CHAPTER-5
RESULTS, RESULT ANALYSIS AND DISCUSSION

PREAMBLE
This chapter elaborates findings of experimental investigations on settling and rheological behaviour of the magnetite ore suspensions and various models used to fit the experimental data. Section 5.1 is focused on settling studies of the suspensions where the effects of dispersant concentration, solids concentration and particle size on the settling of the suspensions are discussed. The mathematical formulation to calculate particle Reynolds number and drag coefficient of settling particles and the drag coefficient-particle Reynolds number relationships obtained are presented. Section 5.2 is discussion on findings of rheological studies of the suspensions. The rheological nature of the suspensions under consideration, effect of particle size and solids concentration on suspension rheology and effect of temperature on suspension viscosity is also presented in sections 5.2.1 to 5.2.3 of this chapter. Model fitting for suspension rheology and concentration effects on relative viscosity is presented in section 5.2.4 and 5.2.5. Reported the constants of different models used to fit the experimental data. The development of artificial neural network model for the prediction of the suspension rheology and relative viscosity, its results and comparison with other models is discussed at the end of the chapter.

5.1 Settling studies

5.1.1 Effect of dispersant concentration on suspension settling

Aqueous CMC and guar gum solutions of varying concentrations were used to study the effect of concentration of dispersant on the settling of suspensions. The influence of the concentration of dispersant on the sedimentation properties was investigated at a constant solid volume fraction and particle size. The CMC and guar gum powders dissociate into water prior to being absorbed on to the surface of the particles. Once the surface of the particles gets covered with the layer of the dispersant, due to the identical charge on the particle, adjacent particles in suspensions repel each other and keep them suspended without settling.
Typical Figures 5.1 to 5.6 depict the effect of dispersant concentration on settling velocity \( (u_m) \) of suspensions in CMC and guar gum solutions, same behaviour were displayed by other suspensions studied. It has been found that, the increasing concentration of the dispersants imparts stability to the suspensions and hence decrease in the settling velocity was observed. For the suspensions of alumina powder Tsubaki et al \cite{1} found delayed rate of sedimentation for increase in the dose of polyacrylic acid dispersant. With the same dispersant Belastre et al \cite{2} reported similar results for barium sulphate suspensions.

![Figure 5.1: Effect of dispersant concentration on settling of suspensions](image)

Solids concentration: 10 weight %
Particle size: 50 µm
Dispersant: CMC
Figure 5.2: Effect of dispersant concentration on settling of suspensions

Figure 5.3: Effect of dispersant concentration on settling of suspensions
Figure 5.4: Effect of dispersant concentration on settling of suspensions

Figure 5.5: Effect of dispersant concentration on settling of suspensions
A high falling rate corresponds to low suspension stability and conversely, a slow falling rate corresponds to high suspension stability. The interface settling rate therefore provides a relative indicator of stability of the suspension. For both the dispersants used in the present studies, it has been found that the settling velocity of the particles decreases with increase in the concentration of dispersants in the dispersing solutions.

For the solid particle immersed in a liquid, three forces acting on it are; drag force, buoyant force and the gravity force. When these three forces are counterbalanced, the net force acting on the particle is zero. This condition favours the stable suspension which is observed above 1.1 and 1.3 weight % dispersant’s concentration for CMC and guar gum respectively. The viscosity of the suspending medium also increases with increase in dispersant’s concentration \[^{3-4}\]. The increase in the suspending medium viscosity increases the drag force acting on the particle that ultimately increases the total force opposing the gravity force on the particle and hence retards the downfall of the particle.

**Figure 5.6: Effect of dispersant concentration on settling of suspensions**
5.1.2 Effect of solids concentration on suspension settling

The following Figures 5.7 to 5.10 present typical plots showing the effect of solids concentration on the suspension settling for some of the suspensions prepared in CMC and guar gum aqueous solutions. From the figures, it is clear that with the increase in solids concentration, the suspension settling velocity decreases. The retardation of the settling of particles has been observed because settling rate in multiparticle systems are influenced by particle interaction effects consists of collisions among the particles and the hydrodynamic and non hydrodynamic reactions. The presence of container wall at finite distance also exerts retarding effect on the falling of the particles.

With increase in solids concentration the effective viscosity of the suspension increases. It may be expected that the increase in effective viscosity of the suspension can also contribute to the retardation in the settling of the suspensions. But according to Davis and Dallimore [5], the increased effective viscosity may not the cause for the decrease in the suspension settling rate. The decreased settling velocity is solely due to the hindrance caused by the particle crowding and the wall presence.

![Figure 5.7: Effect of solids concentration on settling of suspensions](image-url)

**Figure 5.7: Effect of solids concentration on settling of suspensions**
Figure 5.8: Effect of solids concentration on settling of suspensions

Figure 5.9: Effect of solids concentration on settling of suspensions
The effect of solids concentration on the suspension settling rate was studied for different solids concentrations such as 10, 20 and 30 weight % prepared in aqueous CMC and guar gum solutions. It has been found that at the 10 weight % solids concentration the suspension settling velocity was highest, whereas for highest solids concentration i.e. 30 weight %, the settling velocity was lowest. This is because of the hindrance at higher solids concentrations.

More important for this work was to obtain the single particle settling velocity from the experimentally obtained hindered settling velocity of the concentrated suspensions. The dependence of single particle velocity on the solid volume fraction of the suspensions was extensively studied by Richardson and Zaki [6]. The work of Richardson and Zaki indicated that the relation between the solids concentration and the settling velocity of suspended solid particle can be approximated with good accuracy.

The basic form of the Richardson and Zaki’s equation (Equation 2.5) is confirmed by several studies [7-9]. The concentration coefficient parameter ‘n’ of the Equation 2.5 was found to be the function of flow regime and the ratio of particle to container diameter. For the suspensions under considerations, values of ‘n’ were calculated by
using the equation 5.6 given by Richardson and Zaki as the ‘Reₚ’ value were less than 0.2. The values of the exponent ‘n’, thus obtained are reported in the following Table 5.1.

Table 5.1: The values of exponent n for the suspensions

<table>
<thead>
<tr>
<th>Particle Size</th>
<th>50 µm</th>
<th>52.3 µm</th>
<th>58.4 µm</th>
<th>74.8 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>4.692</td>
<td>4.694</td>
<td>4.699</td>
<td>4.713</td>
</tr>
</tbody>
</table>

These values of ‘n’ are further used to correct the velocity of suspension settling and to obtain free fall velocity of a single particle. The values of the exponent ‘n’ obtained are similar to those obtained by Berna and Mizrahi [7], Capes [8] and Turian et al [9].

5.1.3 Effect of particle size on suspension settling

The settling rates of the solid particles in a suspension depend on their size. The gravitational force which makes the particle settles down increases with increase in the particle size of the solids. For larger particles the wall effect becomes significant. The wall effect is a function of ratio of container diameter to the particle diameter (D/Dₚ). Wall effect is significant when this ratio is less than 100 and is negligible for higher radios.

Settling tests were conducted with the suspensions of four average particle size solids i.e. 50, 52.3, 58.4 and 74.8 µm, to investigate the effect of particle size on the settling behaviour of the suspensions. Figures 5.11 to 5.16 show typical settling rate curves depicting the effect of particle size on settling rate of suspensions. It has been found that settling velocity of the suspensions increases with increase in the particle size of the solids.

The settling rate curve for suspensions with 74.8 µm average diameter particles show that the rate of descent of the solid-liquid interface in these suspensions is faster as compared to suspensions made of the next three smaller particle size solids i.e. 58.4, 52.3 and 50 µm size particles. The settling rate curves for suspensions made of the next three smaller particle size solids i.e. 58.4, 52.3 and 50 µm size particles were found to be qualitatively identical with regard to the rapidity and certainty of establishment, as well as its persistence to the end of the settling.

In the present study the minimum ratio of container to particle diameter was 333 hence it is assumed that the effect of presence of solid boundary of container on the
suspension settling is negligible. Hence the increase in the rate of settling of suspensions with increase in the particle size of solids is due higher gravitational force acting on larger particle size solids. Similar results were obtained by Chin et al \cite{10} for the suspensions of silica and quartzite particles. For suspensions of glass particles ranging between 170 to 540 $\mu$m sizes, Davis et al \cite{11} reported the increase in settling rates of the suspensions with the increase in particles size of the solids.

![Graph showing the effect of particle size on settling of suspensions](image)

**Figure 5.11: Effect of particle size on settling of suspensions**
Figure 5.12: Effect of particle size on settling of suspensions

Figure 5.13: Effect of particle size on settling of suspensions
Figure 5.14: Effect of particle size on settling of suspensions

Figure 5.15: Effect of particle size on settling of suspensions
5.1.4 Drag coefficient ($C_D$) particle Reynolds number ($Re_p$) relationship

5.1.4.1 Mathematical Formulation

Settling rates in multiparticle systems are influenced by particle interaction effects, which consist of collision among particles and nonhydrodynamic interactions. In batch settling experiments, the rate of descent of suspension-supernatant interface during the course of sedimentation is determined, which corresponds to the rate of settling of solid particles.

The settling velocity of all the suspensions studied has been calculated by following the descending heights of the interface as function of time.

$$ u_m = \frac{\Delta h}{\Delta t} \quad (5.1) $$

The relative velocity between the settling solids and the liquid displaced by them is obtained according to the law of continuity as given below in Equation 5.2:

$$ u = \frac{u_m}{(1 - \phi)} \quad (5.2) $$
The hindered velocity is then corrected with Richardson and Zaki’s[^6] equation to calculate the single particle free falling velocity (Equation 5.3).

\[ u = u_i(1 - \phi)^n \]  

(5.3)

Where ‘n’ is a function of particle Reynolds number ‘Re_p’ and the ratio of particle to cylinder diameter ratio ‘d_p/D’. The following Equation 5.4 given by Richardson and Zaki[^6] is used to calculate the value of exponent ‘n’ for the ‘Re_p’ values less than 0.2:

\[ n = 4.65 + 19.5 \left( \frac{d_p}{D} \right) \]  

(5.4)

The single particle free falling velocity thus obtained is corrected with the following Equation 5.5 recommended by Garside and Al-Dibouni[^12] for wall effect on the suspension settling for the Re_p values less than 0.2:

\[ \frac{u_x}{u_i} = \left[ \left( 1 - 0.475 \frac{d_p}{D} \right) \left( 1 - \frac{d_p}{D} \right) \right]^4 \]  

(5.5)

Particle Reynolds number, Re_p is then calculated with the corrected velocity u_x.

\[ Re_p = \frac{\rho_f u_x d_p}{\mu_f} \]  

(5.6)

All the values of Re_p were obtained were less than one. Hence the drag force was calculated by using the following equation:

\[ F_D = 3\pi \mu u_x d_p \]  

(5.7)

The drag coefficient is then calculated by using the following equation:

\[ C_D = \frac{F_D}{\frac{1}{2} \rho_f u_x^2 A_p} \]  

(5.8)

The C_D-Re_p relationship forms a basic piece of information in suspension processing operations; it helps to determine influence of rheology, particle size and terminal settling velocity on the fluid drag. This relationship is as given below:

\[ C_D = f(Re_p) \]  

(5.9)

The plots of C_D-Re_p relationships, obtained from calculations of experimental results by using the above set of equations (Equation 5.1 to 5.9) are shown in the Figures 5.17 to 5.24 below:
Figure 5.17 Drag coefficient-particle Reynolds number relationship

Figure 5.18 Drag coefficient-particle Reynolds number relationship
Figure 5.19 Drag coefficient-particle Reynolds number relationship

Dispersant: CMC
Particle Size: 58.4 μm

Figure 5.20 Drag coefficient-particle Reynolds number relationship

Dispersant: CMC
Particle Size: 74.8 μm
Figure 5.21 Drag coefficient-particle Reynolds number relationship

Dispersant: guar gum
Particle Size: 50 μm

Figure 5.22 Drag coefficient-particle Reynolds number relationship

Dispersant: guar gum
Particle Size: 52.3 μm
Figure 5.23 Drag coefficient-particle Reynolds number relationship

Dispersant: guar gum
Particle Size: 58.4 µm

Figure 5.24 Drag coefficient-particle Reynolds number relationship

Dispersant: guar gum
Particle Size: 74.8 µm
5.1.4.2 $C_D$-Re$_p$ Relationship

The general relationship between drag coefficient $C_D$ and particle Reynolds number $Re_p$ can be expressed as,

$$C_D = a(Re_p)^b$$ (5.10)

Values of the constant ‘a’ and ‘b’ in Equation 5.10 are 24 and –1 respectively for Stoke’s law. The $C_D$-Re$_p$ relationships were developed for very low particle Reynolds numbers from experimental data of settling studies of all four particle sizes. The values of the constants ‘a’ and ‘b’ obtained as a result of curve fitting of $C_D$-Re$_p$ data for all suspensions prepared in CMC and guar gum solutions and are reported in the following Table 5.2. The values obtained for the constants of $C_D$-Re$_p$ relationship in the present work for the suspensions studied are almost same as that of Stoke's equation.

Table 5.2: Constants a and b of the $C_D$-Re$_p$ relationships for the suspensions

<table>
<thead>
<tr>
<th>Suspending medium</th>
<th>Particle size</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMC solution</td>
<td>50 µm</td>
<td>23.994</td>
<td>-1.0001</td>
</tr>
<tr>
<td>CMC solution</td>
<td>52.3 µm</td>
<td>23.997</td>
<td>-1</td>
</tr>
<tr>
<td>CMC solution</td>
<td>58.4 µm</td>
<td>24.012</td>
<td>-1</td>
</tr>
<tr>
<td>CMC solution</td>
<td>74.8 µm</td>
<td>23.99</td>
<td>-1</td>
</tr>
<tr>
<td>guar gum solution</td>
<td>50 µm</td>
<td>23.996</td>
<td>-1</td>
</tr>
<tr>
<td>guar gum solution</td>
<td>52.3 µm</td>
<td>24.089</td>
<td>-1</td>
</tr>
<tr>
<td>guar gum solution</td>
<td>58.4 µm</td>
<td>24.001</td>
<td>-0.9997</td>
</tr>
<tr>
<td>guar gum solution</td>
<td>74.8 µm</td>
<td>24.00</td>
<td>-1</td>
</tr>
</tbody>
</table>
5.2 Rheological Studies

5.2.1 Effect of particle size on the suspension rheology

Magnetite ore suspensions of four average particle size solids i.e. 50, 52.3, 58.4 and 74.8 μm prepared in aqueous CMC and guar gum solutions were used to study the effect of particle size on their rheology. All the suspensions studied under shear have shown shear thinning behaviour, the shear stress-shear rate data of these suspensions were tested with the Power Law Model. The Power law constants consistency index \( k \) and flow index \( n \) obtained by least square curve fitting are as reported below in the Table 5.3.

Table 5.3: Power law model constants for the suspensions

a) Suspensions prepared in aqueous CMC solutions

<table>
<thead>
<tr>
<th>Particle size (μm)</th>
<th>10 weight % solids</th>
<th>20 weight % solids</th>
<th>30 weight % solids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k</td>
<td>n</td>
<td>k</td>
</tr>
<tr>
<td>50</td>
<td>6.59</td>
<td>0.69</td>
<td>8.23</td>
</tr>
<tr>
<td>52.3</td>
<td>7.26</td>
<td>0.71</td>
<td>8.50</td>
</tr>
<tr>
<td>58.4</td>
<td>9.28</td>
<td>0.80</td>
<td>8.83</td>
</tr>
<tr>
<td>74.8</td>
<td>10.35</td>
<td>0.70</td>
<td>10.97</td>
</tr>
</tbody>
</table>

b) Suspensions prepared in aqueous guar gum solutions

<table>
<thead>
<tr>
<th>Particle size (μm)</th>
<th>10 weight % solids</th>
<th>20 weight % solids</th>
<th>30 weight % solids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k</td>
<td>n</td>
<td>k</td>
</tr>
<tr>
<td>50</td>
<td>6.28</td>
<td>0.68</td>
<td>8.34</td>
</tr>
<tr>
<td>52.3</td>
<td>7.15</td>
<td>0.76</td>
<td>8.28</td>
</tr>
<tr>
<td>58.4</td>
<td>8.41</td>
<td>0.86</td>
<td>10.22</td>
</tr>
<tr>
<td>74.8</td>
<td>10.40</td>
<td>0.83</td>
<td>12.87</td>
</tr>
</tbody>
</table>

From the flow index values obtained (Table 5.3) it is understood that more shear thinning has been observed for smaller particle sizes in suspensions with 10 and 20 weight % solids concentration in both the dispersants used. It indicates the aggregation effects are higher for smaller particles as compared to larger ones. These results are in line with the observations of Parkinson et al \(^{[13]}\) and Saunders \(^{[14]}\). At higher solids concentration i.e. 30 weight % solids, the non-Newtonian behaviour of
suspensions increase with increasing in particle size for suspensions prepared in CMC as well as guar gum solutions. This can be attributed to the greater hydrodynamic interactions at higher solids concentration and the inertia associated with the larger particle which makes them colloid rather than past each other.

The following Figures 5.25 to 5.30 show typical plots of apparent viscosity with shear rate. From the figures it is very clear that the apparent viscosity of the suspensions increases with increase in the particle size. Table 5.3 reflects the increase in the consistency of the suspensions with the particle size increase. Mangesana et al \[15\] and Thomas \[16\] reported similar results. According to Ghanta and Purohit \[17\], change in the surface characteristics of the solids with particle size depends on nature of the solid. Generally, for soft solids the surface irregularity decreases with increase in the particle size, where as it increases with increasing particle size of hard solids. It should be noted that magnetite is hard solid material.

![Figure 5.25: Effect of particle size on suspension rheology](image-url)
Figure 5.26: Effect of particle size on suspension rheology

Figure 5.27: Effect of particle size on suspension rheology
Figure 5.28: Effect of particle size on suspension rheology

Dispersant: guar gum
Solids Conc.: 10 weight %

Figure 5.29: Effect of particle size on suspension rheology

Dispersant: guar gum
Solids Conc.: 20 weight %
The observations of increase in the apparent viscosity of the suspensions with the increased particle size may be either due to increase in surface irregularities with increase in particle size or solids distribution for the larger particle size range is such that fluid available for movement of the particles is less than that of smaller particle size range so that the fluidity of smaller particles in slurry is larger than that of larger particles.

### 5.2.2 Effect of Solids Concentration on Suspension Rheology

From the experimental results of rheological measurements the flow curves were established with the apparent viscosity versus shear rate with a different solid concentration as shown in the following Figures 5.31 to 5.36. For all the suspensions prepared in CMC solutions it has been observed that the shear thinning increases with increase in solids concentration in the suspension. It is because at higher solids concentrations the hydrodynamic interactions among the particles increase, the magnitude of inter-particle forces would be large, due to the relatively small distance between the particles. These results are inline with those obtained by Sun et al.\textsuperscript{[18]}. 

---

**Figure 5.30: Effect of Particle Size on Suspension Rheology**

![Figure 5.30: Effect of Particle Size on Suspension Rheology](image-url)
Figure 5.31: Effect of solids concentration on suspension rheology

Dispersant: CMC
Particle Size: 50 μm

Figure 5.32: Effect of solids concentration on suspension rheology

Dispersant: CMC
Particle Size: 52.3 μm
Figure 5.33: Effect of solids concentration on suspension rheology

Dispersant: CMC  
Particle Size: 58.4 μm

Dispersant: GG  
Particle Size: 52.3 μm
Figure 5.35: Effect of solids concentration on suspension rheology

Dispersant: GG
Particle Size: 58.4 µm

Figure 5.36: Effect of solids concentration on suspension rheology

Dispersant: GG
Particle Size: 74.8 µm
The suspension prepared in guar gum solutions show the same behaviour but only for larger particle sizes i.e. 58.4 and 74.8 \( \mu m \). This may be due to pronounced aggregation of solids of smaller particle sizes i.e. 50 and 52.3 \( \mu m \) in guar gum solutions. Consistency index data of the suspensions reported in Table 5.3 show increase in the consistency of suspensions with increased solids concentration. Similar results were reported by Mangesana et al.\cite{15} and Sun et al.\cite{18}. Increase in concentration increases hindrance and thereby the resistance to flow of particles.

To observe the effect of solids concentration on apparent viscosity of the suspensions, suspensions were prepared as 5, 10, 15, 20, 25 and 30 weight % solids in aqueous CMC and guar gum solutions. Apparent viscosity of these suspensions was measured at a shear rate of 0.4 s\(^{-1}\) for CMC solutions and 0.55s\(^{-1}\) for guar gum solutions respectively. The suspending medium apparent viscosity at this shear rates were 838 cP for CMC and 720 cP for guar gum solutions. The relative viscosity of the suspensions were then calculated by dividing the apparent viscosity of these suspensions by the apparent viscosity of the suspending medium at the given shear rate. The exponential increase in the relative viscosity of these suspensions was observed with increased concentration of solids. The results are depicted in the Figures 5.37 and 5.38.

The increase in viscosity of the slurry observed at higher solid concentrations is due to the fact that increased solid concentration increases the crowding of the particles, thereby increasing particle-particle interaction in the slurry. The large particles present in the surrounding obstruct the motion of an individual particle. Cheng and Law\cite{19} Mooney\cite{20} and Dabak and Yucel\cite{21} attributed the increase in viscosity to the particle crowding and particle-particle interactions. Khodakov\cite{22} suggested that the viscosity of such slurry is determined by strength and number of contacts of the particles which are obviously more at higher solids concentration. As the particle volume fraction increases the distance between particles decreases as a result significant amount of the liquid is trapped between particles and become less mobilized leading to the situation that the flow around a particle is influenced by the flow induced by other particles.
Figure 5.37: Effect of solids concentration on suspension viscosity

Figure 5.38: Effect of S solids concentration on suspension viscosity
5.2.3 **Effect of Temperature on Suspension Viscosity**

Effect of temperature on the viscosity of the suspensions of 5 to 30 weight % solids concentration has been studied. For the suspensions prepared in both CMC and guar gum aqueous solutions, their apparent viscosity were measured by varying the temperature in the range of 30 to 50 °C. It has been fund that the viscosity decreases with increase in temperature of the suspension. The rate of decrease in the viscosity is more for increase from 30 to 40 °C and is less for rise in temperature from 40 to 50 °C as shown in Figures 5.39 to 5.44. Similar results obtained for slurries prepared in CMC as well as guar gum solutions.

The trend of decreasing viscosity at elevated temperatures might occurs due to increased kinetic energy of the particles promoting the breakage of intermolecular bond between adjacent layers, hence decrease in the interparticle forces between particles which results in decrease in viscosity of the suspension. Another reason of decreasing viscosity of the suspensions as temperature increases may be the drop in viscosity of the suspending medium which is obvious for all liquids. These results are similar to He et al [23], Mikulasek et al [24] and Senapati et al [25], but are contradictory to the results obtained by Li et al [26], who reported the increase in viscosity of silicon carbide when temperature increased in the range from 20 to 50 °C.
Figure 5.39: Effect of temperature on suspension viscosity

Figure 5.40: Effect of temperature on suspension viscosity
Figure 5.41: Effect of temperature on suspension viscosity

Solids Concentration: 15% (wt)
Shear Rate: 0.4 s⁻¹
Dispersant: CMC

Solids Concentration: 20% (wt)
Shear Rate: 0.55 s⁻¹
Dispersant: Guar Gum

Figure 5.42: Effect of temperature on suspension viscosity
Solids Concentration: 25 % (wt)
Shear Rate: 0.4s⁻¹
Dispersant: CMC

Solids Concentration: 30 % (wt)
Shear Rate: 0.55s⁻¹
Dispersant: Guar Gum

Figure 5.43: Effect of temperature on suspension viscosity

Figure 5.44: Effect of temperature on suspension viscosity
5.2.4 **Rheology Model Fitting**

All the suspensions have shown shear-thinning behavior (Figures 5.25 to 5.36); were tested with different non Newtonian rheological models to describe the shear stress-shear rate relationship. The two-parameter power law and Bingham plastic model and three-parameter Herschel-Bulkley model were used to describe the rheological behavior. These are given by the following equations:

**Power Law Model**: \( \tau = k \left( \frac{du}{dr} \right)^n \) (511)

**Bingham Plastic Model**: \( \tau = \eta \left( \frac{du}{dr} \right) \) (5.12)

**Herschel-Bulkley Model**: \( \tau = \tau_0 + k \left( \frac{du}{dr} \right)^n \) (5.13)

The rheological parameters \( k \) and \( n \) of Power Law equation, \( \eta \) and \( \tau_0 \) for Bingham Plastic equation for the suspensions were determined by least square method of linear regression of the experimental data. Parameters of the Herschel-Bulkley equation \( \tau_0, k \) and \( n \) were obtained by using the Mathematica 4.1 software. The values of these parameters thus obtained are reported in Table 5.4 and Table 5.5.

It is found that the apparent viscosity predictions by the Power Law equation are more accurate than that of the Bingham Plastic and Herschel-Bulkley equations. Typical Figures 5.45 to 5.50 show that the apparent viscosity predicted by power law is closer to the experimental one for the suspensions in CMC as well as guar gum solutions, similar results were obtained for other suspensions studied. Thus the power law can approximate the viscosity- shear rate relationship. It can also be used other suspensions of fine particles [7]. The average errors of the predictions by using the above discussed three equations are reported in the Table 5.6 and 5.7.
Figure 5.45: Comparison between empirical models for prediction of apparent viscosity of suspensions

Dispersant: CMC
Particle Size: 50 µm
Solids Concentration: 10 % weight

Figure 5.46: Comparison between empirical models for prediction of apparent viscosity of suspensions

Dispersant: CMC
Particle Size: 52.3 µm
Solids concentration: 20 weight %
Figure 5.47: Comparison between empirical models for prediction of apparent viscosity of suspensions

Figure 5.48: Comparison between empirical models for prediction of apparent viscosity of suspensions
Figure 5.49: Comparison between empirical models for prediction of apparent viscosity of suspensions

Figure 5.50: Comparison between empirical models for prediction of apparent viscosity of suspensions
Table 5.4: Rheological parameters of the empirical equations for the suspensions prepared in aqueous CMC solutions

<table>
<thead>
<tr>
<th>Particle Size (μm)</th>
<th>Solids Concentration (Weight %)</th>
<th>Constants of Power Law Model</th>
<th>Constants of Bingham Plastic Model</th>
<th>Constants of Herschel-Bulkley Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>k</td>
<td>n</td>
<td>τ₀</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>6.59</td>
<td>0.69</td>
<td>0.76</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>8.23</td>
<td>0.64</td>
<td>1.38</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>10.86</td>
<td>0.66</td>
<td>1.61</td>
</tr>
<tr>
<td>52.3</td>
<td>10</td>
<td>7.26</td>
<td>0.71</td>
<td>0.55</td>
</tr>
<tr>
<td>52.3</td>
<td>20</td>
<td>8.50</td>
<td>0.65</td>
<td>1.43</td>
</tr>
<tr>
<td>52.3</td>
<td>30</td>
<td>10.80</td>
<td>0.65</td>
<td>1.68</td>
</tr>
<tr>
<td>58.4</td>
<td>10</td>
<td>9.28</td>
<td>0.80</td>
<td>0.75</td>
</tr>
<tr>
<td>58.4</td>
<td>20</td>
<td>8.83</td>
<td>0.62</td>
<td>1.53</td>
</tr>
<tr>
<td>58.4</td>
<td>30</td>
<td>12.09</td>
<td>0.64</td>
<td>1.58</td>
</tr>
<tr>
<td>74.8</td>
<td>10</td>
<td>10.35</td>
<td>0.70</td>
<td>1.39</td>
</tr>
<tr>
<td>74.8</td>
<td>20</td>
<td>10.97</td>
<td>0.65</td>
<td>1.56</td>
</tr>
<tr>
<td>74.8</td>
<td>30</td>
<td>10.56</td>
<td>0.54</td>
<td>2.14</td>
</tr>
</tbody>
</table>
Table 5.5: Rheological parameters of the empirical equations for the suspensions prepared in aqueous guar gum solutions

<table>
<thead>
<tr>
<th>Particle Size (µm)</th>
<th>Solids Concentration (Weight %)</th>
<th>Constants of Power Law Model</th>
<th>Constants of Bingham Plastic Model</th>
<th>Constants of Herschel-Bulkley Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>k</td>
<td>n</td>
<td>(\tau_0)</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>6.28</td>
<td>0.68</td>
<td>1.17</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>8.34</td>
<td>0.80</td>
<td>0.84</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>9.49</td>
<td>0.80</td>
<td>0.99</td>
</tr>
<tr>
<td>52.3</td>
<td>10</td>
<td>7.15</td>
<td>0.76</td>
<td>0.80</td>
</tr>
<tr>
<td>52.3</td>
<td>20</td>
<td>8.28</td>
<td>0.72</td>
<td>1.46</td>
</tr>
<tr>
<td>52.3</td>
<td>30</td>
<td>11.14</td>
<td>0.81</td>
<td>0.97</td>
</tr>
<tr>
<td>58.4</td>
<td>10</td>
<td>8.41</td>
<td>0.86</td>
<td>0.58</td>
</tr>
<tr>
<td>58.4</td>
<td>20</td>
<td>10.22</td>
<td>0.87</td>
<td>1.53</td>
</tr>
<tr>
<td>58.4</td>
<td>30</td>
<td>10.38</td>
<td>0.64</td>
<td>1.95</td>
</tr>
<tr>
<td>74.8</td>
<td>10</td>
<td>10.40</td>
<td>0.83</td>
<td>0.77</td>
</tr>
<tr>
<td>74.8</td>
<td>20</td>
<td>12.87</td>
<td>0.87</td>
<td>0.85</td>
</tr>
<tr>
<td>74.8</td>
<td>30</td>
<td>12.37</td>
<td>0.75</td>
<td>1.27</td>
</tr>
</tbody>
</table>
Table 5.6: Average percent error of the predictions for the suspensions prepared in aqueous CMC solutions

<table>
<thead>
<tr>
<th>Particle Size (µm)</th>
<th>Solids concentration (Weight %)</th>
<th>Power law model</th>
<th>Bingham plastic model</th>
<th>Herschel-Bulkley Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>10</td>
<td>1.86</td>
<td>2.18</td>
<td>1.96</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>1.53</td>
<td>3.69</td>
<td>1.61</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>0.61</td>
<td>2.70</td>
<td>0.58</td>
</tr>
<tr>
<td>52.3</td>
<td>10</td>
<td>0.76</td>
<td>2.50</td>
<td>0.72</td>
</tr>
<tr>
<td>52.3</td>
<td>20</td>
<td>1.88</td>
<td>4.17</td>
<td>2.18</td>
</tr>
<tr>
<td>52.3</td>
<td>30</td>
<td>0.86</td>
<td>2.99</td>
<td>7.93</td>
</tr>
<tr>
<td>58.4</td>
<td>10</td>
<td>1.14</td>
<td>2.60</td>
<td>1.46</td>
</tr>
<tr>
<td>58.4</td>
<td>20</td>
<td>2.40</td>
<td>1.82</td>
<td>8.24</td>
</tr>
<tr>
<td>58.4</td>
<td>30</td>
<td>3.03</td>
<td>1.87</td>
<td>3.07</td>
</tr>
<tr>
<td>74.8</td>
<td>10</td>
<td>1.11</td>
<td>2.92</td>
<td>1.17</td>
</tr>
<tr>
<td>74.8</td>
<td>20</td>
<td>2.30</td>
<td>2.40</td>
<td>2.24</td>
</tr>
<tr>
<td>74.8</td>
<td>30</td>
<td>3.84</td>
<td>2.80</td>
<td>4.20</td>
</tr>
</tbody>
</table>

Table 5.7: Average percent error of the predictions for the suspensions prepared in aqueous guar gum solutions

<table>
<thead>
<tr>
<th>Particle Size (µm)</th>
<th>Solids concentration (Weight %)</th>
<th>Power law model</th>
<th>Bingham plastic model</th>
<th>Herschel-Bulkley Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>10</td>
<td>5.94</td>
<td>4.78</td>
<td>5.96</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>1.09</td>
<td>2.84</td>
<td>1.17</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>1.95</td>
<td>4.63</td>
<td>1.96</td>
</tr>
<tr>
<td>52.3</td>
<td>10</td>
<td>2.20</td>
<td>1.20</td>
<td>2.23</td>
</tr>
<tr>
<td>52.3</td>
<td>20</td>
<td>4.31</td>
<td>7.10</td>
<td>4.47</td>
</tr>
<tr>
<td>52.3</td>
<td>30</td>
<td>1.54</td>
<td>3.57</td>
<td>1.56</td>
</tr>
<tr>
<td>58.4</td>
<td>10</td>
<td>0.45</td>
<td>2.36</td>
<td>0.53</td>
</tr>
<tr>
<td>58.4</td>
<td>20</td>
<td>2.14</td>
<td>11.34</td>
<td>2.18</td>
</tr>
<tr>
<td>58.4</td>
<td>30</td>
<td>2.65</td>
<td>5.36</td>
<td>2.67</td>
</tr>
<tr>
<td>74.8</td>
<td>10</td>
<td>1.15</td>
<td>2.76</td>
<td>1.19</td>
</tr>
<tr>
<td>74.8</td>
<td>20</td>
<td>3.72</td>
<td>5.81</td>
<td>4.03</td>
</tr>
<tr>
<td>74.8</td>
<td>30</td>
<td>1.66</td>
<td>3.04</td>
<td>1.66</td>
</tr>
</tbody>
</table>
5.2.5 **Viscosity Model Fitting**

One of the physically significant parameters affecting the suspension viscosity is \((\phi_m - \phi)\). This parameter represents the effective space available for particles to disperse. At smaller values of \(\phi\), the particles can move easily. As \(\phi\) increases, the suspension gets thicker and the relative space available will decrease which results in increased viscosity of the suspension. Theoretically speaking there will be no space available for the particles to move when \(\phi\) approaches \(\phi_m\). The ratio \(\phi/\phi_m\) is a representation of degree of freedom the particles have to move within the mixture. Other parameters \(\eta\) and \(n\) reflect the effects of particle shape and particle interaction in the given fluid respectively. For the prediction of effective viscosity of magnetite ore suspension, various models available in the literature, which include one or more of the above discussed parameters, were selected. Six models namely Einstein’s equation, Leighton and Acrivos’s equation, Chong et al equation, Krieger- Dowarty’s equation, Liu’s equation and Metzner’s equation presented in Table 2.2 were utilized to predict the suspension viscosity.

Liu \cite{24} has proposed a model to estimate maximum volume fraction \((\phi_m)\) allowable for given suspension at which suspension viscosity approaches infinity. The Equation 5.14 is a linear relationship between \(1 - \eta_{fr}^{-0.5}\) and \(\phi\) which predicts the maximum solid volume fraction \((\phi_m)\) and is given as:

\[
1 - \eta_{fr}^{-0.5} = a\phi + b
\]  

(5.14)

Where, the constant \(a\) (slope of the straight line) and \(b\) (intercept value) were determined from the relation \((1 - \eta_{fr}^{-0.5} - \phi)\) using experimental data.

The Figure 5.51 shows the graph of \(1 - \eta_{fr}^{-0.5}\) with \(\phi\) for the suspensions of 50 micrometer particle size solids in aqueous CMC solutions. The maximum volume fraction of the solids is obtained as: \(\phi_m = (1+0.0284)/3.475 = 0.296\)

The Liu’s equation is

\[
\eta_{fr} = [a(\phi_m - \phi)]^{-n}
\]  

(5.15)

This in logarithmic form can be written as

\[
\ln(\eta_{fr}) = \ln[a(\phi_m - \phi)]^{-n}
\]

\[
\ln(\eta_{fr}) = n \ln(a) - n \ln(\phi_m - \phi)
\]  

(5.16)
Graph of \(\ln(\eta_r)\) vs \(-\ln(\phi_{in} - \phi)\) (Figure 5.52) is plotted and the values of the constants \(a\) and \(n\) are obtained by curve fitting.

**Figure 5.51: Plot of \(1 - \eta_r^{-0.5}\) versus \(\phi\)**

**Figure 5.52: Plot of \(\ln(\eta_r)\) versus \(-\ln(\phi_{in} - \phi)\)**
For the same suspension the value of the Liu’s constants ‘a’ and ‘n’ obtained by the curve fitting were 3.471 and 1.9833 respectively. The Krieger- Dowarty’s equation \(^{[25]}\)
is of the following form:

\[
\eta_i = \left[1 - \frac{\phi}{\phi_m}\right]^{-\eta\phi_m}
\]  

(5.17)

Logarithmic form of Equation 5.17 is:

\[
\ln(\eta_i) = -\eta\phi_m \ln\left(1 - \frac{\phi}{\phi_m}\right)
\]  

(5.18)

As shown in Figure 5.53 graph of \(\ln(\eta_i)\) vs \(\ln[(1-\phi/\phi_m)]\) is plotted, slope of this straight line graph passing through origin gives value of \(-\eta\phi_m\) and thus the value of intrinsic viscosity is calculated by using the \(\phi_m\) comes to be 6.114

![Figure 5.53: Plot of ln(\(\eta_i\)) vs (1- \(\phi/\phi_m\))](image)

Thus, maximum volume fraction, Liu’s constants and the intrinsic viscosity were calculated by data fitting analysis of the experimental data. The above obtained values are for the suspension of 50 \(\mu m\) size solids prepared in CMC solution. Similarly the values of these constants were obtained for all other suspensions and are reported Table 5.8.
The suspension viscosity is then predicted by using all six models discussed earlier. The comparison of predictive ‘\( \eta_r \)’ and the experimentally measured ‘\( \eta_r \)’ at all the solids concentration studied in the present investigation are presented in the typical Figures 5.54 and 5.55 for the suspensions prepared in CMC and guar gum solutions respectively. From the figures it is very clear that the viscosity values predicted by Liu’s equation are very close to the experimental values as compared to all other equations used for predictions. Similar results were observed for all other suspensions studied. RMSE values of the predictions by different models are compared in the Table 5.9.

For all the suspensions studied it has been found that the RMSE for the prediction of effective viscosity by Liu’s model is lowest as compared to the other models. It accounts for the two parameters, which are relative space available for movement of particles and the particle-particle interactions. These two parameters, as now we can infer, influence the effective viscosity of magnetite ore suspensions more strongly than the shape of the particles and the degree of freedom the particles have to move.

Table 5.8: Model parameter values utilized to compute relative viscosity of Suspensions

(a) Suspending medium: CMC, shear rate: 0.4s\(^{-1}\), suspending medium viscosity: 838 cP.

<table>
<thead>
<tr>
<th>Particle size ( \mu m )</th>
<th>Maximum volume fraction of solids ( \phi_m )</th>
<th>Constants of Liu’s model</th>
<th>Intrinsic viscosity ( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( a )</td>
<td>( n )</td>
</tr>
<tr>
<td>50</td>
<td>0.296</td>
<td>3.471</td>
<td>1.9833</td>
</tr>
<tr>
<td>52.3</td>
<td>0.332</td>
<td>2.982</td>
<td>1.9894</td>
</tr>
<tr>
<td>58.4</td>
<td>0.295</td>
<td>3.231</td>
<td>1.9631</td>
</tr>
<tr>
<td>74.8</td>
<td>0.487</td>
<td>1.703</td>
<td>1.9688</td>
</tr>
</tbody>
</table>

(b) Suspending Medium: guar gum, shear rate: 0.55s\(^{-1}\), suspending medium viscosity: 720 cP.

<table>
<thead>
<tr>
<th>Particle size ( \mu m )</th>
<th>Maximum volume fraction of solids ( \phi_m )</th>
<th>Constants of Liu’s model</th>
<th>Intrinsic viscosity ( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( a )</td>
<td>( n )</td>
</tr>
<tr>
<td>50</td>
<td>0.365</td>
<td>2.794</td>
<td>1.9623</td>
</tr>
<tr>
<td>52.3</td>
<td>0.313</td>
<td>3.211</td>
<td>1.9684</td>
</tr>
<tr>
<td>58.4</td>
<td>0.299</td>
<td>3.249</td>
<td>1.9625</td>
</tr>
<tr>
<td>74.8</td>
<td>0.567</td>
<td>1.441</td>
<td>1.955</td>
</tr>
</tbody>
</table>
Table 5.9: RMSE in predicting relative viscosity with different models

a) Suspending medium: aqueous CMC solution

<table>
<thead>
<tr>
<th>Particle size (μm)</th>
<th>Root mean square error (RMSE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Einstein’s equation</td>
</tr>
<tr>
<td>50</td>
<td>0.300087</td>
</tr>
<tr>
<td>52.3</td>
<td>0.316426</td>
</tr>
<tr>
<td>58.4</td>
<td>0.496755</td>
</tr>
<tr>
<td>74.8</td>
<td>0.654912</td>
</tr>
</tbody>
</table>

a) Suspending medium: aqueous guar gum solution

<table>
<thead>
<tr>
<th>Particle size (μm)</th>
<th>Root mean square error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Einstein’s equation</td>
</tr>
<tr>
<td>50</td>
<td>0.19538</td>
</tr>
<tr>
<td>52.3</td>
<td>0.310896</td>
</tr>
<tr>
<td>58.4</td>
<td>0.413826</td>
</tr>
<tr>
<td>74.8</td>
<td>0.646691</td>
</tr>
</tbody>
</table>
Figure 5.54: Comparison of relative viscosity predictions by different models

Particle size: 74.8 μm
Dispersant: CMC

Figure 5.55: Comparison of relative viscosity predictions by different models

Particle size: 58.4 μm
Dispersant: guar gum
5.2.6 Predictions by ANN model

5.2.6.1 Developing the ANN Model

In the present work backpropagation ANN (Figure 5.56) with sigmoid transfer function has been used for training and testing of rheological data considering different architectures. All the input and output parameters in the training and testing were normalized. These were obtained by using the following equation:

\[
X_{i,\text{norm}} = \frac{X_i}{X_{i,\text{max}}} \quad (5.19)
\]

Where,

- \(X_i\) = any value of a particular variable
- \(X_{i,\text{max}}\) = maximum value of that variable
- \(X_{i,\text{norm}}\) = normalized value of that variable

![Figure 5.56: Schematic of backpropagation network](image-url)
5.2.6.2 Predictions of rheological behaviour of suspensions by ANN model and comparison with the power law model

For the suspensions in CMC solution five inputs i.e. particle size, solids volume fraction, speed of rotation of rheometer, shear rate and shear stress were used and the output was the apparent viscosity, but in case of suspensions in guar gum solution four inputs i.e. particle size, solids volume fraction, shear rate and shear stress were used. Different architectures were tested for varying iterations, number of hidden layers and number of neurons in hidden layers. It has been found that the prediction error decreases with increase in number of hidden layers. It also has been observed during the ANN training that the prediction error changes with number of iterations.

By trial and error procedure a three hidden layers ANN of the architecture 5-25-20-15-1 for prediction of viscosity of suspensions in CMC solutions and a single hidden layer ANN of the architecture 5-20-1 for suspensions in guar gum solutions were obtained as best models respectively. Using these models, apparent viscosity of 172 data sets of suspensions in CMC solution (Figures 5.57 to 5.60 and 38 data sets of suspensions in guar gum solution (Figures 5.61 to 5.63) were predicted.

It has been found that the apparent viscosity values predicted by using ANN models are closer to the experimental data as compared to those predicted by power law model. The Average error values of predictions using ANN and Power Law model are as reported in the Table 5.10.

The values of apparent viscosity of the suspensions obtained experimentally, predicted by ANN model and predicted by power law model are plotted against the shear rate as shown in Figures 5.57 to 5.60 for suspensions in CMC solutions and Figures 5.61 to 5.63, for suspensions in guar gum solutions. From these figures it is well understood that Power law model can be used to predict the viscosity of these slurries but ANN model can give comparatively better prediction. The maximum average error of the predicted values over the experimental one is $\pm 0.86\%$ which indicates that the ANN model’s predictions of suspension rheology are very accurate than all other models tested.
### Table 5.10: Average percent error of the predictions by power law model and ANN model

<table>
<thead>
<tr>
<th>Dispersing medium</th>
<th>Particle size (µm)</th>
<th>Solids concentration (weight %)</th>
<th>Power law model</th>
<th>ANN model</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMC solution</td>
<td>50</td>
<td>20</td>
<td>1.53</td>
<td>0.32</td>
</tr>
<tr>
<td>CMC solution</td>
<td>52.3</td>
<td>20</td>
<td>1.88</td>
<td>0.29</td>
</tr>
<tr>
<td>CMC solution</td>
<td>58.4</td>
<td>20</td>
<td>2.40</td>
<td>0.21</td>
</tr>
<tr>
<td>CMC solution</td>
<td>74.8</td>
<td>30</td>
<td>3.84</td>
<td>0.48</td>
</tr>
<tr>
<td>guar gum solution</td>
<td>50</td>
<td>20</td>
<td>1.09</td>
<td>0.70</td>
</tr>
<tr>
<td>guar gum solution</td>
<td>52.3</td>
<td>30</td>
<td>1.54</td>
<td>0.86</td>
</tr>
<tr>
<td>guar gum solution</td>
<td>58.4</td>
<td>10</td>
<td>0.45</td>
<td>0.74</td>
</tr>
</tbody>
</table>

![Experimental vs. Model Comparison](image_url)

**Figure 5.57:** Comparison between power law model and ANN model for prediction of apparent viscosity of suspensions
Figure 5.58: Comparison between power law model and ANN model for prediction of apparent viscosity of suspensions

Dispersant: CMC
Particle size: 52.3 μm
Solids concentration: 20 weight %

Figure 5.59: Comparison between power law model and ANN model for prediction of apparent viscosity of suspensions

Dispersant: CMC
Particle size: 58.4 μm
Solids concentration: 20 weight %
Dispersant: CMC  
Particle size: 74.8 µm  
Solids concentration: 30 weight %

Figure 5.60: Comparison between power law model and ANN model for prediction of apparent viscosity of suspensions

Dispersant: guar gum  
Particle size: 50 µm  
Solids concentration: 20 weight %

Figure 5.61: Comparison between power law model and ANN model for prediction of apparent viscosity of suspensions
Figure 5.62: Comparison between power law model and ANN model for prediction of apparent viscosity of suspensions

Dispersant: guar gum
Particle size: 52.3 μm
Solids concentration: 30 weight %

Figure 5.63: Comparison between power law model and ANN model for prediction of apparent viscosity of suspensions

Dispersant: guar gum
Particle size: 58.4 μm
Solids concentration: 10 weight %
5.2.6.3 Predictions of relative viscosity of suspensions by ANN model and comparison with the Liu’s model

A two hidden layers ANN model of the architecture 3-30-30-1 has been obtained as the best model for prediction of effective viscosity of suspensions prepared in CMC solutions and for suspensions in guar gum solutions a single hidden layer model of the architecture 3-30-1 was selected. Using these models, relative viscosity of 6 data sets of suspensions in CMC solution and 6 data sets of suspensions in guar gum solution was predicted.

The RMSE values of predictions using ANN and Liu’s model are as reported in the Table 5.11. The figures 5.64 and 5.65 show the comparison between the effective viscosity values predicted by ANN model and the Liu’s model for the suspensions prepared in aqueous CMC and guar gum solutions respectively. From these figures it is well understood that Liu’s model can be used to predict the viscosity of magnetite ore slurries for the concentration range used in the present studies. But ANN model can give comparatively better predictions.

**Table 5.11: Comparison of RMSE of the predictions by ANN and Liu’s model**

<table>
<thead>
<tr>
<th>Dispersant</th>
<th>Particle size (μm)</th>
<th>Liu’s Model</th>
<th>ANN Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMC</td>
<td>74.8</td>
<td>0.048641</td>
<td>0.029291</td>
</tr>
<tr>
<td>guar gum</td>
<td>58.4</td>
<td>0.081991</td>
<td>0.073568</td>
</tr>
</tbody>
</table>
Figure 5.64: Comparison between the predictions of relative viscosity by Liu’s model and ANN model

Figure 5.65: Comparison between the predictions of relative viscosity by Liu’s model and ANN model
5.3 Summary

In the thesis, the settling and rheological behaviours of magnetite ore suspensions were studied. Four different average particle size solids in the range of 50 to 75 μm were considered and the solids concentration in the suspensions were varies up to 30 weight %. CMC and guar gum were the dispersants selected for the preparation of the suspensions.

The effect of dispersant concentration on the rate of settling of suspensions was studied by varying the concentration of CMC and guar gum in the suspending mediums. With both the dispersants, it has been found that, the rate of settling of the suspensions decreases with the increase in the dispersant’s concentration. The increase hindrance has been observed for the increase in the solids concentration from 10 to 30 weight % for any particle size studied. By using Richardson-Zaki’s equation, the single particle terminal settling velocity was calculated for the concentrated suspensions. The calculated values of hindered settling coefficient ‘n’ were nearly same for all four particle sizes studied (4.692 to 4.713). These values were in the range 4.65 to 5.1, reported by Berna and Mizrahi and are also close to the value 4.68 recommended by Turian et al.

As the particle size of the solids in the suspensions increased, it has been found that, the rate of settling of suspension increases at all the solids concentrated considered. Earlier workers have suggested to neglect the wall effects for particle to cylinder diameter ratio higher than 100. In the present study, the single particle settling velocity given by Richardson-Zaki’s equation was further corrected for wall effects by using the equation recommended by Garside and Al-Dibouni. The particle Reynolds number ‘Re_p’ and drag coefficient ‘C_D’ were calculated by using the corrected single particle terminal settling velocity. The C_D-Re_p relationships were developed by data fitting of the experimentally obtained results. The relationships were found inline with the well known Stoke’s law i.e. C_D = 24/Re_p.

When examined under shear, magnetite ore suspensions studied have shown pseudoplastic behaviour. It has been found that the non Newtonian behaviour of the suspensions increases with the decrease in particle size for suspensions with 10 and 20 weight % solids. For 30 weight % solids concentration, however, the suspensions show increase in non Newtonian behaviour for increased particle size. At 10, 20 and
30 weight % solids concentration, the power law model consistency index and the apparent viscosity of the suspensions were found to be increasing with the increase in the particle size. For all the suspensions prepared in aqueous CMC solutions, increase in the shear thinning was observed as solids content increased from 10 to 30 weight %.

The suspensions of 50 and 52.3 μm solids, prepared in aqueous guar gum solutions show more shear thinning at lower solids concentration. For suspensions with 58.4 and 74.8 μm solids, increase in shear thinning was observed as solids concentration increased. Exponential increase in the apparent viscosity of the suspensions with the solids concentration was observed for all the suspensions studied, the power law model consistency index values were also found to be increasing. The decrease in apparent viscosity of the suspensions was observed when the temperature of the suspensions was increased from 30 to 50 °C. The relative decrease in the suspension apparent viscosity was found slightly more for temperature rise from 30 to 40 °C as compared to the temperature rise from 40 to 50 °C.

Three models, power law, Bingham plastic and Herschel Bulkley were presented to describe the experimental flow curves of the magnetite ore suspensions. However, the Bingham plastic model inadequately describes the flow curve data. The power law model was found to be better in describing the flow curves over the solid concentration range from 10 to 30 weight %. Artificial neural network (ANN) models were developed to describe the flow curves and found to be more effective than power law model.

Six models, Einstein’s equation, Leighton and Acrivos’s equation, Chong et al’s equation, Krieger-Dowart’s equation, Liu’s equation and Metzner’s equation were used to present the the relationship between relative viscosity ‘μr’ and volume fraction of solids ‘ϕ’ of the suspensions. Among the six models tested, Liu’s equation was found better fitting the experimental data. Further ANN models were developed for predicting the relative viscosity of the suspensions. It has been found that the ANN models give more accurate predictions as compared to the Liu’s equation.
References


4. Yoshiyuki Fakuda, Tsunetaka Togachi, Yoshio Suzuki, Makio Naito and Hidehiro Kamiya. 'Influence of Additive Content of Anionic Polymer Dispersant on Dense Alumina Suspension Viscosity'. Chemical Engineering Science, 56(9), (2001), 3005-3010


8. E. Capes, “Particle Agglomeration and the Value of the Exponent n in the Richardson-Zaki Equation”, Powder Technology, 10, (1074), 303-306


