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van Netten, K.; Ernst, T.; Moreno-Atanasio, R.; Galvin, K. P. "Fine particle beneficiation through selective agglomeration with an emulsion binder", Published in *Industrial and Engineering Chemistry Research* Vol. 53, Issue 40, p. 15747-15754. (2014)

Available from: <http://dx.doi.org/10.1021/ie5027502>

Accessed from: <http://hdl.handle.net/1959.13/1301014>

Fine particle beneficiation through selective agglomeration with an emulsion binder

*Kim van Netten, * Roberto Moreno-Atanasio, and Kevin P. Galvin*

Centre for Advanced Particle Processing and Transport, Newcastle Institute for Energy and Resources, The University of Newcastle, Callaghan, NSW 2308, Australia

*kim.vannetten@uon.edu.au

A high internal phase (HIP) water-in-oil emulsion was used as the binder in the selective agglomeration of fine coal from an aqueous suspension of coal and mineral particles. Traditionally, this agglomeration is achieved by a pure oil, hydrophobic, binder. However, the high cost associated with using pure oil makes the process economically unfeasible. Therefore, the emulsion binder introduced in this work was motivated by the economic need to reduce the amount of organic liquid required in the process. The effect of agitation time during the agglomeration process and the composition of the emulsion on its performance as a binder were investigated. The best result obtained was for a HIP emulsion made from 3 wt% aqueous NaCl and diesel oil with sorbitan monooleate as the emulsifier. This emulsion had a dispersed phase volume fraction of 0.94 and achieved a seven-and-a-half-fold reduction in the amount of organic liquid required to achieve agglomeration.

1. Introduction

Fine coal beneficiation has become increasingly more important for the continued production of high quality coal products.¹ However, fine coal beneficiation also remains as one of the more difficult and expensive operations in coal preparation plants due to the limited effectiveness of the conventional technologies.^{1,2} Froth flotation machines and spiral concentrators are currently used to process fine coal although both technologies become less effective when there is a high proportion of clay present or there is a significant amount of ultra-fine, or slimes material.^{3,4,5} In these cases, if the fine coal is deemed to be too difficult or expensive to process it is discarded into tailings ponds and held indefinitely as a waste. Over time, however, these tailings ponds become a store of valuable resources and, due to their inherent nature, an environmental liability.⁶ Therefore, if a technology was developed that could recover this fine coal resource not only would site rehabilitation be an economic proposition, but the overall efficiency of any coal preparation plant would be greatly improved.⁷

In actual fact, a technique already exists that is capable of processing even the most difficult fine coal feeds; selective oil agglomeration.⁸ In this technique, oil is dispersed into an aqueous suspension of fine coal and mineral particles, preferentially wetting and agglomerating only the hydrophobic coal particles, permitting recovery using a screen separation.⁹ In general, 10 – 20 wt% (dry coal feed basis) of oil is required to successfully agglomerate a fine coal feed as, at this dosage, there is sufficient oil present to just fill the void spaces in the interior of the agglomerates, thus allowing the agglomerates to reach a peak in strength and sphericity.^{5, 8, 10, 11}

Oil agglomeration is a remarkable technique which routinely achieves a high quality beneficiation with the almost complete recovery of the combustible material.^{5, 12, 13} The process also appears to have no lower limit on the size of particle that can be processed and is not hindered

by the presence of clays, unlike its counterparts in the area of fine coal processing.^{8, 14} It would appear, from these highly beneficial attributes, that oil agglomeration is the perfect candidate for the processing of fine coal and it was for this reason a considerable amount of research was completed in this area.^{7, 10, 11, 12, 13, 15, 16, 17} However, in the end, it was concluded that the process was not economically feasible due, mainly, to the high cost of the oil required. Many authors noted that for oil agglomeration to be a commercial success the oil requirement would have to be greatly reduced.^{14, 15, 18} This need for a reduction in oil consumption was the motivation for the present study.

In this study a novel binder was introduced to replace the pure oil used in traditional oil agglomeration as a means of reducing the amount of organic liquid required. The novel binder used was a high internal phase (HIP) water-in-oil emulsion. A HIP emulsion is an emulsion in which the dispersed phase has a volume fraction of at least 0.74.¹⁹ Figure 1 presents a light microscope image of a coarse HIP water-in-oil emulsion which has a dispersed phase volume fraction of 0.84. Also presented in Figure 1 is a schematic representation of one of the dispersed water droplets within the continuous oil phase which has been stabilized by the emulsifier.

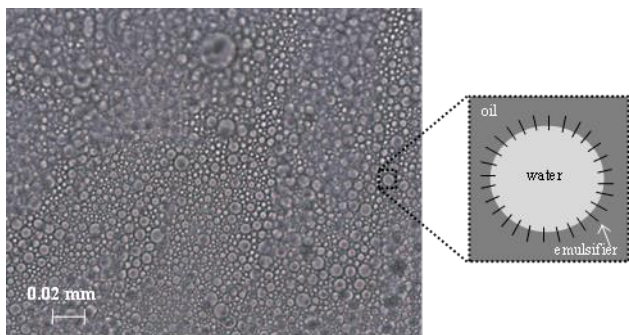


Figure 1: A light microscope image and a schematic representation of a HIP water-in-oil emulsion with a dispersed phase volume fraction of 0.84.

Figure 1 shows the tightly packed water droplets that make up the majority of the emulsion and the surrounding thin, continuous layer of oil. It was hypothesized that the use of this type of emulsion as the binder would lead to a reduction in the amount of oil required as the space filling functionality of the binder is occupied by water, while the surface functionality of the oil remains. To further clarify this point, Figure 2 presents a schematic of agglomerated particles held together by a liquid binder. The liquid binder used in case a) is pure oil and in the liquid binder used in case b) is a high internal phase water-in-oil emulsion.

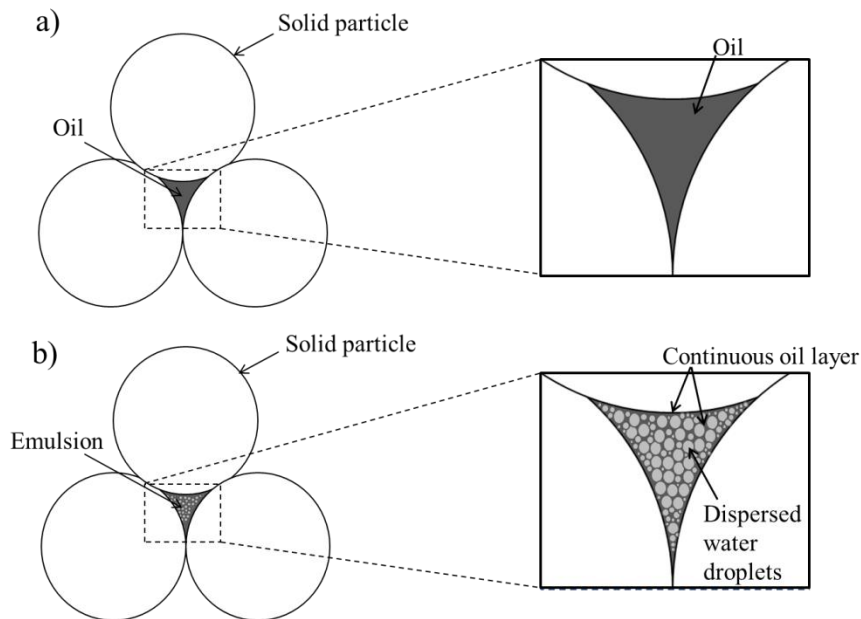


Figure 2: A schematic of agglomerated particles using a) a pure oil binder and b) a high internal phase water-in-oil emulsion binder.

As shown in Figure 2, both liquid binders selectively adhere to the surface of hydrophobic coal particles as both are hydrophobic materials. That is, pure oils, such as diesel or kerosene, are inherently hydrophobic and the HIP water-in-oil emulsion is hydrophobic as the oil forms the continuous phase. In addition, both binders fill the space within the agglomerate, thus satisfying

the condition for the creation of strong, spherical agglomerates. However, as can be seen in Figure 2b) when a HIP water-in-oil emulsion is used as the binder, the void space is primarily filled by the dispersed water droplets within the emulsion and filled only to a small extent by the oil. This means that the volume of oil required to create agglomerates is theoretically reduced through the use of a HIP water-in-oil emulsion as the binder.

The reduction in the oil requirement can be quantified for the limiting case in which the HIP water-in-oil emulsion is as effective as pure oil in agglomerating fine coal. In this case, it is assumed that the same volume of binder is required to achieve agglomeration regardless of which hydrophobic liquid is used. Then, to calculate the maximum theoretical reduction in the oil requirement the oil content of an emulsion binder is compared to that of a pure oil. For example, if a HIP water-in-oil emulsion with a dispersed, aqueous phase volume fraction of 0.90 was used, a 10-fold reduction in the oil requirement could be achieved as only one-tenth of the binder is organic liquid. This calculation was repeated for a number of dispersed, aqueous phase volume fractions to produce Figure 3. Figure 3 presents the relationship between the maximum theoretical reduction in the oil requirement and the volume fraction of the aqueous phase within the emulsion binder.

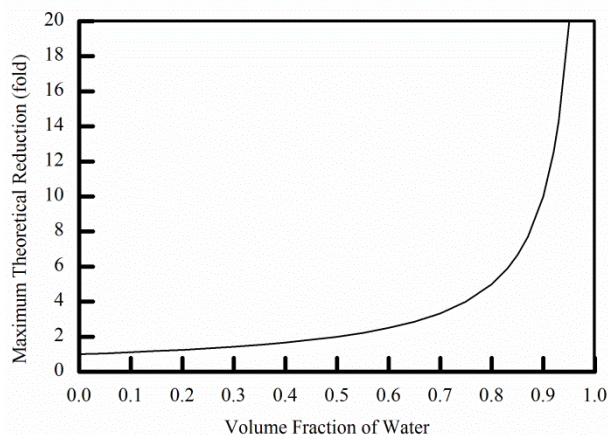


Figure 3: The maximum theoretical reduction in the organic liquid requirement achievable through use of the emulsion (as compared to a pure oil) as a function of the volume fraction of water within the emulsion.

Figure 3 clearly shows that as the volume fraction of the water increases the reduction in the amount of oil required also increases and thus why HIP emulsions were used in this work. In particular, Figure 3 shows that if an emulsion with a dispersed, aqueous phase volume fraction of between 0.90 and 0.95 was used, a 10 – 20-fold reduction in the volume of organic liquid required could be achieved. This kind of reduction would mean that the oil requirement in an agglomeration process would change from 10 – 20 wt% to 1 – 2 wt%, making the process more economically feasible. It should be remembered, however, that these reduction values are dependent upon the emulsion binder being as effective in agglomerating fine coal as pure oil. This means the emulsion binder is assumed to: agglomerates the coal using the same mechanism as pure oil; selectively adhere to the surface of coal in the same manner as pure oil; and be effectively dispersed under high shear in the coal slurry in such a way that the water forming the binder is not released. In the agglomeration process, high shear rates are required, initially, to ensure dispersion of the binder and then, subsequently, for excellent particle-binder and particle-particle contact.¹⁰

Therefore, this study was carried out to determine whether the HIP emulsion would actually agglomerate fine coal and if so, whether it was in a manner that was comparable to pure oil. Oil agglomeration experiments using pure diesel as the binder were also carried out to serve as a comparison with the result achieved by the emulsion binder.

2. Experimental system

2.1 Materials

The diesel was sourced from a local fuel distribution center. The viscosity and density of automotive diesel are 0.0025 Pa.s and 830 kg/m³, respectively.²⁰ The emulsifier used in the emulsion binder, unless noted otherwise, was an ethanolamine derivative of polyisobutylene and is referred to from here on in as the PIB emulsifier.^{21, 22} This PIB emulsifier was sourced from Orica Pty Ltd and was used without any further chemical or physical modifications. Span 80 (sorbitan mono-oleate), sourced from Sigma-Aldrich, was also used as the emulsifier in a select number of experiments and was used without any further chemical or physical modifications. Tap water was used as the suspending liquid for all agglomeration experiments. Tap water was also used as the aqueous, dispersed phase of the emulsion binder. In some cases, sodium chloride (3 wt%) was dissolved in the tap water prior to its inclusion within the emulsion binder.

An Australian coal, sourced from the Lower Hunter Valley, was used in this study. The coal was a high quality coking coal with an ash % of 10%. To maintain the surface hydrophobicity of the coal and, thus, limit surface oxidation, all samples were received and stored submerged in water. Storage of coal in water has been shown to delay oxidative aging by providing a barrier between the coal surface and air.²³ The size distribution of the feed sample was measured using a Mastersizer 2000 (Malvern Instruments, Malvern, UK). The Mastersizer 2000 measures particle size distributions by laser diffraction. A laser is passed through a dispersed particulate sample and the angular variation in the intensity of scattered light is measured. The liquid medium used to disperse the particles was a 50% w/w ethanol/water mixture. A mixture of ethanol and water was used as the dispersant to facilitate the submersion of the dry coal particles. The results from the size analysis are presented in Figure 4. As can be seen, the feed had a significant proportion of fine material.

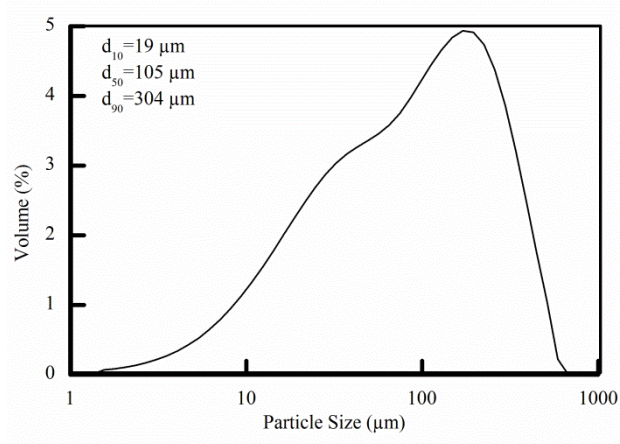


Figure 4: The size distribution of the coal feed used in the agglomeration experiments measured by laser diffraction using the Mastersizer 2000.

2.2 Preparation of the High Internal Phase Emulsion

The high internal phase emulsion binder was prepared from diesel, an emulsifier, and water. The water formed the dispersed phase of the emulsion and had a volume fraction of at least 0.84. The continuous phase consisted of diesel and emulsifier in a 1:1 ratio, by weight. The emulsion binder was prepared in 310 ml batches prior to each set of experiments. To prepare the emulsion binder, the organic components were placed in a stainless steel mixing bowl. The comparably large volume of water was then slowly added in small increments to the organic phase under continuous mixing provided by a Russell Hobbs hand-held mixer (350 watt motor). To ensure that phase inversion did not occur during mixing the volume of water added at one time was limited to 10 – 15 ml. Furthermore, this small volume of water was completely incorporated into the organic phase prior to the addition of the next volume of water. It should be noted that the water was considered to be incorporated into the organic phase when water droplets were no longer visible on the surface of the hydrophobic emulsion. The total time taken to add the water was usually 5 min. Presented in Figure 5 is, a) the initial mixture of the organic components of the emulsion and b) the final

emulsion product after all the water has been incorporated into the organic phase. The emulsion pictured has a dispersed phase volume fraction of 0.84. As can be seen in Figure 5 the appearance of the mixture changes from a clear, thin orange liquid into a white, opaque, firm substance (due to the addition of the water). It should also be noted that both of the mixtures pictured in Figure 5 are hydrophobic and contain the same volume of organic liquid, however, there is a much greater volume of the mixture pictured in Figure 5b.

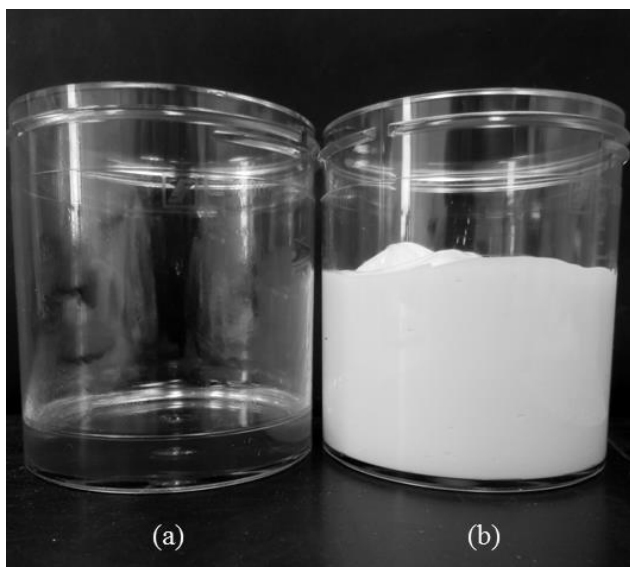


Figure 5: (a) the organic liquids (diesel and emulsifier) prior to the addition of any water (b) the final emulsion product after all of the water has been incorporated into the organic phase.

2.3 Selective agglomeration

In the agglomeration experiments, 500 ml of coal slurry, with a solids concentration of approximately 10 wt%, was placed in a 1 L glass beaker which was positioned on a Waring variable speed blender. The sample was agitated at 12 000 – 20 000 rpm such that the fine coal was dispersed prior to the addition of the hydrophobic binder. The binder (either the pure diesel, the emulsion binder or a straight mixture of diesel and emulsifier) was then added in a single dose and the agitation was continued until the agglomeration was complete. For successful

agglomeration tests (where there was sufficient binder present) the point at which agglomeration was complete was distinct as the bulk liquid turned from being black, in color, to a sandy yellow. The change in the color of the bulk liquid was a result of the agglomeration, and growth, of the fine coal agglomerates. Figure 6 shows the agglomerated suspension. Large, black coal agglomerates can be seen in a mineral-rich liquid.



Figure 6: The agglomerated suspension. Large discrete agglomerates can be seen in mineral-rich water.

To retrieve the product coal agglomerates, the agglomerated suspension was passed over a screen with an aperture size of $355\text{ }\mu\text{m}$. The coal agglomerates remained on top of the screen while the finely dispersed mineral matter passed through the screen with the water to form the reject. The product agglomerates were washed while on the screen to remove any entrapped mineral matter. Both the product and reject samples were dried in an oven (set at $110\text{ }^{\circ}\text{C}$) and weighed.

The yield of a given agglomeration experiment was defined as the mass of the dried, agglomerated product as a fraction of the total dry coal feed. In the experiments in which the kinetics of agglomeration were being investigated the suspension was not screened rather, the entire agglomerated suspension was dried and the size distribution was measured by laser diffraction using the Mastersizer 2000. The dispersant used for the laser diffraction was a 50% w/w ethanol/water mixture.

3. Results and Discussion

3.1 Influence of agitation time

Preliminary experiments (not shown) indicated that agglomeration using the emulsion binder was relatively fast compared to diesel and that extended agitation of the agglomerated coal slurry would result in a decrease in yield. As a result of these observations an investigation into the influence of agitation time on the agglomeration process using the emulsion binder was deemed necessary. Figure 7 presents the change in the size distribution of the coal sample at different stages during the agitation. The size distribution of the agglomerated samples was measured by the Mastersizer 2000. The liquid medium in which the particles were dispersed was a 50% w/w ethanol/water mixture. A mixture of ethanol and water was used to facilitate the submersion of the dry agglomerates into the liquid medium.

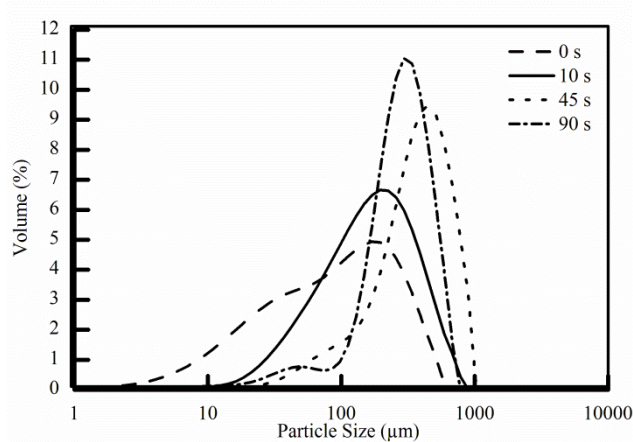


Figure 7: The change in the size distribution of the coal sample at different stages during the agitation measured by laser diffraction using the Mastersizer 2000. The binder used was the HIP water-in-oil emulsion. Note logarithmic scale for particle size.

Figure 7 shows a number of size distribution curves for different times during the agglomeration process. It can be seen that the size distribution of the feed (0 s) is quite wide, with a high proportion of ultra-fine particles ($< 100 \mu\text{m}$). However, after only 10 s of agitation, a significant proportion of these ultra-fine particles have been collected and formed into larger agglomerates and the size distribution has narrowed and shifted to the right. By 45 s the size distribution has narrowed significantly and only a small proportion of the particles remaining are $< 100 \mu\text{m}$. The continued growth of the agglomerates is also reflected in the further movement of the size distribution to the right. Observation of the agglomeration process indicated that the agglomeration was complete at about 45 s as the bulk liquid had changed from being black in color to a sandy yellow. However, the agitation was allowed to continue for a total of 90 s to monitor any further changes in the size distribution. The size distribution for 90 s showed a further narrowing of the distribution with almost all of the ultra-fine particles collected and formed into larger

agglomerates. In addition, the size distribution also moved slightly to the left, indicating that the mean agglomerate diameter had decreased.

Figure 7 clearly shows a growth process as the size distribution narrows and the mean agglomerate size increases over the course of the agitation time. To further highlight this growth process, Figure 8 presents the change in the mean diameter of the agglomerates during the agglomeration process.

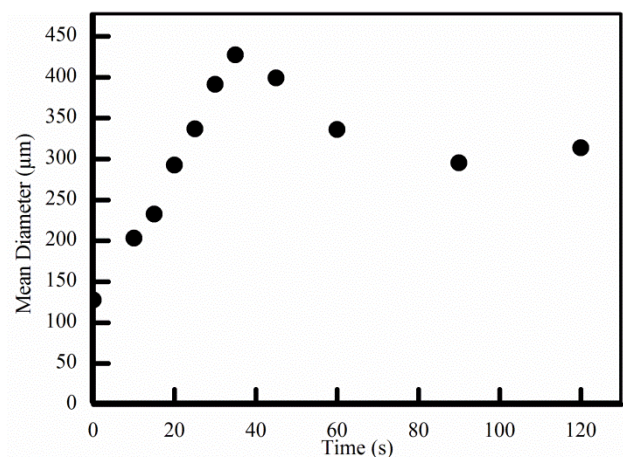


Figure 8: The mean diameter of the agglomerates as a function of agitation time. The binder used was the water-in-oil emulsion.

Figure 8 clearly shows that the growth of the agglomerates occurs rapidly. Within 35 s, the feed particles, with a mean diameter of 128 μm, have grown into agglomerates with a mean diameter of 427 μm. However, it is also interesting to note that after approximately 40 s the mean diameter of the agglomerates drops and plateaus at around 300 μm. This decrease in size with extended agitation is most likely due to the continued shearing and reworking of the agglomerates, by the mixer, to an equilibrium size. However, the decrease may also be an indication that the emulsion binder is being broken down in the turbulent, aqueous environment of the agglomeration process.

Emulsion breakdown would result in a decrease in agglomerate diameter as there would no longer be sufficient binder present to maintain the structural integrity of the agglomerates.

3.2 Initial binder performance comparison

In the previous section, it was shown that the emulsion binder can agglomerate a fine coal feed. Therefore, the following set of experiments was used to conduct an initial performance comparison of the different binders. The performance of a binder is quantified, in this work, by the organic liquid dosage required to achieve a given yield, where the organic liquid dosage is defined as:

$$\text{Organic Liquid Dosage} = \frac{\text{mass organic liquid}}{\text{mass of coal feed}} \times 100\%$$

Figure 9 presents the results from the agglomeration experiment in which the emulsion binder was used. As a consequence of the results presented in Figures 7 and 8, the agitation time used in experiments in which the emulsion binder was used was set at 40 s. Also presented in Figure 9 are the results from experiments in which pure diesel was used as the binder. For completeness, a 50:50 mixture of diesel and emulsifier was also tested. The agitation time used for the pure diesel and the diesel/emulsifier mixture was 120 s. It should be noted that the pure diesel and the diesel/emulsifier mixture comprise entirely of organic liquid. However, only a small fraction (0.16) of the emulsion binder is organic liquid and thus, only the mass of the emulsifier and diesel are considered in the calculation of the organic liquid dosage. Trend lines have been added to each data set.

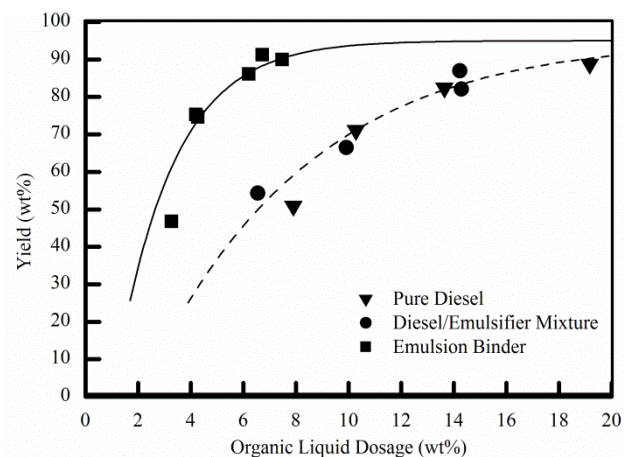


Figure 9: The yield obtained using three different binders. The diesel and the diesel and emulsifier mixture comprise entirely of organic liquid, whereas the emulsion has only a small fraction of organic liquid (emulsifier and diesel) and the remainder is water.

As can be seen in Figure 9 each data set displays a similar trend. Initially, increasing the amount of organic liquid results in an increase in the yield obtained. This increase in yield continues until there is sufficient binder present to fully agglomerate all the combustible material such that is recoverable by screening. After this point, a plateau is observed as further additions of binding liquid only serve to strengthen and grow the agglomerates. As expected, the results for the diesel/emulsifier binder are consistent with the results for the pure diesel binder. This result agrees with the results of Capes and Germain which showed that under the right mixing conditions, oils of different compositions and viscosities could be made to achieve similar recoveries for a given organic liquid dosage.⁸

However, a comparison between the results for pure diesel and the emulsion binder revealed a three-fold reduction in the organic liquid required to achieve a given yield. For example, to achieve a well agglomerated product (i.e. reach the plateau in yield), the emulsion binder required 5 - 6 wt% organic liquid while the pure diesel required 16 - 17 wt%. This was an encouraging result

however, as shown in Figure 3, if the binders are assumed to be equally effective in agglomerating fine coal then the reduction should be closer to six-fold (for an emulsion with a dispersed phase volume fraction of 0.84). Therefore, it appeared that the full benefit of creating the emulsion was not being realized and it was considered that this could be due to break down of the emulsion binder within the agglomeration process.

During the dispersal of the emulsion binder in the aqueous coal slurry it is of critical importance that emulsion does not degrade or break down as this would nullify the purpose of using the emulsion binder in the first place. However, according to the literature, systems in which an emulsion is dispersed into another suspending liquid (double emulsions) are known to be quite unstable, especially when the emulsion to be dispersed is highly concentrated (i.e. has a high internal phase ratio).²⁴ This instability is, in part, related to the tendency of the internal water of the emulsion to be released into the external water phase.²⁴ This release may occur by diffusion and coalescence of the internal water droplets with the external water phase. Parameters such as shear rate, emulsion composition and internal droplet diameter have been shown to influence the rate with which these destabilizing processes occur.^{24, 25}

3.3 Influence of electrolytes within the dispersed phase of the emulsion

In the work presented thus far, tap water was used to form the dispersed phase of the emulsion. However, as the stability of the emulsion binder appeared to be an issue in the agglomeration process, the influence of electrolytes (within the dispersed phase of the emulsion) on the performance of the emulsion binder was investigated. It is well known the presence of electrolytes within the dispersed, aqueous phase of an emulsion retard the rate of diffusion of water from the small to large internal droplets (Ostwald ripening) and, the rate of droplet coalescence due to film

rupture.^{26, 27} By impeding the growth of the internal droplets, the electrolyte therefore serves to improve the stability of the emulsion as the internal droplets remain small.²⁸ Therefore, an emulsion binder was made with a 3 wt% aqueous sodium chloride solution as the dispersed phase and tested in the agglomeration process. Figure 10 presents the results for the 3 wt% aqueous NaCl-in-diesel emulsion, which had a dispersed, aqueous phase volume fraction of 0.84. Also presented in Figure 10 are the results from Figure 9 for the pure diesel binder and the emulsion binder (made from tap water), for comparison. Trend lines have been added for each data set.

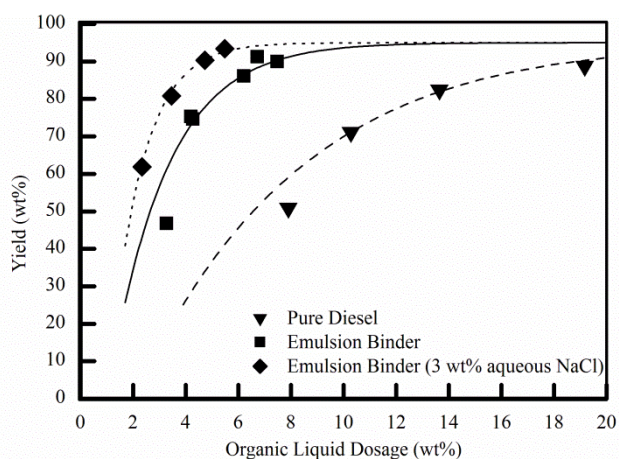


Figure 10: The yield obtained using three different binders. Both emulsion binders have a dispersed, aqueous phase volume fraction of 0.84.

Figure 10 shows that the inclusion of salt into the dispersed, aqueous phase of the emulsion binder has led to an improvement in the performance of the emulsion binder as indicated by the curve shifting further to the left (i.e. to lower organic liquid dosages). This improvement is of the order of a four-fold reduction in the organic liquid requirement (as compared to pure diesel), which is greater than the three-fold reduction achieved by the emulsion binder made with tap water. These

results, therefore, suggest that by hindering the growth of the internal water droplets, the stability of the emulsion during dispersal within the agglomeration process has been improved.

3.4 Influence of the dispersed phase volume fraction

Figure 3 showed that the use of emulsions with higher dispersed phase volume fractions can theoretically lead to greater reductions in the amount of organic liquid required to achieve agglomeration. Greater reductions can be achieved with these highly concentrated emulsions as the continuous oil phase separating the tightly packed water droplets becomes thinner and thus the oil is able to create more hydrophobic surface area. To investigate this notion, the effects of using emulsions with different dispersed, aqueous phase volume fractions were investigated as shown in Figure 11. Once again, the result for the pure diesel binder (from Figure 9) is also shown, along with the result for the 3 wt% aqueous NaCl-in-diesel emulsion binder with a dispersed phase volume fraction of 0.84. As the inclusion of salt into the dispersed phase of the emulsion was shown to improve its stability, all of the results presented in this section are for emulsion made from a 3 wt% aqueous salt solution.

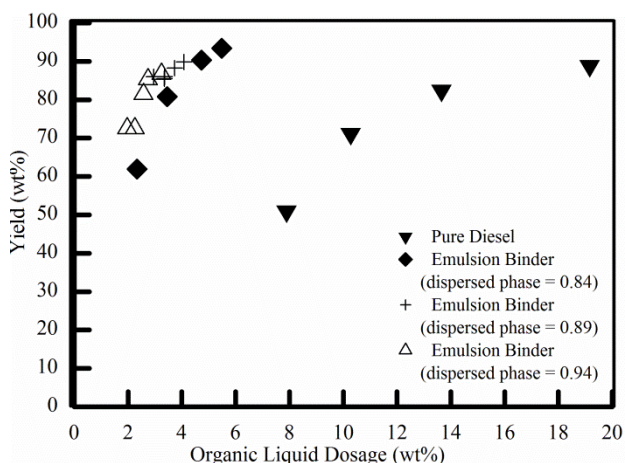


Figure 11: The yield obtained using various binders. The emulsion binders comprise of diesel, emulsifier and 3wt% aqueous salt solution.

Small improvements were achieved through the use of more concentrated emulsions, as indicated by the results for the emulsions with dispersed phase volume fractions of 0.89 and 0.94 shifting further to the left (i.e. to lower organic liquid dosages). The emulsion with a dispersed phase volume fraction of 0.89 achieved approximately a five-fold reduction in the organic liquid requirement, while the emulsion with a dispersed phase volume fraction of 0.94 achieved the best result with a six-fold reduction (as compared to pure diesel). On re-inspection of Figure 3 it can be seen that the reductions achieved by the emulsion binder are significantly less than were predicted. That is, the reductions in organic liquid achieved by the emulsions with dispersed phase volume fractions of 0.89 and 0.94 should have been nine-fold and seventeen-fold, respectively. Consequently, it may be suggested that degradation of the emulsion is still occurring during the agglomeration process. However, it may also be that the maximum theoretical reductions depicted in Figure 3 cannot be realized as other factors limit the functionality of the HIP emulsion as a binder.

3.5 Influence of emulsifier type

In this study thus far, the entirety of the work has been completed with emulsion binders made from one emulsifier: the PIB emulsifier. The PIB emulsifier was selected as it is an emulsifier with a low hydrophile - lipophile (HLB) value which means that it is soluble in the oil phase and therefore, by Bancroft's rule, will form a W/O emulsion.^{29, 30} However, while the PIB emulsifier did allow for the successful creation of HIP W/O emulsions, it was not known whether it was the most suitable emulsifier for this original application. Therefore, a small set of experiments were undertaken using an emulsion binder made from a different emulsifier, Span 80. Once again a 3 wt% aqueous salt solution was used for the dispersed phase and the dispersed phase had a volume fraction of 0.89. Figure 12 presents the results from these experiments, along with the results from

Figure 11 for the emulsion binder made with the PIB emulsifier and, also, with an aqueous phase volume fraction of 0.89. The results for the pure diesel binder are also presented for comparison.

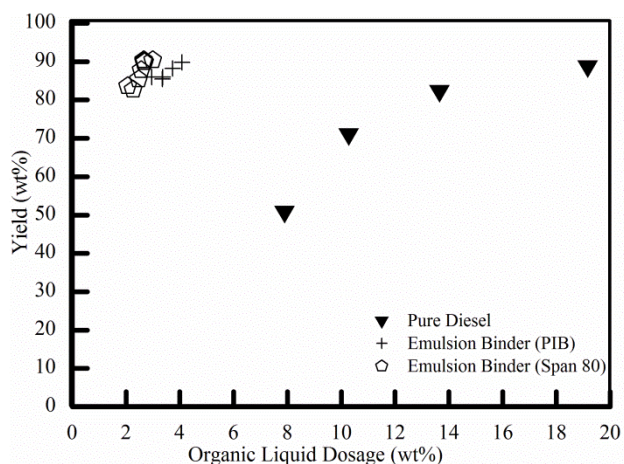


Figure 12: The yield obtained using various binders. The emulsion binders comprise of diesel, emulsifier and 3wt% aqueous salt solution.

Figure 12 shows that a further, small improvement has been made through the use of Span 80 as the emulsifier as a decreased amount of organic liquid is required to achieve a given yield. This result is of the order of a seven-and-a-half-fold reduction in the amount of organic liquid required, as compared to the pure diesel binder, and is greater than the five-fold reduction achieved by the emulsion binder made with the PIB emulsifier. As Span 80 has been shown, in the past, to provide lower stability for HIP aqueous salt-in-oil emulsions than a PIB type emulsifier, this was a surprising result.³¹ It was considered that an emulsion binder with a lower stability would break down more rapidly and, thus, result in lower yields for a given organic liquid dosage. As the opposite effect has been observed in Figure 12, it suggests that the use of Span 80 has resulted in some other beneficial change in the properties of the emulsion binder. Further work is, therefore, required in this area to establish the ideal properties of the HIP emulsion for the application of agglomeration of fine coal.

3.6 Economic Consideration

The motivation for this work was the economic need to reduce the amount of organic liquid required in the agglomeration of fine coal. Thus, the study would not be complete without a preliminary estimate of the cost reduction achieved through the use of the emulsion binder. The emulsion binder that achieved the greatest reduction in the organic liquid requirement had an organic phase made from Span 80 and diesel and, thus, this formulation would be preferred in future applications of this work. Following on, Span 80 and diesel can be sourced at approximately the same price which means that the seven-and-a-half-fold reduction in the volume of oil required to achieve agglomeration also applies to the cost of the oil. Therefore, through the implementation of the emulsion binder it can be stated that the cost of the organic liquid is reduced by a factor of seven-and-a-half when compared to a similar process using a pure oil binder. It is anticipated that there would also be capital cost reductions due to the reduced residence time required when using the novel binder, though those considerations are considered to be outside the scope of this purely technical paper.

4.0 Conclusion

This study has shown that fine coal can be successfully agglomerated using a high internal phase water-in-oil emulsion. The emulsion was tested in an attempt to find an economical substitute for the pure oil binder used in the traditional oil agglomeration process. Preliminary work with the emulsion binder indicated that the stability of the emulsion within the turbulent, aqueous environment and the tendency for the emulsion to breakdown or degrade may be an issue. Degradation of the emulsion is undesirable as it negates the benefit of having created the emulsion in the first place. The presence of salt within the aqueous, dispersed phase of the emulsion was shown to have a positive effect on the performance of the emulsion binder as the amount of binder,

and thus organic liquid, required to achieve agglomeration was reduced. The dispersed phase volume fraction was also shown to have a small effect on the performance of the emulsion binder. By increasing the dispersed, aqueous phase volume fraction of the emulsion, the amount of organic liquid required to achieve agglomeration was further reduced. The best result for emulsions made from the PIB emulsifier was for a 3 wt% aqueous NaCl-in-diesel emulsion with a dispersed phase volume fraction of 0.94, which achieved a six-fold reduction in the amount of organic liquid required as compared to tests using pure diesel. However, when a different emulsifier, Span 80, was used to form the emulsion binder, a seven-and-a-half-fold reduction was achieved. This result indicates that Span 80 is more suitable than the PIB emulsifier for use in this application. In addition, Span 80 is a low cost emulsifier which is similar in price to diesel. This means that the seven-and-a-half-fold reduction in the volume of organic liquid required to achieve agglomeration also equates to a seven-and-a-half-fold reduction in the cost of organic liquid required in the process. Future work will explore the effect of the properties of the emulsion binder on its ability to agglomerate fine coal.

ACKNOWLEDGMENT

The financial support of the Australian Research Council (ARC) and the Australian Coal Research Program (ACARP) for this project was greatly appreciated.

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Figure 1: A light microscope image and a schematic representation of a HIP water-in-oil emulsion with a dispersed phase volume fraction of 0.84.

Figure 2: A schematic of agglomerated particles using a) a pure oil binder and b) a high internal phase water-in-oil emulsion binder.

Figure 3: The maximum theoretical reduction in the organic liquid requirement achievable through use of the emulsion (as compared to a pure oil) as a function of the volume fraction of water within the emulsion.

Figure 4: The size distribution of the coal feed used in the agglomeration experiments measured by laser diffraction using the Mastersizer 2000.

Figure 5: (a) the organic liquids (diesel and emulsifier) prior to the addition of any water (b) the final emulsion product after all of the water has been incorporated into the organic phase.

Figure 6: The agglomerated suspension. Large discrete agglomerates can be seen in mineral-rich water.

Figure 7: The change in the size distribution of the coal sample at different stages during the agitation measured by laser diffraction using the Mastersizer 2000. The binder used was the HIP water-in-oil emulsion. Note logarithmic scale for particle size.

Figure 8: The mean diameter of the agglomerates as a function of agitation time. The binder used was the water-in-oil emulsion.

Figure 9: The yield obtained using three different binders. The diesel and the diesel and emulsifier mixture comprise entirely of organic liquid, whereas the emulsion has only a small fraction of organic liquid (emulsifier and diesel) and the remainder is water.

Figure 10: The yield obtained using three different binders. Both emulsion binders have a dispersed, aqueous phase volume fraction of 0.84.

Figure 11: The yield obtained using various binders. The emulsion binders comprise of diesel, emulsifier and 3wt% aqueous salt solution.

Figure 12: The yield obtained using various binders. The emulsion binders comprise of diesel, emulsifier and 3wt% aqueous salt solution.