Effect of some commercial flocculating agents on settling and filtration rates of low grade, fragile manganese ores of Andhra Pradesh

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The highly weathered, fragile and low grade manganese ores of Visakhapatnam district of Andhra Pradesh are subjected to wet high intensity magnetic separation (WHIMS) to give beneficiated magnetic fraction. However, the original ore and its non-magnetic fraction contain large quantities of slimy particles which are difficult to separate from their aqueous suspensions. Three different commercial flocculating agents with anionic, cationic and non-ionic characters have been used to improve settling and filtration behaviour of the suspensions. While a small dose of anionic flocculant has been found to be very effective, cationic flocculant is poorly effective even at high dosage. The behaviour of non-ionic flocculant is intermediate between the two. Since extremely fine particles constitute the non-magnetic fraction, it needs higher dosage of anionic flocculant to form large or aggregated flocs which make the filter cake porous even with increasing slurry concentration.

Keywords: Manganese ore fines, flocculation, polymeric flocculants, settling and filtration rates, specific cake resistance

IPC Code: C02F1/52

The beneficiation of highly weathered, low grade, high phosphorus manganese ores of Visakhapatnam district, Andhra Pradesh has been a challenging task. Because of their fragileness a large quantity of fines, which has little demand in metallurgical industries, is generated during mining and transportation. Many attempts\(^1\)\(^-\)\(^3\) have been made to beneficiate the ore by conventional methods, such as jigging, tabling, magnetic separation, flotation etc. Though some success has been achieved in upgrading the manganese content of the ore, phosphorus content, however, remains more or less unchanged. Extensive investigation carried out at RRL, Bhubaneswar has led to the development of beneficiation methods using wet high intensity magnetic separation (WHIMS)\(^4\) and combination of WHIMS and hydrocyclone classification\(^5\). The beneficiated ore is dephosphorized by roast-leaching method\(^6\)\(^,\)\(^7\). All these methods involve solid-liquid separation at several stages which become tedious because of the presence of fine slimy particles. However, by using a suitable flocculating agent, the efficiency of solid-liquid separation can be improved.

The phenomenon of selective flocculation is well-known to mineral processing engineers and indeed, has been in industrial practice for a long time. Flocculants can be either natural or synthetic. Natural flocculants are starches (e.g., tapioca flour, pearl starch, waxy milos), gums, resins etc. These non-ionic flocculants are extensively used in the flocculation of iron ore slimes. Synthetic flocculants are generally acrylamide based polymers or modified by copolymerization with monomers containing suitable functional groups.

The polyacrylamide based flocculants of different molecular weights (MW) are extensively used in the processing of fine and slimy ore particles. Polymers of low MW generally show low degree of flocculation, and of too high MW give viscous solution which hinders free settling of flocs. Therefore, polymers of medium MW\((10^5-10^6)\) generally give desired result for low dosage use. These polymers themselves are non-ionic, though in practice they are weakly anionic due to some hydrolysis that takes place during their production. However, anionic polymers can be produced by partial hydrolysis of polyacrylamide or copolymerization of acrylamide and acrylic acid. Cationic derivatives result from copolymerization of acrylamide with quarternary ammonium compounds but usually have much lower molecular weight. The present paper deals with this aspect using the three different types of flocculating agents.

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Experimental Procedure

Materials

The sample used in the present investigation was collected from the huge dump of disintegrated ores accumulated during handling and transportation at the siding of Garividi Railway Station on Vizianagram-Visakhapatnam section of East Coast Railway. The mineralogical characteristics of the manganese ores of this region have been reported by several authors. About 6 kg of ore sample was further ground in a 9"×9" ball mill for about 25-30 min so that the entire product passes through 100 mesh B.S. sieve (−283 μm). The ground ore was subjected to wet high intensity magnetic separation (WHIMS) using a BOX-MAG RAPID (Birmingham, U K) wet magnetic separator. The suspensions containing both magnetic and non-magnetic fractions were allowed to settle, filtered and the residues were dried in an air oven. The distribution pattern of different size fractions was determined by wet sieving method. Chemical analysis was carried out according to the procedure described elsewhere.

Three commercial water soluble flocculating agents supplied by Allied Colloids, UK, were used in the present work. These polymeric compounds (possibly, polyacrylamide) of high molecular weight contain cationic, anionic and non-ionic functional groups. The flocculating agents had the following brand names viz. (a) magnafloc 140 (cationic) (b) magnafloc 155 (anionic) (c) magnafloc 351(non-ionic). Stock solutions (0.5-1.0% w/v) of these flocculants prepared in double distilled water are generally stable for weeks as indicated by the clarity of the stock solutions.

Determination of pH_pzc of the ore samples

The pH_pzc of the ore samples were determined by simple solid addition or pH drift method. To a series of 125 mL polyethylene bottles 45 mL of either 10^{-2} or 10^{-3} M KNO_{3} solution was added. The pH values of the solutions were adjusted roughly from 4 to 10 by adding known volumes of either 0.1 M HNO_{3} or NaOH. The total volume of solution in each bottle was made up to 50 mL by adding the balance volume of liquid with the relevant KNO_{3} solution. The pH values of the solutions were again noted and are designated as initial pH (pH_i). The difference between the two sets of pH values (pH_i−pH_f = ΔpH) are plotted against pH_i. The point at which the curves intersect ΔpH = 0 i.e., the pH value at which no liberation of either H^+ or OH^- takes place gives the pH_pzc values of the samples.

Determination of settling rate of suspension

The settling rates of the aqueous suspensions of ground ore and its non-magnetic fraction were studied in the absence and in the presence of flocculating agents. The magnetic fraction being rich in iron and manganese minerals is considerably heavier and therefore exhibits high settling and filtration rates.

The settling rates were determined in 100 mL calibrated measuring cylinders. The suspensions (20% w/v) were prepared in a 250 mL beaker by uniformly mixing ore sample with deionized water in the presence of requisite dose of flocculant under mildly agitated condition. The suspensions were transferred to the cylinders up to the height of 21 cm. The suspensions were further mixed by inverting the cylinders end over end for 7-8 times and placed in front of diffused light and the fall in the suspension/liquid boundary was noted at suitable intervals of time.

Determination of filtration rate

Unlike settling studies different amounts (60-100 g) of ore and its non-magnetic fraction were suspended in water so that total volume of suspension in each case was 300 mL. A circle of Whatman filter paper No. 1 (8 cm) was placed on a Buchner funnel of the same size and fitted to 500 mL graduated cylinder through an air tight rubber bunge. The uniformly mixed suspension was transferred to the funnel all at a time and the pressure difference was adjusted to 50 cm of mercury immediately after which the collection of the volume of filtrate began at suitable interval of time. The vacuum line was disconnected at least 15-20 s before the completion to avoid cracks in the filter cake. The entire volume of filtrate was transferred back to the funnel and the rate of cake filtration (refiltration) was noted at a regular interval of time under the condition of same pressure difference i.e. 50 cm of Hg.

Results

Size distribution and chemical analysis

Table 1 shows that particles finer than 45 μm constitute more than 60% by weight in the original
ore and its magnetic portion and 85% by weight in the non-magnetic portion. While there is about 4% loss in both −45 μm and −105, +75 μm fractions in the magnetic portion, there are corresponding gains in the intermediate size fractions, which are possibly rich in heavier manganese minerals. Chemical analysis suggests that while Mn and Fe contents in the non-magnetic portion exhibit sharp decrease, the acid insoluble content which consists mostly of siliceous minerals show at least three times increase in the fraction coarser than 45 μm, but only two times increase in fraction finer than 45 μm with respect to the original ore. This suggests that −45 μm fraction in non-magnetic portion still contains substantial amounts of very fine iron and manganese minerals. This is reflected in the pH PZC of the samples in aqueous medium as discussed below.

**pH PZC of the ore samples**

Figure 1 shows the plot of Δ pH versus pH for original ore, non-magnetic and magnetic fractions. The figure also shows similar plot for magnetic fraction roasted at 800°C followed by leaching in dilute HNO₃ (or HCl), a process developed for the dephosphorization of beneficiated ore. It can be seen from the figure that for both the concentrations of KNO₃ there is a common point of intersection with Δ pH = 0 axis in respect of all the solid samples. This suggests that KNO₃ acts an indifferent electrolyte. The pH PZC values for ore and its non-magnetic fraction are 8.3 and 8.2 respectively which are higher than the pH PZC values lying between 1.5 and 7.0 for synthetic MnO₂ of different crystalline modifications. However, the present values are close to near-amorphous hydrous iron oxide which lies at pH above 8.0. This compound occurs as major iron-bearing phase in highly weathered ores and is also known as limonitic iron oxide (FeOOH.nH₂O). The corresponding pH PZC values for silica and clay minerals are less than 3.5. Therefore, at pH around 8 there occurs mutual interaction of various oxide colloids, such as adsorption of negatively charged silica and silicate minerals onto positively charged

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### Table 1—Particle size distribution and partial chemical analysis of −150 μm ground ore and its products of wet high intensity magnetic separation (WHIMS)

<table>
<thead>
<tr>
<th>Sieve fraction (μm)</th>
<th>Ground ore</th>
<th>Magnetic fraction</th>
<th>Non-magnetic fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wt% Mn% Fe% AI%</td>
<td>Wt% Mn% Fe% AI%</td>
<td>Wt% Mn% Fe% AI%</td>
</tr>
<tr>
<td>150,+105</td>
<td>7.38 25.72 13.35 23.91</td>
<td>7.60 31.71 13.60 20.19</td>
<td>2.79 10.98 5.02 67.17</td>
</tr>
<tr>
<td>−75,+63</td>
<td>7.42 25.22 16.16 18.40</td>
<td>12.35 33.91 15.29 11.28</td>
<td>4.85 14.22 6.67 55.77</td>
</tr>
<tr>
<td>−63,+53</td>
<td>3.13 25.70 15.57 17.92</td>
<td>6.70 32.77 15.54 11.47</td>
<td>3.45 15.82 7.67 53.26</td>
</tr>
<tr>
<td>−53,+45</td>
<td>1.88 25.29 15.65 15.75</td>
<td>2.05 33.43 15.88 10.07</td>
<td>1.45 16.74 8.09 38.91</td>
</tr>
<tr>
<td>−45</td>
<td>65.22 21.26 12.75 24.93</td>
<td>61.15 31.25 17.84 11.43</td>
<td>84.40 19.89 9.42 49.00</td>
</tr>
<tr>
<td>Calculated head</td>
<td>100.00 22.90 13.03 23.35</td>
<td>100.00 31.94 16.64 12.41</td>
<td>100.00 19.00 9.00 50.21</td>
</tr>
<tr>
<td>Found</td>
<td>25.20 13.39 24.50</td>
<td>32.00 15.00 13.60</td>
<td>18.96 9.80 40.30</td>
</tr>
</tbody>
</table>

A I = Acid Insolubles

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![Graph showing pH PZC values](image-url)
limonitic iron oxide. Adsorption may also take place onto pyrolusite, a manganese dioxide mineral phase having pH_{PZC} value of about 7.0. Such adsorption leads not only to the formation of aggregates with heterogeneous surface charge, but also shifts the overall pH_{PZC} to the alkaline side. Since the non-magnetic fraction also contain appreciable amounts of iron and manganese minerals it’s interfacial behaviour is closely similar to that of the original ore. On the other hand, the magnetic fraction is rich in hematite, pyrolusite, jacobsite etc. and low in fine clayey minerals content. As a result, mutual interaction between oppositely charged particles is not as predominant as in the ore or its non-magnetic fraction and therefore, pH_{PZC} does not shift to alkaline side. On calcination to higher temperature followed by acid leaching, the fraction loses the original capability of rehydration and therefore pH_{PZC} value shows further decrease.

Settling rate of ore suspension

When either ore or its non-magnetic fraction is suspended in water the pH value is stabilized around 8.0. This shows that the major constituent oxides tend to release OH\(^-\) in the solution. Since this pH value is close to the pH_{PZC} of the samples, all the three flocculating agents should more or less be effective. Figure 2 shows typical examples of the effect of the three types of flocculating agents on the settling rate of 20% suspension (w/v) of –150 μm ore at the common dosage of 0.126 g/kg of ore. It can be seen that the anionic flocculant (magnafloc 155) shows the highest initial uniform rate. While the cationic flocculant (magnafloc 140) exhibits only minor increase, non-ionic flocculant (magnafloc 351) exhibits rate, which is intermediate between the two.

The pH value at which the settling studies were carried out was about 8.0, which is very close to the pH_{PZC} of the samples. At this pH, besides charged particles, there are also particles which carry very little or no charges. Since the numbers of such particles are limited compared to those of negatively or positively charged particles, non-ionic flocculant acts as intermediate between the other two ionic flocculants. However, it should also be borne in mind that non-ionic flocculant also carry certain anionic charges because of some unavoidable hydrolysis that takes place during its preparation. As a result, non-ionic flocculant exhibits more flocculation (higher settling rate) than cationic flocculant.

Table 2 shows the initial uniform settling rates in cm/min and final sediment volume at different dosages of the three flocculants. It can be noted from the table that for the addition of magnafloc 140 the maximum rate increases from 1.3 cm/min for no addition to 3.7 cm/min at the dosage 0.21 g/kg.

Fig. 2—Typical settling behaviour of 20% (w/v) aqueous suspensions of manganese ore in the absence as well as in the presence of three different flocculants.

<table>
<thead>
<tr>
<th>Flocculant dose g/kg of ore</th>
<th>Magnafloc 140 (Cationic)</th>
<th>Magnafloc 155 (Anionic)</th>
<th>Magnafloc 351 (Non-ionic)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate cm/min</td>
<td>Sp. sediment vol. cm(^3)/g</td>
<td>Rate cm/min</td>
</tr>
<tr>
<td>0</td>
<td>1.30</td>
<td>1.13</td>
<td>1.30</td>
</tr>
<tr>
<td>0.021</td>
<td>-</td>
<td>-</td>
<td>2.10</td>
</tr>
<tr>
<td>0.042</td>
<td>-</td>
<td>-</td>
<td>3.90</td>
</tr>
<tr>
<td>0.084</td>
<td>-</td>
<td>-</td>
<td>4.40</td>
</tr>
<tr>
<td>0.126</td>
<td>1.75</td>
<td>1.23</td>
<td>4.40</td>
</tr>
<tr>
<td>0.147</td>
<td>-</td>
<td>-</td>
<td>5.80</td>
</tr>
<tr>
<td>0.168</td>
<td>2.60</td>
<td>1.28</td>
<td>-</td>
</tr>
<tr>
<td>0.210</td>
<td>3.70</td>
<td>1.28</td>
<td>-</td>
</tr>
<tr>
<td>0.250</td>
<td>3.70</td>
<td>1.31</td>
<td>-</td>
</tr>
</tbody>
</table>
Further increase in the addition of this flocculant has no beneficial effect. The specific sediment volume also increases from 1.13 cm$^3$/g at no addition to 1.28 cm$^3$/g at 0.210 g/kg indicating clearly that the suspension gets partially flocculated by the cationic flocculant.

The effect of anionic flocculant is very sharp on the settling rates of the suspension of original ore. An initial rate of 3.9 cm/min is obtained even with the addition of 0.042 g/kg compared to highest rate of 3.7 cm/min observed for cationic flocculant at 0.210 g/kg. In case of non-ionic flocculant a maximum rate of 3.5 cm/min is attained for a dose of 0.126 g/kg. Further addition of flocculant tends to decrease the initial rate indicating the reverse effect of dispersion under high dosage. This is an usual phenomenon observed in polymer flocculation and is attributed either to mutual repulsion of particles covered with ionic flocculant molecules or to steric hindrance to the coalescence of particles fully covered by non-ionic flocculant.$^{16}$

**Settling rate of non-magnetic fraction of the ore**

Typical settling behaviour of 20% (w/v) of aqueous suspension of non-magnetic fraction in the absence as well as in the presence of the types of flocculant is illustrated in Fig. 3. It can be seen that, like raw ore, the addition of anionic flocculant shows highest settling rate followed by non-ionic and cationic flocculants. The data in Table 3, however, suggest that the increase in settling rate with increase in dosage up to 0.10 g/kg is slower compared to original ore but increases sharply from 0.126 g/kg. This is because extremely fine particles constitute the non-magnetic fraction as shown in Table 1. Consequently, the quantity of flocculant required to counterbalance the high charge per unit area is higher than that of the ore. It may also be observed from Table 3 that the sediment volumes are higher than those observed in Table 2 for the original ore. As stated earlier that below pH 8.0 aggregates are formed by the mutual interaction between oppositely charged fine particles. The flocculant polymer anchors onto a limited number of charged patches of these aggregates leaving free some other patches for bridging with additional aggregates through free ends of the polymer. In this way, the clusters of aggregated particles form large flocs which settle rapidly to give puffy or loose sediment volume.

**Filtration rates of flocculated suspensions**

Beside observing the settling behaviour of the suspension of ore and its non-magnetic fraction at different dosages of flocculants, an attempt has been made to study the filtration behaviour of the above suspensions only in the presence of anionic flocculant which has been found to be most effective in increasing the settling rate. However, the dosage employed in the filtration studies is smaller than those used in the settling studies. According to LaMer and

<table>
<thead>
<tr>
<th>Flocculant dose g /kg of ore</th>
<th>Magnafloc 140 (Cationic)</th>
<th>Magnafloc 155 (Anionic)</th>
<th>Magnafloc 351 (Non-ionic)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate cm/min</td>
<td>Sp. sediment vol. cm$^3$/g</td>
<td>Rate cm/min</td>
</tr>
<tr>
<td>0</td>
<td>0.95</td>
<td>1.36</td>
<td>0.95</td>
</tr>
<tr>
<td>0.021</td>
<td>1.10</td>
<td>1.38</td>
<td>1.80</td>
</tr>
<tr>
<td>0.042</td>
<td>1.40</td>
<td>1.40</td>
<td>2.40</td>
</tr>
<tr>
<td>0.084</td>
<td>2.00</td>
<td>1.44</td>
<td>3.70</td>
</tr>
<tr>
<td>0.126</td>
<td>2.30</td>
<td>1.46</td>
<td>5.00</td>
</tr>
<tr>
<td>0.168</td>
<td>3.00</td>
<td>1.46</td>
<td>10.80</td>
</tr>
<tr>
<td>0.210</td>
<td>3.00</td>
<td>1.51</td>
<td>-</td>
</tr>
</tbody>
</table>

![Fig. 3—Typical settling behaviour of 20% (w/v) aqueous suspensions of non-magnetic fraction of the ore in the absence as well as in the presence of three different flocculants.](image)
Healy filtration rate measurements are of particular value in characterizing the flocculated suspension, as they take cognizance of the presence of both large flocs which create porous bed and incompletely flocculated material which tend to obstruct pores.

Figure 4 shows the slurry filtration rate of the ore at different concentrations of solid in the absence of flocculant as well as in the presence of magnafloc 155. It may be noted that for 25% suspension (solid/liquid = 1:4) of the ore the rate of filtration increases sharply from without any addition to the presence of 0.042 g/kg of flocculant. It may also be noted that the rate decreases with increase in solid concentration from 16.6 to 33.3%. Figure 5 shows the corresponding cake filtration rate of the same suspension. As expected, the rates are linear for the entire period of filtration. This refiltration method is used to test the compressibility of the cake containing flocs. Figure 6 shows the filtration rates of the aqueous suspension of non-magnetic fraction. It may be noted that on increasing the flocculant dose from 0.04 to 0.08 g/kg, the filtration rate remains unchanged in the initial stage. But the rate increases in the later stage as growing thickness of the filter bed become more porous due to the presence of large flocs consisting of particle aggregates. The corresponding cake filtration rates are as usual linear and therefore not shown here.

Calculation of specific resistance

One of the most important parameters in the study of the filtration properties of the solid-liquid suspension is the specific resistance or reciprocal of permeability of the filter cake. This is based on the Darcy’s equation of the permeability of fluid through porous bed and is given by,
\[
\frac{dV}{dt} = \frac{k\Delta PA}{\mu L} \quad \text{...(1)}
\]

where, \(dV/dt\) = volumetric flow rate (cm\(^3\)/s)
\(\Delta P\) = pressure difference (N/cm\(^2\))
\(A\) = area of the bed (cm\(^2\))
\(L\) = total thickness of bed + medium (cm)
\(\mu\) = fluid viscosity (N.s/cm\(^2\))
\(k\) = permeability (cm\(^2\))

In the initial stage of slurry filtration the resistance due to solid particle bed is minimum, but as the bed begins to build up the rate is slowed down. When the process of filtration approaches completion, the pressure drop is related to the combined resistance of cake and filtering medium. The above equation may, therefore, be written as:

\[
\frac{dV}{dt} = \frac{\Delta PA}{\mu R_t} = \frac{\Delta PA}{\mu (R_c + R_f)} \quad \text{...(2)}
\]

where
\(R_t\) = total resistance (L/k, cm\(^{-1}\))
\(R_c\) = resistance due to cake
\(R_f\) = resistance due to filtering medium

The resistance due to cake is the product of mass of particles deposited (\(W\)) per unit area and specific cake resistance per unit mass (\(\alpha\)). Since \(W\) is a function of time in batch filtration, it can be related to the volume of filtrate \(V\) collected in time \(t\) per unit area of the bed as follows,

\[
W = C \frac{V}{A} \quad \text{...(3)}
\]

where, \(C\) is the mass of solid per unit volume of filtrate i.e., concentration of suspension (kg/m\(^3\)). After substitution, rearrangement and integration Eq. (2) may be written as follows\(^{19}\),

\[
\frac{t - t_o}{V - V_o} = a(V - V_o) + b \quad \text{...(4)}
\]

where
\(a = \alpha C \mu /2 \Delta PA^2\)
\(b = \mu R_f /\Delta PA\) and
\(V_o\) = volume of fluid collected at the start of the reckoning of time \(t_o\).

The data in Figs 4 and 6 which represent the slurry filtration rates of raw ore and its non-magnetic fraction respectively have been used to plot \((t-t_o)/(V-V_o)\) versus \((V-V_o)\) (Figs 7a and 7b). It can be seen that the linear behaviour is followed for the initial 160-190 s during which filtration takes place with uniform growth of the filter cake. From the slope values of the linear plots \(\alpha C\) values were calculated. The results are presented in Tables 4 and 5.

In case of cake filtration, Eq. (4) is redundant, and the specific resistance \((1/k)\) can be obtained directly from Eq. (1) using the slope values of the linear plots of volume \(V\) versus time as illustrated in Fig. 5. Dimensionally, these are equivalent to \(\alpha C\) values obtained from slurry filtration. The results are shown in Tables 4 and 5. However, specific resistance values calculated from cake filtration are generally higher than those obtained from slurry filtration for compressible solids. It may also be noted from Table 4 that an addition of small quantity (0.042 g/kg) of anionic flocculent considerably decreases specific

![Fig. 7—Plot of \((t-t_o)/(V-V_o)\) versus \((V-V_o)\) for the slurry filtration rates of (a) manganese ore and (b) non-magnetic fraction of the ore.](image)
resistance values of both slurry and cake filtration of the raw ore.

The results in Table 5 suggest that specific resistance of slurry filtration of non-magnetic fraction does not show any variation from no addition to the addition of 0.042 g/kg of magnafloc 155. Even with increase in solid concentration the change in the values are not significant. The effect is, however, perceptible when the dosage is increased to 0.084 g/kg. However, it is interesting to note from Table 5 that for a similar addition of anionic flocculant there is sharp decrease in sp. resistance value for cake filtration which decreases further with increase in solid content in the cake. The reason lies in the very fine particle size of non-magnetic fraction. As the concentration of solid increases, fine particles are mechanically trapped within the flocs without polymer chains getting anchored on them. These loosely bound or trapped particles which are mostly siliceous minerals form incompressible cake whose permeability does not vary with increase in solid content.

**Discussion**

There are several ways by which flocculant molecules are adsorbed on ore particles. It may be stated here that for effective flocculation to occur the molecules need not have to carry charges of opposite sign to that of ore particles. In fact, strong electrostatic attraction leads to adsorption on single particle instead of bridging of several particles. This is particularly observed with cationic polymers which sometimes adsorb so strongly on negatively charged particles that it may even lead to local charge reversal and subsequent collisions with the negatively charged particles result in the formation of aggregates. On the other hand, adsorption of anionic polymer onto positively charged particles or onto patches of heterogeneous surface takes place through either electrostatic or covalent or hydrogen bonding using carboxylic groups, polymer ends and amide groups respectively as exemplified in Fig. 8.

The adsorption of non-ionic flocculant takes place mostly through hydrogen bonding between amide group and surface oxygen of ore particles. It has now been established that flocculation occurs by bridging mechanism proposed first by Ruehrwein and Ward and subsequently developed by LaMer and coworkers to provide quantitative approach to the phenomenon. However, a flocculated suspension tends to be dispersed again under the following

<table>
<thead>
<tr>
<th>Slurry concn. % (w/v) of solid</th>
<th>Flocculant dose (g/kg of ore)</th>
<th>Specific resistance (×10⁻¹⁰ cm²)</th>
<th>Moisture content (%) from slurry filtration</th>
<th>Moisture content (%) from cake filtration</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.7</td>
<td>0.042</td>
<td>0.219</td>
<td>0.870</td>
<td>33.2</td>
</tr>
<tr>
<td>25.0</td>
<td>0.042</td>
<td>0.319</td>
<td>1.418</td>
<td>35.5</td>
</tr>
<tr>
<td>33.3</td>
<td>0.042</td>
<td>0.500</td>
<td>1.325</td>
<td>40.7</td>
</tr>
<tr>
<td>25.0</td>
<td>nil</td>
<td>1.297</td>
<td>1.946</td>
<td>35.0</td>
</tr>
</tbody>
</table>

Table 5—Specific resistance values obtained from slurry and cake filtration rates of aqueous suspension of non-magnetic fraction in presence of magnafloc 155

<table>
<thead>
<tr>
<th>Slurry concn. % (w/v) of solid</th>
<th>Flocculant dose (g/kg of ore)</th>
<th>Specific resistance (×10⁻¹⁰ cm²)</th>
<th>Moisture content (%) from slurry filtration</th>
<th>Moisture content (%) from cake filtration</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.7</td>
<td>nil</td>
<td>0.439</td>
<td>1.909</td>
<td>33.2</td>
</tr>
<tr>
<td>16.7</td>
<td>0.042</td>
<td>0.459</td>
<td>1.175</td>
<td>35.7</td>
</tr>
<tr>
<td>16.7</td>
<td>0.084</td>
<td>0.080</td>
<td>0.509</td>
<td>41.5</td>
</tr>
<tr>
<td>25.0</td>
<td>0.042</td>
<td>0.439</td>
<td>0.597</td>
<td>46.9</td>
</tr>
<tr>
<td>33.3</td>
<td>0.042</td>
<td>0.486</td>
<td>0.764</td>
<td>55.2</td>
</tr>
</tbody>
</table>

Fig. 8—Schematic illustration of the formation of particle aggregates and consequent formation large flocs through bridging mechanism. The nature of possible bonding between a flocculant in solution and solid surface is also illustrated in the figure.
situations: (a) the surface is almost fully covered by the polymer due to its strong adsorption so that no uncovered surface is left for bridging. Therefore, in mineral processing application flocculation is carried out under such solution conditions that ore particles do not possess high surface charge, such as pH close to PZC and medium of low ionic strength, (b) pulp density or solid concentration is also an important factor. If after adsorption on a particle the free ends of polymer chain do not get opportunity to be adsorbed quickly on a second or more particles it is likely to be adsorbed on the first particle forming a series of loops thereby preventing bridge formation to take place. La-Mer et al.\textsuperscript{23} have shown that the rate of aggregate formation is proportional to the square of solid concentration, (c) the extended segment bridges are so long to be unable to withstand the thermal motion of the individual particles in the floc, (d) the extended segments physically interfere with one another to prevent bridge formation, (e) intense agitation during the process of flocculant addition to the slurry leads to irreversible destruction of flocs, and (f) the mutual repulsion between particles fully covered by the polymer is also responsible for dispersion.

**Conclusion**

From the above investigation the following conclusions may be drawn:

1. The highly weathered low grade manganese ores (~150 μm) of Andhra Pradesh is subjected to wet high intensity magnetic separation. The particle size distribution pattern shows that ~45 μm fraction constitutes about 65 and 85% by weight of the ore and non-magnetic fraction respectively. Chemical analysis suggests that besides siliceous minerals fine (weathered) manganese and iron minerals are also present in appreciable quantities in ~45 μm fraction of the non-magnetic portion.

2. The pH\textsubscript{PZC} values of the ore and its non-magnetic portion are almost similar (8.3 and 8.2 respectively), while the corresponding value for magnetic portion is about 7.0.

3. The aqueous suspensions (pH ~ 8) ore and its non-magnetic portion can be flocculated with three types of commercial flocculating agents to improve the settling and filtration rates.

4. The effectiveness of the three types of polymeric flocculants obeys the following decreasing order: anionic > non-ionic > cationic. Since the particle size of non-magnetic portion is finer than the ore, the amount of flocculant required for efficient flocculation is higher.

5. The rate of filtration is also increased with the addition of small quantity of anionic flocculant by effectively decreasing the cake resistance. However, specific cake resistance values tend to increase or remain almost unchanged with increase in slurry concentration depending upon the nature of solid.

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**References**

1. Narayanan P I A & Subrahmanyan N, Beneficiation of Low Grade Manganese Ores of India (CSIR, New Delhi, India), 1959.