



# A new method for ultra-fast concentration of hydrophobic particles



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## ABSTRACT

In froth flotation, fine hydrophobic particles selectively attach to the surface of air bubbles, in turn rising through the liquid and then more slowly as part of the foam that emerges from the system. This paper proposes a paradigm shift from the traditional use of air bubbles as the hydrophobic separation medium to potentially a far more powerful version that utilises a novel hydrophobic binder, a concentrated water in oil emulsion. We show empirically the oil consumption increases linearly with the specific surface area of the particles, with an average oil film thickness of 178 nm for fine coal particles, well below the level required for conventional oil agglomeration. The new approach is ultrafast, achieving agglomeration within seconds under batch conditions, with strong selectivity. We also show for the first time continuous steady state agglomeration can be achieved by simply passing the feed and binder suspensions through a partially closed ball valve. Here the residence time through the valve is less than 0.1 s. And, by subjecting the agglomerated product to further shear, the emulsion is inverted, releasing bound water. Pressure driven filtration then delivers remarkably low product moistures. Operational aspects of this new technology are discussed.

## 1. Introduction

In mining it is common practice to liberate the valuable components of the ore through a process of breakage and grinding (Kelly and Spottiswood, 1995). The challenge is to then recover those valuable particles while rejecting the waste ore. The traditional approach, for over a century, has involved the process of flotation, attaching fine hydrophobic particles to a hydrophobic medium, which has normally involved air bubbles (Wills, 1988). This paper proposes a new concept which utilises a novel hydrophobic binder technology, detailing for the first time recent research findings in achieving ultra-fast, steady state, recovery and concentration of fine hydrophobic particles using a novel hydrophobic binder medium. It is believed there are strong links between the new binder technology and the more traditional flotation process. The kinetics are governed by the rate of collision between the particles and the hydrophobic medium (Phan et al., 2003), and rapid adhesion and indeed selectivity are assumed to be initiated primarily via a long-range hydrophobic force (Israelachvili and Pashley, 1982; Zeng et al., 2016), leading to the binding of the hydrophobic particles with the hydrophobic medium. And, in some cases, the product is highly buoyant, assisting its recovery from the tailings. This paper identifies the final separation of the concentrate from the tailings as the rate limiting step in conventional flotation. However, by forming large agglomerates, it may be possible to remove this limitation, increasing

the processing rate by up to two orders of magnitude.

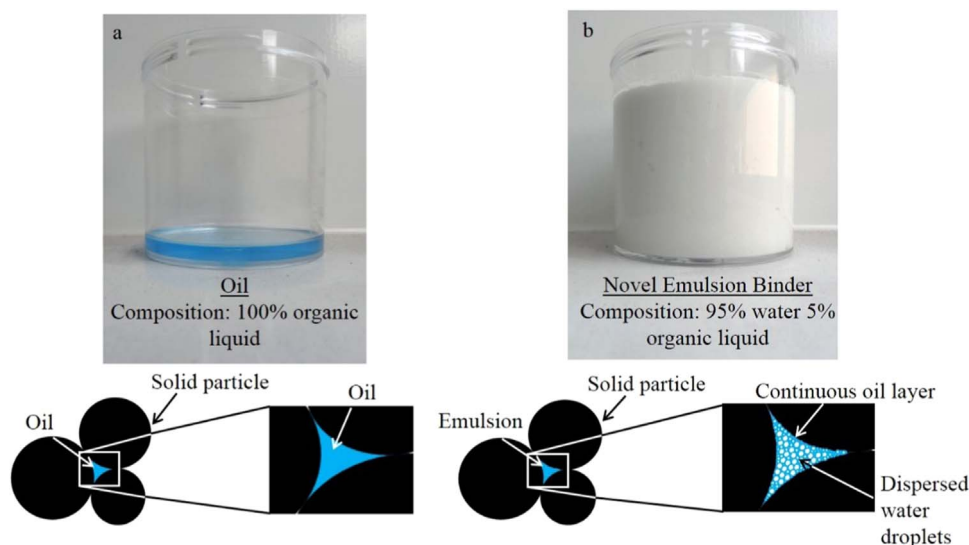
The original inspiration for developing a novel binder was the remarkable effectiveness of oil agglomeration, which involves the addition of oil and subsequent collision of hydrophobic particles, evolving large agglomerates that can be separated easily using a mechanical screen (Capes and Darcovich, 1984). This well-known process is not economic, requiring up to 200 kg of oil per tonne of product (Mehrotra et al., 1983; Swanson et al., 1977). Recently, Yoon et al. (2016) have achieved almost complete rejection of the aqueous phase, choosing to recycle the oil to deliver an economic process.

Here, we replaced the oil with a novel binder, described here as a highly viscous concentrated water in oil emulsion to deliver an economic process. This material has the physical characteristics of a low-fat spread, presenting an oil-like surface despite its aqueous interior bulk, even when divided into smaller portions. These smaller portions, which we describe as fragments, are typically of up to 95% aqueous phase (containing 3% by weight NaCl) dispersed into a 5% oil phase containing an emulsifier, sorbitan mono oleate. Thus, the binder is significantly more economic than pure oil, providing the necessary interfacial functionality of a binder via thin films of oil, while achieving the necessary space-filling functionality of a binder via the closely packed droplets of water.

Fig. 1 presents a comparison of the water in oil emulsion with a pure oil. The upper section of the figure shows a) the oil binder and b)

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**Fig. 1.** a) Pure oil binder and b) novel emulsion binder. The inserts below indicate the functionality of each binder in the formation of agglomerates.

the novel hydrophobic emulsion binder. It should be noted that both contain the same volume of organic liquid. In the lower section, the interfacial and space-filling functionalities of the two binders are also shown. As can be seen, the dispersed water drops of the novel binder fill the void space within the agglomerate, thus lowering the amount of oil required to fill this space.

The new binder is so viscous that, when dispersed into water, it forms irregular shaped fragments with a plastic-like rheology. The surface of the fragments, and even the 3D interior bulk, present an oil-like feel, promoting hydrophobic adhesion and providing a highly concentrated carrying capacity for accumulating hydrophobic particles. The fragments of white binder sweep out large volumes in a shear field, incorporating the hydrophobic particles at their surface, and then deeper into their bulk, while permitting additional hydrophobic particles to adhere to their surface. This mechanism is different to normal agglomeration, which relies on the efficient dispersion of the oil and slower initial wetting of the particle surface by the oil, followed by collisions between the agglomerating particles (Capes and Germain, 1982).

In the laboratory initial investigations were readily studied using a Waring variable speed blender (van Netten et al., 2014, 2015, 2016a). The feed used throughout all of the experiments was a low ash coal; coal being a naturally hydrophobic material. The early work only achieved a modest reduction in oil consumption compared to using a pure oil binder. However through a series of changes to the methodology the targeted ten-fold reduction in oil consumption was eventually achieved, meaning that organic liquid dosages as low as 0.5–1.5 wt% (dry product basis) were required to recover effectively all of the hydrophobic coal particles (van Netten et al., 2014, 2016a). It was also discovered the process could be completed within just 2–3 s of mixing, provided the binder was already divided into fragments (van Netten et al., 2016a). Typically, the black coal slurry “phase separates” into a distinct brown and black colour within seconds, indicating full recovery of the black particles into an agglomerated product. Fig. 2 shows this separation in a bench-scale blender. As can be seen in the figure, in the case of coal the product rises to the surface with buoyancy far stronger than would be expected for the level of oil used, perhaps due to the presence of some entrained air. This buoyancy can assist with the final separation, however the entire slurry can also simply be poured over a screen and washed to recover the agglomerated concentrate.

This paper follows on from the previous work, relating the organic liquid required to achieve agglomeration to the specific surface area of the hydrophobic particles, comparing the result with the much larger demands of conventional oil agglomeration. The paper also details the

development of the novel hydrophobic binder technology for the separation and concentration of hydrophobic coal particles from non-hydrophobic clay particles on a continuous basis. Continuous steady state experiments were carried out at a feed slurry flowrate of 2.1 m<sup>3</sup>/h, utilising little more than a 25 mm diameter ball valve to rapidly form the agglomerates in a fraction of a second. The paper also examines a novel method for dewatering the final product to moisture levels well below that currently possible within the industry.

## 2. Materials and methods

### 2.1. Materials

Sorbitan monooleate (SMO), sourced from Sigma-Aldrich was used as an emulsifier without any physical or chemical modification. Kerosene, sourced from Recochem, was also used without any physical or chemical modification. Tap water was used as the suspending liquid in the batch and continuous separation processes. Sodium chloride, sourced from Cerebos Ltd., was dissolved in tap water (3% w/w) and used to form the internal aqueous phase of the emulsion. Tap water from the Hunter region, Australia typically has a pH of 8.6, a conductivity of 200  $\mu\text{m}/\text{cm}$  and a sodium concentration of 21 mg/L.

The feed materials used in this work were Australian bituminous coals sourced from the Upper and Lower Hunter Valley. Each feed was received and stored in a wet form to inhibit surface oxidation of the hydrophobic particles. Size characterisation of the feed material was achieved by laser light scattering using a Mastersizer 3000.

### 2.2. Preparation of the emulsion binder

A detailed description of the preparation procedure for the emulsion binder can be found in previously published work (van Netten et al., 2014, 2016a), and further background on the rheological properties of the concentrated water in oil emulsion is given by Galvin et al. (2001). The composition of the emulsion remained unchanged from that described in the latter work (van Netten et al., 2016a) and was 95 vol% aqueous NaCl solution, 2.5 vol% kerosene, and 2.5 vol% sorbitan mono oleate. The NaCl solution consisted of 3 wt % NaCl and 97 wt% tap water. In short, the oil phase was prepared as a solution of the SMO within the kerosene. The aqueous salt solution was then gradually added to the oil phase, using a hand held mixer to form a water in oil emulsion. The addition of the aqueous phase continued until a viscous, concentrated, water in oil emulsion had been formed.

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