to achieve agglomeration. Moreover, filtration of the agglomerated product material subjected to further high shear demonstrated low moistures of approximately 16 wt%. Therefore, it appears that agglomeration using the emulsion binder offers a method for producing valuable products from fine coal tailings.

1. Introduction

Following mining, valuable materials must be recovered and concentrated by removing the low value gangue. For example, coal is often associated with clays and other non-combustible minerals, gold is often associated with quartz, and platinum group metals can be associated with chromite and other minerals [1,2]. The method used to achieve this separation, or concentration, depends upon the relative physical and surface chemical properties of the valuable component and the associated waste material. In cases where there is a significant variation in the specific gravity of the materials to be separated, techniques that rely on the influence of gravity can be used to achieve the separation. However, these gravity-based techniques become less efficient in the required time scales as particle size decreases. Therefore, techniques that exploit variations in surface chemistry, the most notable being froth flotation, are commonly used for the concentration of fine particles. Froth flotation is a concentration process that relies on the natural or surfactant derived differences in hydrophobicity of solid materials, with the separation achieved by contacting the particles with air bubbles in an aqueous environment. The hydrophobic particles attach to the air bubbles and report to the surface of the water, forming a froth that flows over the lip of the vessel, whereas the hydrophilic particles do not attach and are discharged with the water [3].

Froth flotation has experienced wide spread use over the last century for the beneficiation of both coal and mineral particles due to its efficiency in concentrating complex ores that contain particles too small for gravity separation techniques [4]. The increased need to process low grade ores, *i.e.* ores with a low level of valuable material and often with high levels of dissemination has also increased the importance of froth flotation as a separation technique. While the use of froth flotation has been highly successful and, along with the mechanisation of mining, has facilitated the extraction of otherwise uneconomic ores, the process has been affected by certain restrictions relating to the rate at which the bubble/particle concentrate segregates from the aqueous tailings material and to the recovery of ultrafine particles. Until more recently, these restrictions were not of significant concern. However, due to the rapidly increasing demand for coal and mineral resources, the increasing need to optimise process efficiency and reduce waste, and the falling grade of ores, an emphasis has been placed upon finding methods to increase both throughput and ultrafine particle recovery.

Advancements within the field of froth flotation have included the design of new separation devices such as the Reflux Flotation Cell [5] to increase the segregation rate, and the use of nanobubbles to promote ultrafine particle recovery [6]. Two-liquid flotation, for example the Hydrophobic-Hydrophilic Separation (HHS) technology, has also been used to recover ultrafine particles [7]. This method involves contacting
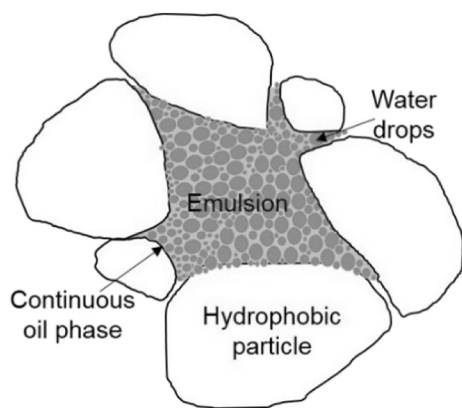

Fig. 1. Schematic of the proposed structure of an agglomerate made using the emulsion binder.

the aqueous slurry containing hydrophobic and hydrophilic particles with a hydrocarbon phase. The ultrafine hydrophobic particles spontaneously move into the hydrocarbon phase, providing a means for achieving selective recovery and a very low product moisture [7]. While the amount of oil required to recover the product is significant in this process, net consumption is minimal due to recovery and recycling of the oil.

In addition to the advancements in the field of flotation, another separation process, inspired by the technique of oil agglomeration, has been developed that may offer an alternative approach [8,9]. The new separation process utilises a hydrophobic binder, consisting of a high internal phase (HIP) water in oil emulsion, to selectively agglomerate only the hydrophobic particles such that they can be easily separated from the hydrophilic material using a screen. The high internal phase emulsion consists of 95% water in the form of dispersed droplets and 5% oil and emulsifier, in the form of a thin continuous layer surrounding each drop. This internal structure can be seen in Fig. 1, which presents a schematic of an agglomerate made using the emulsion binder.

As can be seen in Fig. 1 the emulsion presents a hydrophobic surface for hydrophobic particle recovery, *via* the continuous oil phase, while consisting primarily of dispersed water droplets. It can also be seen that the HIP emulsion is distinctly different to the pure oil binders used previously in traditional oil agglomeration and is dissimilar to emulsifying pure oil in water for use in the agglomeration process.

Previous publications present a thorough treatment of the emulsion as a binder and its development within the selective agglomeration process [10–12]. In short, however, a batch, bench scale system consisting of a high shear blender was used to investigate the influence of the emulsion composition and the operating conditions of the system on the selective agglomeration process. It was found that an emulsion with an aqueous phase consisting of 3 wt% aqueous NaCl solution and an organic phase consisting of kerosene and sorbitan monooleate, in equal parts, had the best performance. When using this binder only ~1.0 wt% was required to achieve agglomeration of fine coal [12]. This organic liquid dosage can be compared to the significantly higher dosage of at least 10 wt% that is required in traditional oil agglomeration using an oil binder, and the lower dosage of 0.2 wt% that is required in froth flotation to condition the particles [5,13]. It was also found that the process was extremely fast, requiring only 3 s if the binder was dispersed in the blender prior to the introduction of the particle slurry.

In a more recent study, a continuous version of the agglomeration process using the emulsion binder was established [8]. This system involved forcing the aqueous mixture of the binder and solid particles through a constriction in a 25 mm diameter line at a high flow rate [8]. The resulting residence time through the constriction was < 1 s, however the separation of the product agglomerates from the aqueous

tailings using a screen was less efficient. Within the same study, it was also shown that the agglomerates formed using the emulsion binder can be dewatered using a filter to moisture levels typically half that achieved for the filtration of fine particles following froth flotation. It is important, however, that the agglomerates are subjected to further high shear, prior to the filtration, to destroy the binder. If the emulsion binder is not destroyed prior to filtration, high product moistures are observed due to the bound water within the emulsion.

Furthermore, in a separate study, a model system consisting of silica conditioned to be hydrophobic using a surfactant was used to examine the mechanisms underpinning the agglomeration process using the emulsion binder. It was found that the network of thin oil films within the emulsion allow for the quick and efficient delivery of organic liquid to the surface of particles in the high shear environment of the agglomeration process [9]. This finding supported some earlier work using a fine coal feed, which illustrated the relationship between the organic liquid volumetric dosage required to achieve agglomeration and the specific surface area of the particles to be agglomerated [8]. The study of the model system also revealed that the emulsion binder can recover ultrafine, < 1 μm, particles with the same efficiency as coarser particles, > 100 μm, over the short time scale applied in the process [9]. Examination of the binder revealed that the thin oil films in the emulsion binder are permeable to water and it appears that it is this permeability that facilitates the recovery of the ultra-fine particles [9].

Due to the ability of the binder to rapidly recover ultra-fine particles, it was considered that the agglomeration technique may be suitable for processing fine, high ash coal; coal that is currently sent to tailings because it cannot be adequately handled by existing technologies. This study was therefore used to examine the ability of the emulsion binder to selectively agglomerate hydrophobic coal particles from a high ash, *i.e.* more difficult to process, feed in the continuous system, which has previously only been used to process a high quality coal feed with a low ash value of < 10%. The performance of the continuous process was also compared to the performance of the batch system, consisting of a high shear blender, for the same feed. The performance comparison was based upon the combustible recovery and product quality, as defined by ash content, for a given organic liquid (binder) dosage. The dewatering characteristics of the product agglomerates formed in the batch system were also examined.

2. Experimental methodology

2.1. Materials

The composition of the emulsion binder remained unchanged from previous work and therefore consisted of 95 vol% aqueous NaCl solution, 2.5 vol% kerosene, and 2.5 vol% sorbitan monooleate (SMO) [8,12]. Within the binder, the aqueous solution formed the dispersed phase, the oil formed the continuous phase, and the SMO acted as the emulsifier. The sorbitan monooleate and kerosene were sourced from Sigma-Aldrich and Recochem, respectively, and used without any physical or chemical modification. The internal aqueous phase was prepared using tap water containing 3% *w*/w sodium chloride, sourced from Cerebos Ltd. Tap water was also used as the suspending liquid in all of the experiments.

The feed material was a high ash (42%) bituminous coal sourced from the Hunter Valley, Australia. The feed was wet-screened at 260 μm to remove the larger particles. The feed was stored and sub-sampled immersed in water to limit surface oxidation of the hydrophobic particles. Storage of coal in water has been shown to delay oxidative aging by providing a barrier between the coal surface and air [14].

2.2. Preparation of the emulsion binder

Detailed descriptions of the procedure for the preparation of the emulsion binder can be found in previous publications [11,12]. Briefly,