

Coagulation and Flocculation in the Mining Industry

by
L. J. Connelly
P. F. Richardson
Nalco Chemical Company

INTRODUCTION

Over the last several decades, use of synthetic, organic, water-soluble polymers in solid/liquid separation processes has increased dramatically. These polymers, coagulants and flocculants, have gained wide acceptance in mineral beneficiation processes, as well.

This paper begins with a brief review on why these products are used in mineral beneficiation processes. Background information on the requirements for development of coagulants and flocculants and basic polymer chemistry will then follow. Since flocculants find greater use in mining applications, greater emphasis will be placed on flocculation. The "primary roles" of the functional groups in these polymers will be covered and supported by their areas of industrial application. The paper will close with a review of how other parameters ultimately have an impact on product choice and cost to the user.

The Need for Coagulants and Flocculants

Generally, mineral processors recover the desired mineral from the gangue by use of physical and/or chemical means. In some instances, the ore is treated in a manner which solubilizes the desired material away from the gangue. In other cases, differences in physical properties such as density, magnetic properties, surface chemistry, etc., are used to make this separation. Use of coagulants and/or flocculants is practiced in order to separate the gangue from the desired material or to allow re-use of the water in the process. Coagulants and flocculants enable the efficient separation of the solids from water at acceptable rates of production.

Solids in nature normally are negatively charged. While the electrostatic charge (zeta potential) on the particle can strongly influence its tendency to agglomerate and settle, other factors such as particle size, particle density, and liquid density come into play as well.

Stokes' Law for spherical particles handles these other factors well.

$$\text{Stokes' Law: } v = \frac{2g r^2 (d_1 - d_2)}{9\eta}$$

where V is the final velocity of the sphere, r is the radius of the sphere, d_1 is the density of the sphere, d_2 is the density of the liquid, η is the coefficient of viscosity and g is the gravitational constant. Table 1 shows the calculated times for a particle with a density of 2.0 g/cc to settle one foot as the diameter of the particle decreases. The table also shows how the total surface area increases and settling rate decreases as the particle size decreases. Dispersions of particles less than about 0.0001 mm are called colloids. Agglomeration of the particles will result in faster settling rates, but occurs only if there are collisions between particles. While collisions occur due to thermal Brownian motion (Perikinetic agglomeration), the rate of collisions can be enhanced by induced velocity gradients in the slurry (Orthokinetic agglomeration). Depending on the balance of attractive and repulsive forces between the particles, a collision between particles may or may not result in the formation

Table 1 — Effect of particle size on settling rate

Diameter of Particle, mm	Order of Size	Total Surface Area*, cm ²	Time required to settle 1 ft**
10	Gravel	3.142	0.03 sec.
1	Coarse sand	3.142 x 10 ¹	0.3 sec.
0.1	Fine sand	3.142 x 10 ²	33 sec.
0.01	Silt	3.142 x 10 ³	55 min.
0.001	Bacteria	3.142 x 10 ⁴	92 hr.
0.0001	Colloidal	3.142 x 10 ⁵	384 days
0.00001	Colloidal	3.142 x 10 ⁶	105 years

*Area for particles of indicated size produced from a particle 10 mm in diameter.

**Calculation based on a sphere with a specific gravity of 2.0 at a temperature of 25° C.

of an agglomerate. Attractive forces are due to Van der Waals' interaction while repulsive forces are due to the fact that the particles carry a surface charge and are kept apart by electrostatic repulsion.

In an aqueous suspension, the particles are surrounded by ions forming an electrical double layer consisting of adsorbed ions (Stern layer) and more diffuse ions (Gouy-Chapman region). In order for particles to agglomerate, they must get close enough so that the Van der Waals' forces of attraction can overcome the electrostatic repulsion. Earlier work has treated this quantitatively, and the theory is known as the DLVO theory after Derjaguin and Landau,¹ and Verwey and Overbeek.²

For purposes of this presentation, coagulation and flocculation are defined as follows:

Coagulation: The process of reducing the surface charge (minimize electrostatic forces) on solids to the point where Van der Waals forces can predominate and cause agglomeration of the suspended particles.

A chemical which brings this about is a *coagulant*.

Flocculation: The process of agglomeration of suspended solids in which no substantial change of surface charge has been accomplished.

A chemical which brings this about is a *flocculant*.

An important point to keep in mind is that the charge (often measured as zeta potential) at the surface of a colloid or particle does not have to be zero to allow agglomeration to take place. Most solid/liquid separation processes in mining employ products which are not designed to have any significant influence on the surface charge of a particle. Since flocculants have a wider range of use in mining than coagulants, they will receive the primary emphasis in this presentation.

Mineral processing industries which find the need for *coagulants* are coal, taconite, soda ash, sand and gravel, and to a lesser extent, the uranium industry.

As indicated earlier, *flocculants* in mining enjoy a greater range of applications. These industries include coal, bauxite, phosphate, potash, copper, sand and gravel, cement, soda ash, copper, silver and gold, beryllium, lead, and zinc.

As stated previously, most suspended solids in aqueous slurries exhibit an over-all negative charge. Most flocculants used in mining applications are either nonionic or anionic (negatively charged). Anionic polymers, however, have a wider range of applications. At first glance, agglomeration of negatively charged particles with negatively charged polymers may appear contradictory.

Flocculants used in the mining industry are believed to act via a bridging mechanism, whereby the polymer molecule adsorbs onto two or more particles, physically holding them together. In mineral processing a number of adsorption mechanisms have been suggested. Based on where various types of flocculants are utilized in mining applications, it is felt that hydrogen bonding be-

tween polar groups is the most important mechanism. Another mechanism which is believed to be important is adsorption due to electrostatic interactions between oppositely charged sites on the polymer and on the particle. Theoretical models have been developed by several researchers on the structure of adsorbed polymers.^{3,4,5} The polymer adsorbs on the particle through functional groups along the chain with loops extending out into the solution. Both adsorption and configuration of the polymer are influenced by properties of the solids, polymer chemistry, and the aqueous environment.

Requirements for Development of Coagulants and Flocculants

Although there are differences of opinion as to the precise mechanism involved in coagulation and flocculation, there is general agreement that these are dynamic processes involving adsorption and desorption.

Since these are dynamic processes and both adsorption and desorption are taking place at the same time, it seems reasonable that, to attain maximum benefit, coagulants or flocculants should contain a sufficient number of functional or reactive groups in order to minimize the probability of complete desorption. This is accomplished via polymerization.

Because coagulants and flocculants function in different ways, their chemical structures, as well as the polymerization mechanism by which they are formed can vary greatly.

The following gives a brief description of some of the more common terms used and the polymerization mechanisms by which the most widely used coagulants and flocculants are formed.

A polymer is a molecule made up of many repeating units (poly=many, mer=units). A monomer (mono=one, mer=unit) is the building block of a polymer. If only one type of monomer is present in the polymer, it is referred to as a homopolymer. If two types of monomers are present, the polymer is referred to as a copolymer. If three types of monomers are present and incorporated into the polymer chain, the resulting polymer is referred to as a terpolymer. Most commercial products are homopolymers or copolymers. If a polymer has a positive charge associated with its backbone, it is referred to as being cationic. Conversely, if the polymer has a negative charge associated with its backbone, it is referred to as being anionic and if the polymer is uncharged it is referred to as being nonionic.

Coagulants and flocculants are sold in various forms. Coagulants are normally sold in liquid form, where the organic polymer is dissolved in water. The two most common forms which flocculants are marketed in are dry powder and emulsions.

Coagulants

Generally coagulants have relatively low molecular weights (2000-200M) in comparison to flocculants

(5–20MM). Since coagulants function by neutralizing the negative charge on the surface of the particle, they are cationic polymers. The mechanism of the polymerization reaction can also be quite different.

In some instances, condensation polymerization processes are used, which are sometimes referred to as step-growth polymerizations. These are reactions between two chemicals capable of reacting at two sites (bifunctional) or more. Although not water-soluble, nylon is an example of a polymer made by this process. Another example, which finds application in mining, is a polymer made from epichlorohydrin and dimethylamine (poly DMA-Epi).

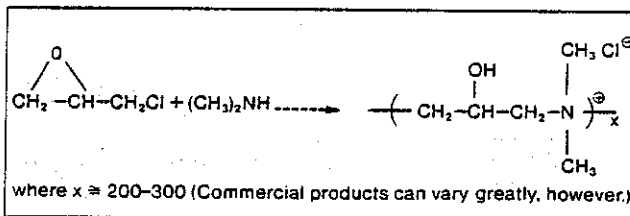


Figure 1 — PolyDMA-Epi.

Another coagulant, which probably finds the widest range of application, is poly diallyldimethylammonium chloride (sometimes referred to as polyDADMAC or polyDMDAAC).

This polymer is produced via a free radical induced cyclopolymerization.

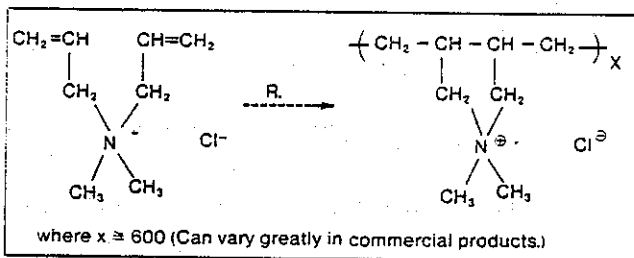


Figure 2 — PolyDADMAC, or polyDMDAAC.

Flocculants

As indicated earlier, flocculants normally have significantly higher molecular weights than coagulants and are made via addition polymerization (chain-growth via free radical initiators). An example of this is the polymerization of acrylamide, shown in Figure 3.

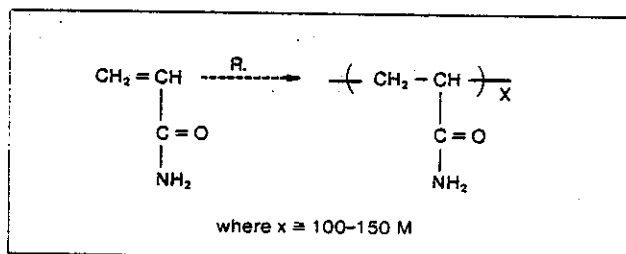


Figure 3 — Acrylamide (left), Polyacrylamide (right).

The molecular weight of both coagulants and flocculants can be controlled and modified by changing process variables. As a result, this allows a product to be tailor-made for specific applications. This is one of the reasons why synthetic polymers are significantly more active than natural polymers in many applications.

Structures have been given for coagulants (Figures 1 and 2) and a nonionic flocculant (Figure 3). The two other most widely used flocculants in mining are acrylamide/sodium acrylate copolymer and sodium polyacrylate (Figures 4 and 5).

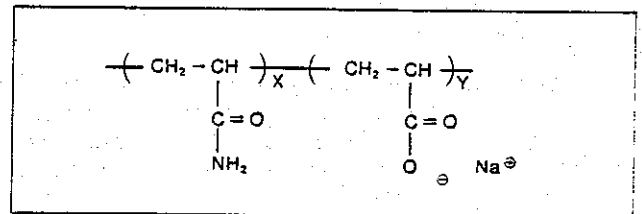


Figure 4 — Copolymer of acrylamide and sodium acrylate.

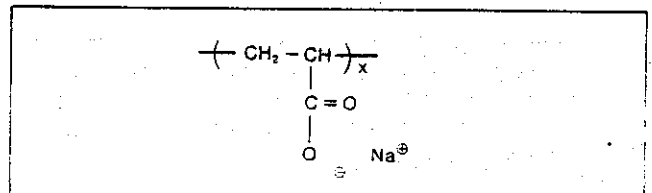


Figure 5 — Sodium polyacrylate.

Most commercial flocculants are copolymers of acrylamide and sodium acrylate. This polymer is anionic because of the negatively charged carboxylate group in the polymer. If the relative amount of sodium acrylate to acrylamide is high, the product is considered highly anionic. If the relative amount of sodium acrylate to acrylamide is low, the polymer is considered slightly anionic.

Factors Affecting Coagulation

Because of the generally greater importance of flocculation over coagulation in mineral beneficiation processes, this area will be covered only briefly.

Basically the need for coagulants arises from the fact that the surface of solids dispersed in water tend to be negatively charged. If the surface charge (measured as zeta potential) is great enough, the electrostatic repulsion between particles will not permit agglomeration. In order to allow agglomeration of these particles for subsequent removal, the surface charge (normally negative) must first be reduced. One way to do this is by adding a positively charged polymer. Coagulants, as mentioned earlier, are cationic polymers having multiple positively charged sites. Adsorption of the coagulant onto particles minimizes the electrostatic repulsion (reduces zeta potential) between them and allows Van der Waals' forces to predominate.

It is important to note that if too much coagulant is added the system can be re-stabilized because of charge reversal. Depending on the application and other factors, the tendency for a particular system to be re-stabilized will vary greatly.

Factors Affecting Flocculation

While the aqueous environment can have a significant influence on the solids being separated, one must also keep in mind that polymers are not resistant to all changes in the aqueous environment either. Being aware of this is extremely important in understanding the basic roles of the functional groups present and also in explaining some of the anomalies seen.

Other factors influencing the performance of polymers are the particle size distribution, chemical nature of the solids, percent solids in the slurry, the particular needs of a plant or application, etc. While these factors are treated separately, it usually is a combination of factors that ultimately determines a polymer's activity as a flocculant.

Polymer Type

As indicated earlier, flocculants used in the mining industry are generally copolymers of acrylamide and sodium acrylate. There are, however, a number of applications where homopolymers of acrylamide or sodium acrylate are most effective.

The driving force (heat of adsorption) for adsorption is controlled by the mineralogical properties of the suspended solids, as well as the aqueous environment.

The following is a possible explanation of the primary roles of functional groups present in the polymer in most mining applications. It should be noted that most bauxite applications should be treated separately. Although both amide and carboxylate groups have the capacity to adsorb onto mineral surfaces, evidence collected in a large number of applications strongly suggests that these functional groups have different primary roles. Results of a large body of work suggests that the primary function of acrylamide groups in copolymers is adsorption (builds strong floc) by hydrogen bonding. The primary function of the carboxylate groups is to extend the polymer chain in solution by electrostatic repulsion, enabling bridging to take place more easily. Figure 6 shows how pH influences the configuration of conventional polymers.

This does not mean that the carboxylate group cannot adsorb, it only says that this is not its primary function in many instances. One example that shows evidence for the activity of the amide group has been obtained by comparing the activity of flocculants with acrylamide versus those containing N, N-dimethylacrylamide. Figure 7 shows the settling rate behavior obtained from cylinder testing a slurry reporting to a wash circuit in a copper acid leach process. Curve I was obtained using polyacrylamide while Curve II was obtained using a copolymer of 25% acrylamide and 75% N, N-dimethylacrylamide. Even though both polymers had similar molecular weights,

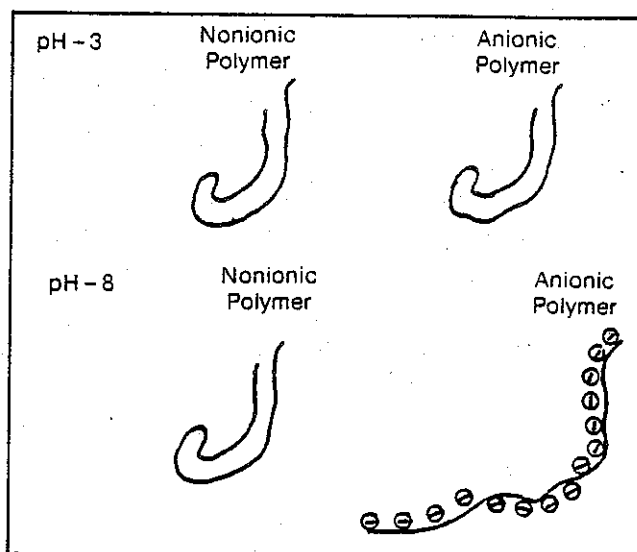


Figure 6 — Schematic of the effect of pH on polymer configuration.

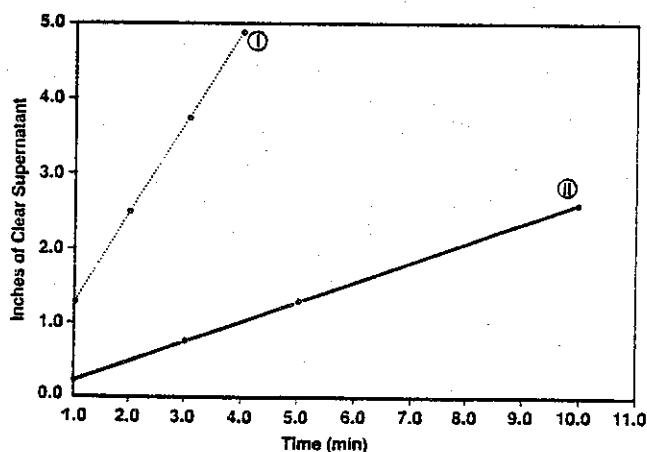


Figure 7 — Effect that N-methyl substitution has on the ability of polyacrylamide to settle a slurry from a copper acid leach process. Curve I was obtained using polyacrylamide. Curve II was obtained using a flocculant that was 75% N, N, dimethylacrylamide and 25% acrylamide.

the methyl substituted acrylamide was much poorer in activity.

Copolymers of acrylamide and sodium acrylate are generally more active than nonionic acrylamide polymers in spite of the fact that most particles carry a negative surface charge. Evidence obtained suggests that the enhanced activity of anionic polyacrylamides is related to uncoiling or extension of the polymers brought about by electrostatic repulsion between the anionic carboxylate groups. Extension of the polymer is expected to increase with increasing anionic charge. One way of measuring polymer extension is by monitoring the effect that added polymer has on solution viscosity. As the polymer uncoils, the viscosity increases. The intrinsic viscosity $[\eta]$ of a polymer is defined by:

$$[\eta] = \lim_{c \rightarrow 0} \left[\frac{1}{c} \left(\frac{\eta}{\eta_0} - 1 \right) \right]$$

Where c is polymer concentrations, η_0 is solvent viscosity, and η is solution viscosity. The intrinsic viscosity of a polyacrylamide solution as the polyacrylamide is made progressively more anionic by hydrolysis is shown in Figure 8. As the degree of hydrolysis is increased, the intrinsic viscosity is also seen to increase.

The best flocculant for a given application balances the need for adsorbing groups (usually acrylamide) with the desire to extend the molecule (usually with acrylate). The proper acrylamide/acrylate ratio depends on many factors, some of which are discussed below.

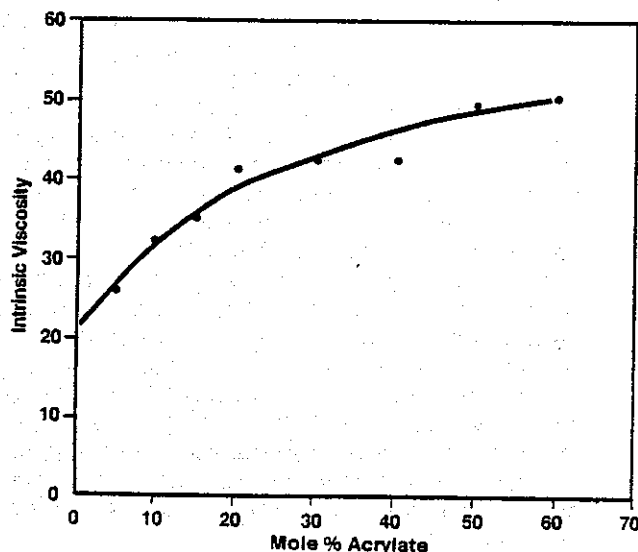


Figure 8 — Effect of hydrolysis on the intrinsic viscosity of polyacrylamide.

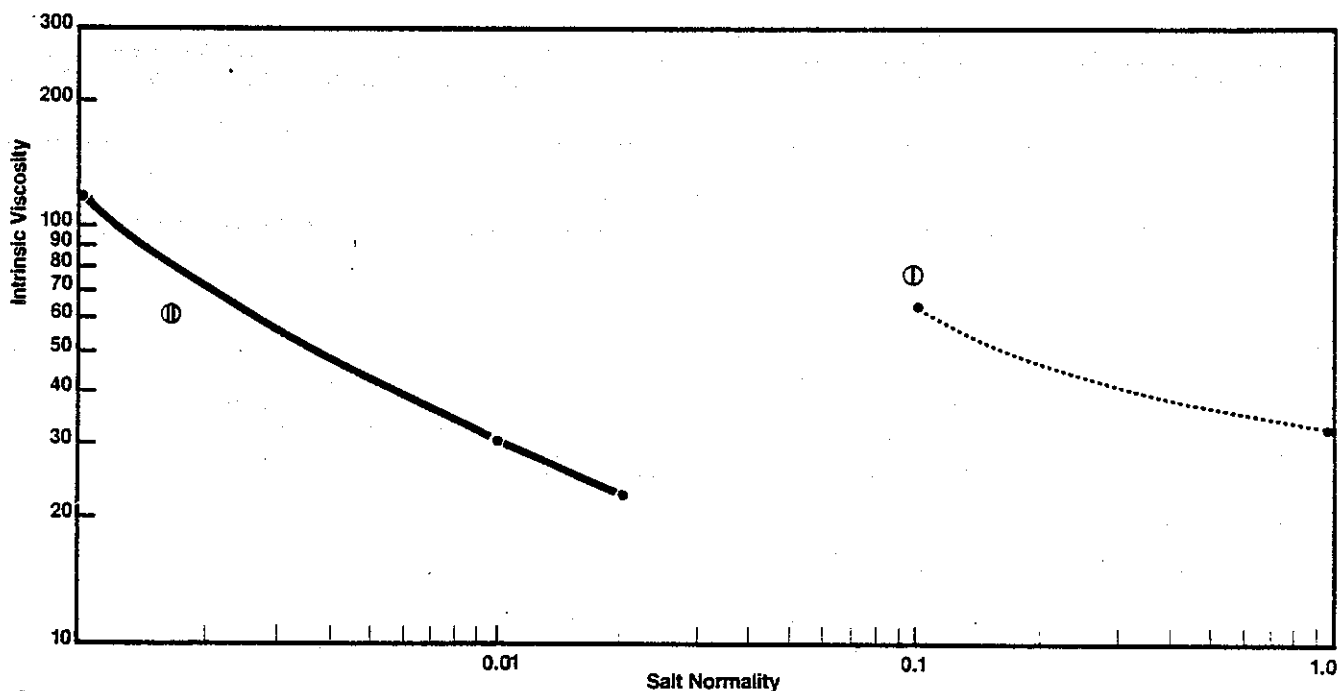


Figure 9 — Effect of mono and divalent cations on the intrinsic viscosity of a copolymer of acrylamide and sodium acrylate. Curve I was with added NaCl. Curve II was obtained with added CaCl_2 .

Ionic Strength

Based upon a model of flocculant activity related to polymer uncoiling, it is easy to understand why ionic strength can have such a large effect on flocculation. At high ionic strengths, the charged groups on the polymer are shielded and the polymer will coil up. A reduction in intrinsic viscosity of an anionic flocculant is observed as the salt concentration is increased, as shown in Figure 9. Curve I shows the influence of sodium chloride while Curve II shows the influence calcium chloride has on the polymer's intrinsic viscosity. As expected, polyvalent ions, such as calcium, have a much greater impact on the solution viscosity. In addition, too high a calcium level will cause highly anionic acrylate polymers to precipitate.

Although high levels of electrolyte can have deleterious effects on the activity of anionic flocculants, the presence of low levels of cations, such as calcium, can result in a marked improvement in flocculant activity. The presence of calcium may reduce the electrostatic repulsion between the anionic centers of the polymer and the particle, allowing easier approach of the polymer to the particle. The possibility that the calcium ions may bind (ion exchange) to the negative particle and serve as a point of attachment for the negatively charged flocculant, cannot be precluded.

pH

The solution pH also changes both the flocculant chemistry and rheology as well as affects the surface chemistry of the mineral particle. At a high pH, acrylamide will hydrolyze to acrylate, while at low pH, acrylate is in chemical equilibrium with the acid form and as indicated earlier the polymer rheology changes.

Considering the acid-base behavior of sodium acrylate and acrylic acid illustrates the influence that lowering the pH can have on conventional anionic polymers. The pK value of acrylic acid, which is 4.25, (similar to acetic acid) allows the relative amounts of acrylate and acrylic acid in solution to be estimated. At a pH of 7, the acrylate/acrylic acid ratio is approximately 560:1. At a pH of 5, this ratio becomes 5.6:1, while at a pH of 3, essentially all the acrylate is in the acid form. This affects the molecular rheology of the polymer. At pH 7, the carboxylate ion will force the polymer to uncoil, while at pH 3, the polymer will be much more coiled. Hence, as the pH is reduced, the performance of conventional anionic polymers normally tends to decrease. One would expect, however, that pH should have a minimal effect on non-ionic polyacrylamide.

Table 2 lists results obtained on a Kaolin slurry. Three high molecular weight flocculants were tested on the slurry at the various slurry pH's indicated. It can be seen that at a pH of 4 the nonionic polymer was by far the best. At this pH, the anionic polymers will be coiled to a large extent and have a configuration similar to the nonionic polymer. The fact that the amide group is replaced partially by more inert carboxylate groups reduces the number of hydrogen bonding sites in the polymer and helps to explain the difference in activity.

Table 2 — Effect of pH on flocculant selection

pH	Nonionic Polymer*	Moderately Anionic Polymer*	Highly Anionic Polymer*
4	64	285	750
6	74	32	325
8	71	18	200
9.5	145	20	24
11	158	24	18
~14	~400	200	15

*ppm required to yield settling rate of 10 ft/hr.

At a pH of 6, the carboxylate group in the moderately anionic copolymer is ionized to an extent that the polymer is more uncoiled. Since the nonionic polymer contains almost no anionic (carboxylate) groups, the configuration of the polymer remains unchanged. It is interesting to note that the relative dose of nonionic polymer required at a pH of 6 is quite similar to that at a pH of 4. The highly anionic polymer (contains no amide groups) is still relatively ineffective.

At a pH of 8, the moderately anionic copolymer continues to improve. At this pH, the carboxylate groups are essentially completely ionized and the polymer is uncoiled to about its maximum. The highly anionic polymer is still relatively ineffective, although one can see that it's improving. Again, the nonionic polymer is displaying activity very similar to that which it had at a pH of 6. Again, the pH change from 6 to 8 should not change its configuration. At a pH of 9.5, one can see several changes taking place. The highly anionic polymer is now similar to that of the moderate anionic polymer, indicating that adsorption through the carboxylate group is gaining in importance and of almost, if not, equal importance to the amide group. On the other hand, the nonionic polymer requires twice as much polymer to yield the same activity as it did at a pH of ~8. At first glance, this appears to be a contradiction. It was stated earlier that the configuration of the nonionic polymer should not change as a function of pH. However, at a pH of 9.5, it is known that polyacrylamide will undergo hydrolysis. It has been noted in a number of cases, when competing reactions (chemical [hydrolysis] vs. physical [adsorption]) are occurring at the same time, a significant reduction in flocculant activity can occur.

Similar behavior is observed at a pH of 11. At a pH of 14, the moderate anionic polymer is seen to lose effectiveness, which again can be attributed to hydrolysis and two competing reactions. If anything, the highly anionic polymer (which contains no acrylamide and as a result is not subject to hydrolysis) may have even gotten better.

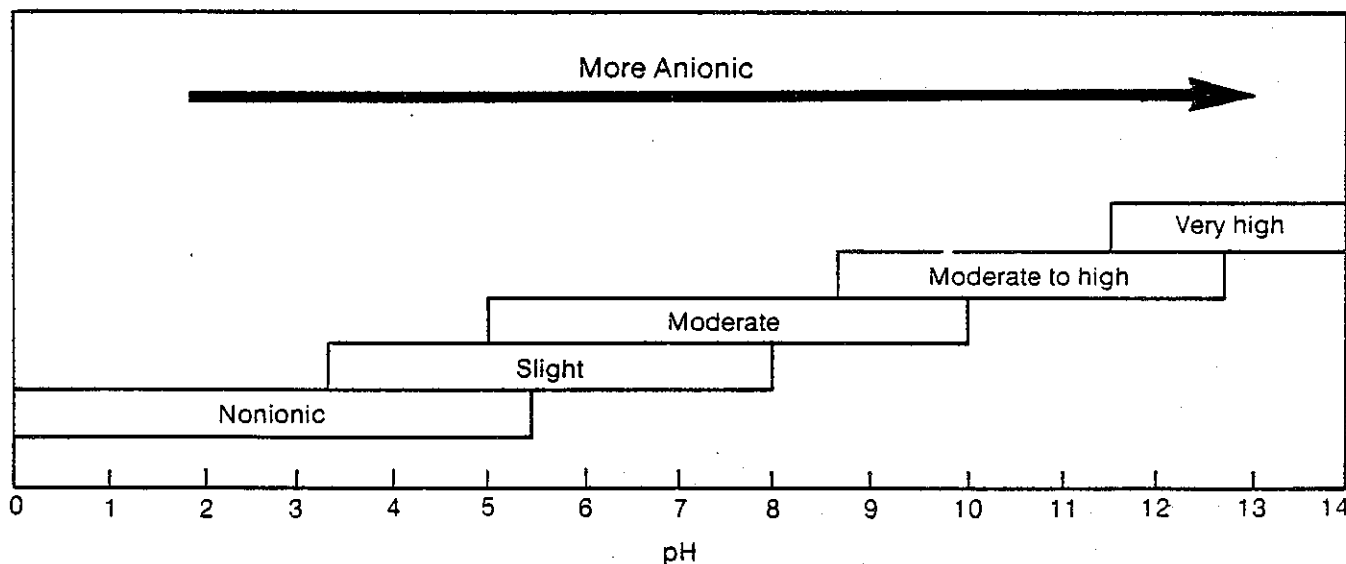


Figure 10 — Typical pH ranges at which varying anionic (acrylate type) polymers find general application.

Results obtained in the course of this study are also supported by where these types of products are used in industry. A depiction of how pH influences the product of choice is given in Figure 10.

Recently, acrylamide-containing copolymers have been prepared with comonomers having a sulfonic acid in place of the carboxylic acid group. Because sulfonic acid is a much stronger acid than acrylic acid, these new flocculants should show improved activity at low pH. As indicated earlier, the polymer's configuration in solution is dependent on having ionized groups present to cause electrostatic repulsion, forcing the polymer to uncoil. The resultant uncoiling generally leads to improved performance. The configuration of a polymer containing a strongly acid group (sulfonate) should not change dramatically as the pH is reduced because the degree of ionization remains the same. The configuration of conventional anionic polymers, on the other hand, does change dramatically as the pH is varied, because the degree of ionization changes. As a result, if flocculation is based on a model of bridging, greater extension should provide better activity. To further support the idea that extension (greater molecular size) affects activity, higher molecular weight polymers generally have better activity than lower molecular weight polymers having the same composition, which have been made by similar processes. This effect was studied using a coal refuse slurry where pH was adjusted from near pH 7 down to pH 5 and then to pH 3. Figure 11 shows the amount of flocculant needed to obtain a settling rate of 4 in/min. as a function of pH using a nonionic, a moderately anionic, and the more acidic sulfonic acid substituted acrylamide. Note that the nonionic and strongly acidic anionic polymers show minimal pH dependence while the conventional anionic acrylamide exhibits a large pH dependence. This supports the idea that uncoiling or polymer extension affects activity.

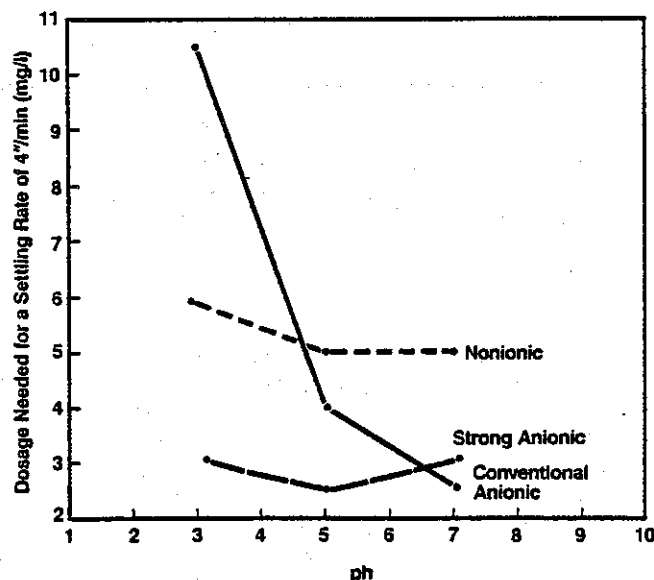


Figure 11 — Effect of pH on the activity of a nonionic, a conventional anionic, and a more acidic anionic acrylamide.

Slurry Solids

High molecular weight polymers can attach to a particle at many points along its chain and desorption therefore is highly unlikely. In the absence of an excess of polymer, adsorption of high molecular weight polyacrylamide onto kaolin has been shown [6] to be irreversible.

Adsorption is also generally very rapid and it is important that the flocculant be well distributed throughout the slurry. The suspended solids concentration of the slurry and the particle size distribution of the solids can influence distribution of the flocculant. As the percent solids of the slurry is increased, it becomes more difficult to uniformly disperse the flocculant and the flocculant demand on a solids basis will normally increase. Similarly, as the mean particle size decreases, the surface area increases (See Table 1). This also hinders uniform distribution of the polymer throughout the slurry.

These effects are illustrated in Figures 12 and 13, which show the effect of suspended solids level on flocculant activity for red mud thickening in bauxite processing and for thickening a coal refuse slurry, respectively. The flocculant for bauxite processing is a very highly anionic sodium acrylate polymer while a moderately anionic acrylamide copolymer was used on the coal refuse slurry. In both instances, the flocculant demand measured in pounds per ton of dry solids increased as the slurry solids increased.

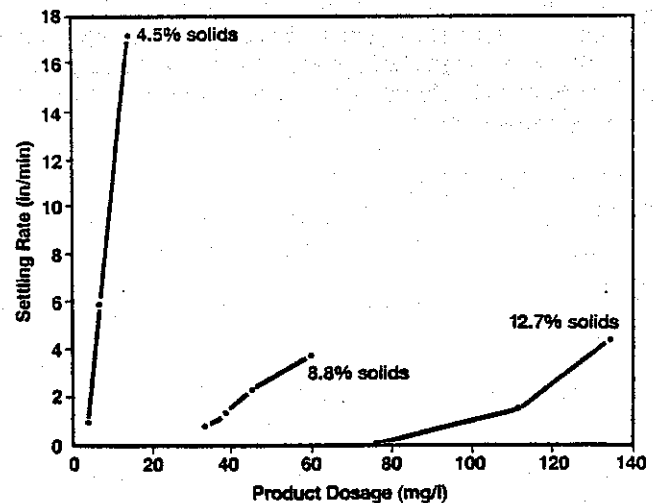


Figure 12 — Effect that slurry solids content has on flocculant demand. A polyacrylate flocculant was used on a red mud slurry obtained in bauxite processing.

Flocculant Dilution

Performance of the polymer can be significantly altered by the concentration of flocculant solution added to the slurry. Figure 14 shows results obtained in cylinder settling tests carried out on phosphate slimes. A moderately anionic flocculant was used at a dose of 20 mg/l for all tests. Improved activity, which is indicated by faster settling rates, was obtained using more dilute polymer solutions. This improved activity, obtained by dilution of the flocculant, can be attributed to better distribution.

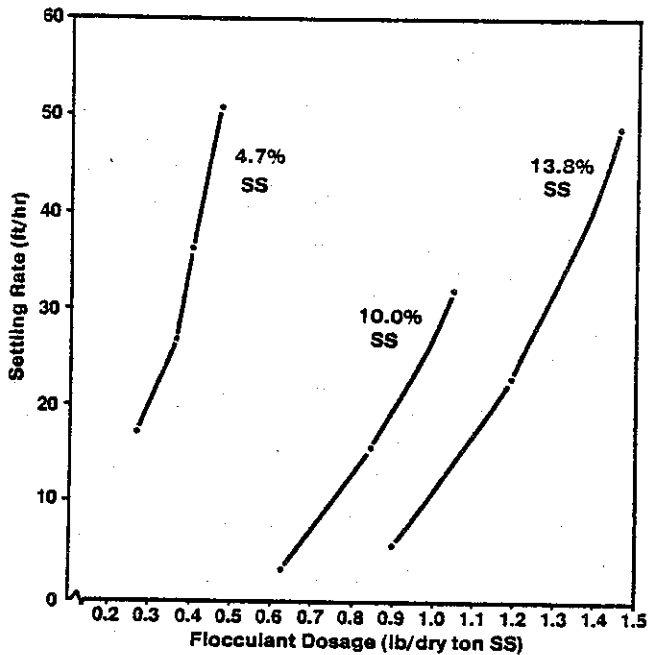


Figure 13 — Effect that slurry solids content has on flocculant demand for a coal refuse slurry. The flocculant was a moderately anionic polyacrylamide.

Shear

Too much shear can break up the floc. The effect of excessive mixing and the resultant decrease in flocculant activity is also shown in Figure 14. A loss in activity is clearly a result of overmixing. Each application forces one to balance the need to achieve good distribution of the flocculant against shear sensitivity of the flocced particles.

Molecular Weight

A polymer's ability to bridge between particles is an important flocculation mechanism and, as a result, it isn't surprising that molecular weight has an effect on activity of a flocculant. In most thickener applications higher molecular weight results in better activity, although there are instances in which increasing molecular weight past a certain point results in loss of activity. Again, a number of factors can account for this loss in performance. Higher molecular weight polymers, because of increased solution viscosity, are not as easily distributed throughout a slurry. Since adsorption is very rapid and usually irreversible, this can cause a loss in activity. With increasing molecular weight, the number of polymer chains per unit weight decreases as well. There may not be enough polymer molecules to floc all the solids in high solids slurries.

The influence that flocculant molecular weight can have on the settling of two coal refuse slurries is illustrated in Figure 15. Note that with coal slurry I, increased molecular weight resulted in steadily improved activity, while with coal slurry II there is an optimum molecular weight. Coal slurry II has a greater amount of bentonite clay present and is higher in suspended solids than slurry I (6% versus 4.3%).

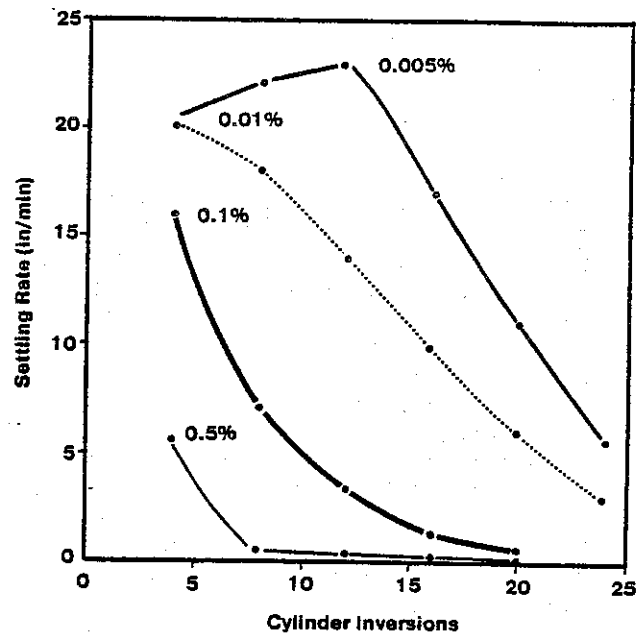


Figure 14 — Effect of flocculant concentration and mixing on the settling rate of phosphate slimes.

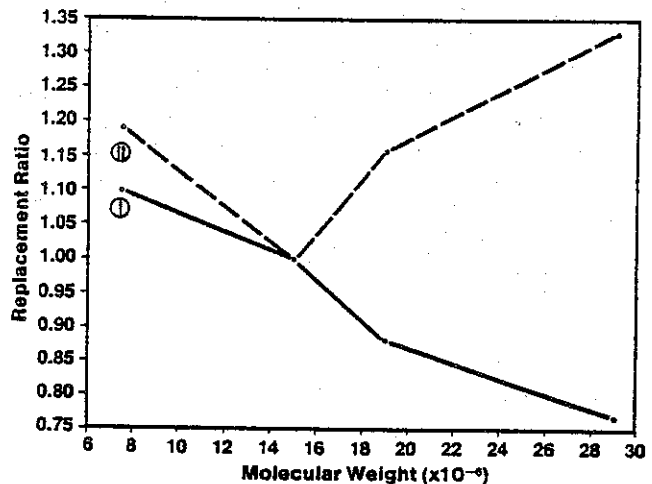


Figure 15 — Effect of the molecular weight of a moderately anionic polyacrylamide on its activity as a flocculant for two different coal refuse slurries.

Process Conditions

Obtaining optimum performance from any chemical program depends to a great extent on how the polymer is applied. Dilution and slurry solids are factors that have already been discussed. Control of these parameters is important in achieving optimum flocculant activity. In addition, the feed point of the polymer (related to shear) can also have a large effect on its activity. The proper feed point is one that provides sufficient mixing without too much shear. It must also be kept in mind that the optimum feed point can change as production rates are changed.

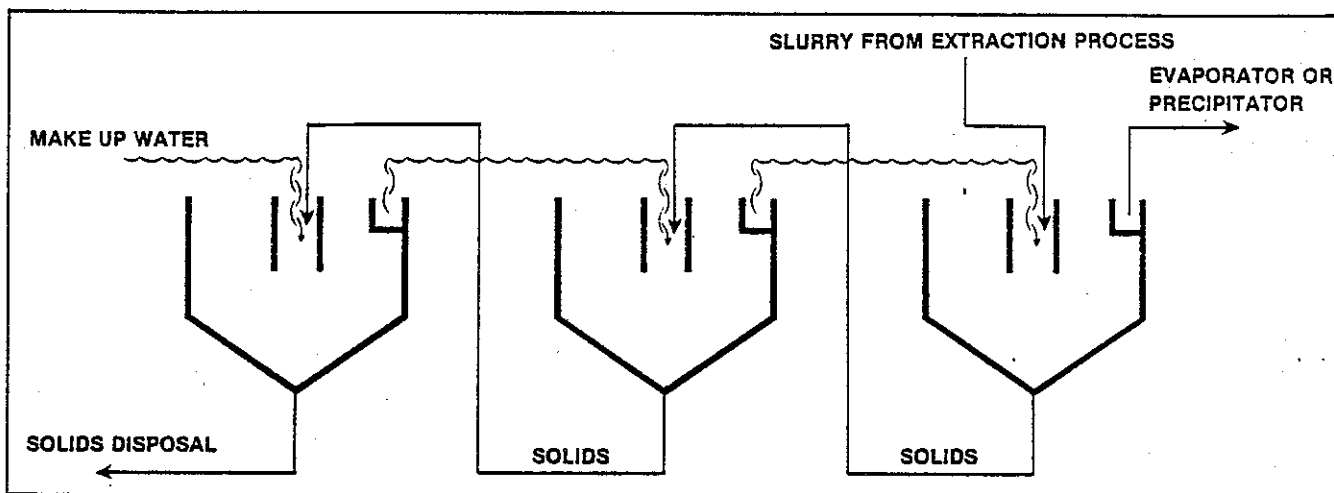


Figure 16 — Schematic of a counter current decantation (CCD) circuit.

As already noted, variables such as ionic strength and pH strongly influence the choice of flocculant. These variables can be dramatically different at different points in the beneficiation process. An example of a process where these changes occur is in countercurrent decantation (CCD). This process is used when the desired mineral is dissolved in the aqueous phase in order to separate it from the gangue. A schematic of a CCD circuit is shown in Figure 16. Here the solids, which are moving out of the circuit, are being washed with increasingly fresh water coming into the circuit. This is normally broken down into several washing stages with each stage receiving flocculant. The water chemistry can change dramatically at each stage and the same flocculant is not necessarily best throughout the circuit as illustrated in Figure 17. Improved performance can be achieved in certain instances by using more than one polymer type for flocculation. However, a compromise must normally be made between the complexities of handling several different flocculants and the desire to have the most cost-effective program.

CONCLUSION

This presentation has dealt with a number of the parameters which have an influence on flocculation. Coagulation was covered only briefly because of the greater relative importance of flocculation in mineral beneficiation.

Results of our work indicate that the amide functionality in commercially available flocculants is the work horse in adsorption and that the carboxylate groups primary role is to keep the polymer chain extended and allow more efficient bridging. In applications at a high pH, the role of the carboxylate group becomes more important in adsorption and flocculation. Problems can also be encountered when competing reactions (chemical vs. physical) are occurring at the same time.

ACKNOWLEDGEMENTS

Much of the work reported in this paper was carried out by our co-workers at Naico. The authors gratefully acknow-

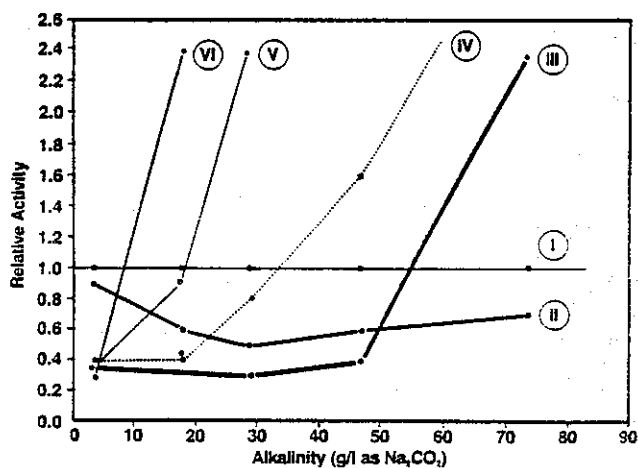


Figure 17 — Effect that alkalinity has on flocculant activity on a bauxite red mud slurry as the degree of anionic character changes. The relative activity is measured versus a polyacrylate flocculant (I). Curves II through VI represent polymers having progressively less anionic character.

ledge the mineral processing studies carried out by William J. Roe, Anthony E. Gross, Merle L. Branning and the polymer studies carried out by Robert Bernot.

REFERENCES

1. B. V. Derjaguin and L. D. Landau, *Acta Physicochem. URSS*, 14: 633 (1941).
2. F. J. Verwey and J. T. Overbeek, *Theory of the Stability of Lyophobic Colloids*, Elsevier, Amsterdam, 1948.
3. H. L. Frisch and R. Simha, *J. Phys. Chem.*, 58: 507-512 (1954).
4. A. Silberg, *J. Phys. Chem.*, 66: 1224-1707 (1962).
5. F. T. Hesselink, *J. Colloid and Interface Sci.*, 60: 448-466 (1977).
6. A. S. Michaels, *Ind. Eng. Chem.*, 46: 1485 (1954).