Original Article

INVESTIGATION OF THE EFFECTS OF FINES CONSISTENCY ON FINES FLOCCULATION USING COFACTOR-POLYETHYLENE OXIDE SYSTEM AND FIND OUT THE AFFECTIVE PARAMETERS

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ABSTRACT

The objective of this work was to investigate the effect of the fines consistency (C_{fn}) on the fines flocculation characteristics using a cofactor (CF) - polyethylene oxide (PEO) retention aid. One result of this work has shown that the floc size (A) and the flocculation rate (r_f) started to increase with the increase in the C_{fn}, reached maximum, plateaued and then started to decrease. Deflocculation with the rate (r_d) was also recorded in the all runs. The flocculation rate constant (k_f), the deflocculation rate constant (k_d), and the reverse equilibrium constant (K_{-equi}) were all determined and plotted versus the C_{fn}. The flocculation rates as functions of the C_{fn} values were verified with Longmuir equation and Smoluschowski isotherm, and the attachment rate constants (k_{att}) were found. The increase in r_f with the increase in C_{fn} was ascribed to the increase in the collision frequency (ω) that caused increases in both the attachment forces and the countered viscous forces. When the rate r_f reached maximum, the attachment forces balanced the viscous forces, but with more increase in C_{fn} the viscous forces increased over the attachment forces, thus resulting negative slopes (negative k_{att}) and a decrease in flocculation rate r_f.

KEYWORDS: Cofactor - Polyethylene oxide, Flocculation, Deflocculation, Consistency, Rate Constant, Reverse Rate Constant.

INTRODUCTION

Flocculation and particle retention are essential in many industrial applications. In papermaking, fines, the negative fiber fragments of 3-76 μm size were found to comprise more than 50% of the feed pulps (Abdallah, Mohammad. R., 2002; Casey, J.P., 1979). Retention of these fines into paper sheet is very essential to minimize the effluent and recycling problems (van de Ven, T.G.M., 1993), and to improve the sheet properties such as strength, permeability, opacity, and apparent density (Brecht, W. and Klemm, K., 1953). Retention aids were used to bridge fines with fibers and deposit these fines on the fibers in heteroflocculation, and bridge fines with fines into fines flocs, which retain in the holes of the paper sheet. In surface water treatment, a lot of particles and colloids from the surrounding mix with water spoiling its purity. These impurities are treated with the retention aids producing flocs, which grow, settle and then removed as sludge. In papermaking, the fines (the > 50% of the pulp) either deposit on fibers in heteroflocculation or attach with fines in homoflocculation resulting flocs that retain in paper sheet (Abdallah, Mohammad. R. 2002). Anionic and cationic polyelectrolyte were used in flocculation processes as retention aids (Bjorkman, 2003; Spicer, T. P. and Pratsinis, S. E., 1996; Higashitani, K., et. al., 1989; van de Ven, T.G.M., 1994). Many of the polyelectrolytes are cationic (Abdallah/Qasaimeh, M. R., et. al., 2014), and the cationic polyacrylamides and polyethylene oxide (PEO) were widely added to pulp suspensions (Pelton, R. H., 1979). For better retention, the dual retention aid, the PEO with a cofactor (CF) was recommended since neutral PEO does not incorporate with the ions in the suspensions (Abdallah, Mohammad. R., 2002; Pelton, R.H., et. al., 1980). The PEO was found more effective in the presence of a CF, which in most common have phenolic hydroxyl groups and presumably form hydrogen bonds with PEO (Abdallah, Mohammad. R., 2002). We (Abdallah Qasaimeh, M.R., 2011; Mohammad Raji Abdallah Qasaimeh, 2022; Dr. Mohammad Raji Abdallah Qasaimeh, 2024) and some others in literature (van de Ven, T.G.M., 1994; Carignan, A., et. al., 1998; Meng R.Wu. and van de Ven, T.G.M., 2009) studied fines flocculation using the CF-PEO retention aid, and found various factors affecting flocculation. Some of these factors were in PEO and some others were in CF and process factors. The in PEO factors were the method of PEO dissolution, delivery and addition, since the PEO is more active in the entangled state that bridge the fines easily (Abdallah, Mohammad. R., 2002; van de Ven, T.G.M., 1997). The factors in CF were the CF types which

most often phenolic (van de Ven, T.G.M., 1997; Lindstrum, T., and Glads-Nordmark, G. 1984), the addition (Pelton, R.H., et. al., 1980) and the cofactor concentration (C) (Mohammad Raji Abdallah Qasaimeh, 2022; Dr. Mohammad Raji Abdallah Qasaimeh, 2024). The mechanism that the CF-PEO retention aid system flocculate fines was called the CF- PEO induced bridging. Here the entangled PEO coils (of size δ) and the CF
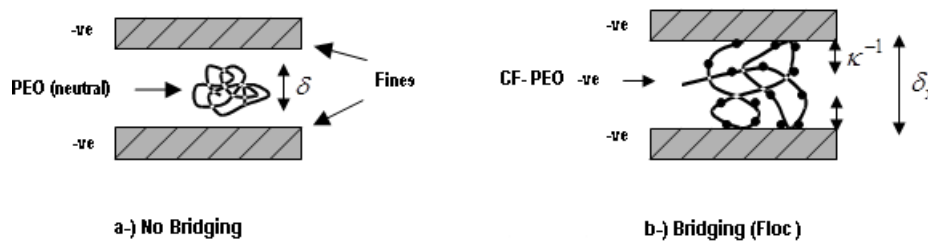

Fig. 1: a-) the PEO coils do not adsorb on the surfaces and pass with no bridging; b-) the CF segments adsorb on PEO coils expand the entangled PEO coils resulting the CF-PEO complex.

segments do not adsorb on fines, but the CF-PEO complex (of size δ_x) resulted from their combination adsorbs on fines surfaces. The size of the adsorbed complex is larger than the thickness of the electrostatic repulsion layer (K^{-1}) and imply bridging (Fig. 1) on the surfaces; here the complex is larger size than the electrostatic repulsion layer ($\delta_x > K^{-1}$) and adsorbs on surfaces inducing bridging (Abdallah Qasaimeh, M.R., 2011; Carignan, A., et. al., 1998). In literature, the dominant hypotheses explained the mechanism that the CF-PEO flocculates the particles and argued the transient network mechanism (Lindström, T. et. al., 1984) was the association-induced polymer bridging proposed by van de Ven and Alince (1996). This hypothesis showed how the CF expand and stiffen the PEO coils into CF-PEO complex that adsorb on surfaces, overcome the repulsion of the electrostatic double layer K^{-1} and bridge the surfaces. This bridging occurs under two conditions: $\delta_x > 2\kappa^{-1}$ and $\theta\,(=\Gamma/\Gamma_m) < 1$, where θ is the fractional coverage of a monolayer of PEO on the surfaces. Here, Γ is the PEO quantity covering the surfaces; and Γ_m is the PEO quantity needed to maintain full coverage of coils on the surfaces (Lindström, T. et. al., 1984; De Witt, J.A. and van de Ven, T.G.M., 1992). The value of the complex size δ_x is a function of the entanglement coil size δ, which in turn is function of the PEO dissolution history and delivery (Abdallah, Mohammad. R., 2002; van de Ven, T.G.M., 1997). In other hand, although PEO alone doesn't adsorb on fines (Lindström, T. et. al., 1984), it

was found to adsorb on some classes of fibers such as Kraft pulp and makes flocculation by asymmetric bridging (Carignan. et.al., 1998; van de Ven, T.G.M. and Alince, B., 1996). In previous work (Abdallah Qasaimeh, M.R., 2011; Abdallah/Qasaimeh, M.R., et.al., 2011), we compared fines flocculation using PEO alone (asymmetric bridging) with fines flocculation using the CF-PEO complex (induced PEO bridging). The floc size (A), the flocculation rate r_f and flocculation efficiency (η) were found in case of induced PEO bridging several times larger than that in asymmetric bridging (Abdallah Qasaimeh, M.R., 2011; Abdallah/Qasaimeh, M.R. et.al., 2011). In asymmetric bridging of fines and in CF-PEO induced bridging and after flocculation equilibrium, the resulted flocs started deflocculation with the rate r_d, a phenomena indicating the transient behavior of flocculation by PEO (Abdallah, Mohammad. R., 2002; Carignan, A., et. al., 1998; van de Ven, T.G.M., 1994). Further flocculation mechanisms, rather than the induce and the asymmetric bridging using PEO with various CF types and using PEO alone were reported in literature; one was the flocculation of microcrystalline cellulose (MCC) using salt to induce bridging. Two CF types have two different mechanisms, one type was the clustering that clusters PEO in solution, while the second was the non-clustering. In MCC flocculation using PEO and tannic acid (TA) as a cofactor, the flocculation mechanism proceeded to cause TA-PEO association followed with PEO clustering, adsorption on MCC, and then bridging the MCC. When a non-clustering CF was used, an induction time was clearly observed, and a surface-induced clustering coupled to association-induced polymer bridging was proposed (Roger Gaudreault et. al., 2005).

In addition to the mentioned bridging mechanisms of CF-PEO, the flocculation kinetics applies to Langmuir isotherm (van de Ven,, 1994). In previous work, Langmuir models were derived for all possible particle interactions at the headbox in papermaking. The kinetics of fines-fines and fines-fibers flocculation at high shear rate near to mill values were found applying Smoluchowski isotherm and Langmuir equation (Smoluchowski, M. 1917); Abdallah, Mohammad. R., 2002). Referred to Smoluchowski and Langmuir, the flocculation rate r_f of the fines at consistency C_{fn}, the resultant of the attachment rate (r_{att}) and the detachment rate (r_{det}) is

$$r_f \ (= \frac{-dC_{fn}}{dt}) = r_{att} - r_{det} = -k_{att} \ C_{fn}^2 + k_{det} \ C_F \ ,$$ where, k_{att} and (k_{det}) are the attachment and detachment rate constants respectively, while (C_F) is the floc concentration (Abdallah, Mohammad. R., 2002). The rate r_f is maximum at initial flocculation and becomes zero when

flocculation reaches equilibrium. At initial time, flocs do not initiate and its number in a unit volume C_F is zero, resulting $r_{det} = 0$ and $r_f (= r_{att})$. Workers directed their work to rise r_{att} and lower r_{det} to get higher values of r_f. To study the rate of attachment, we referred to Smoluchowski isotherm, where the rate constant for a collision between two spherical particles of radii a_1 and a_2 subjected to a process shear rate (G_p) is $k_{sm} (= \frac{4}{3} G_p [a_1 + a_2]^3)$. When all particles are identical having radius (a), the process is homoflocculation and $k_{sm} = \frac{16}{3} G_p a^3$ (Abdallah, Mohammad. R., 2002; van de Ven, T.G.M. and Alince, B., 1996). In this case, the rate r_f resulted from successful collisions of fines in a unit volume becomes $r_f = r_{att} = -\eta k_{sm} C_{fn}^2$, where C_{fn} is the fines number in a unit volume (consistency) and (η) is flocculation efficiency. When a polymeric retention aid such as CF-PEO is used and $\delta_x > 2\kappa^{-1}$ is satisfied, the effect of the operating electrostatic forces will be eliminated and η becomes equal to capture efficiency (α) (Petlicki, J. and van de Ven, T.G.M., 1992). Here α is a function of polymer fractional coverage $\alpha = 2\theta(1-\theta)$ (Hogg, R., 1984). As number of factors in flocculation of fines using the CF-PEO retention system were studied in literature, the consistency C_{fn} of fines was one process factor taken constant in our previous works. The effect of the C_{fn} was remarked mainly in fines flocculation and its application to Langmuir equation and Smoluchowski isotherm (Abdallah, Mohammad. R., 2002; Abdallah Qasaimeh, M.R., 2011; Abdallah Qasaimeh, M.R., 2011; Abdallah/Qasaimeh, M.R. et.al., 2011). Since consistency C_{fn} has significant effects in collision frequency, these effects are expected to contribute to both flocculation rates r_f and deflocculation rate r_d and to their related parameters.

Based on the reviewed results in literature and in previous work, the objectives of this work were to investigate the effect of fines consistency on flocculation process and determine its characteristics. All factors, the former factors and the process factors, were fixed constant in this work while the consistency of fines C_{fn} was taken variable. The PEO quality that define the PEO entangled coil size was fixed for all runs. The PEO and CF additions and the concentration C of CF in fines suspension were fixed constants. The process shear rate G_p used in form of stirring rate (N) in (r.p.m) was taken constant. In experimentation, we took measurements of the initial

rate of flocculation $r_f = -\eta\, k_{sm}\, C_{fn}^2$, deflocculation rate r_d, floc size A, characteristic time of flocculation (τ) and characteristic time of deflocculation (τ_d).

EXPERIMENTATION

MATERIALS

The same materials used in previous works (Abdallah, Mohammad. R., 2002; Abdallah Qasaimeh, M.R., 2011; Abdallah/Qasaimeh, M.R. et.al., 2011; van de Ven, T.G.M. et al., 2004; Mohammad Raji Abdallah Qasaimeh,, 2022; Dr. Mohammad Raji Abdallah Qasaimeh, 2024) were used in this work. The pulp was a mixture of number of pulps from Maclaren Masson Mill with proportions as used in the mill. The mixture was disintegrated and then washed before use. The retention aids used were the Flocc 999 (the 7 million molecular weight neutral PEO) and the cofactor (Interac 1323, the negative phenol material) supplied by I.Q.U.I.P Inc, Canada.

The Transient Flocculation Experiment

The flocculation experiment performed in this work was the same experiment used in previous works (Abdallah, Mohammad. R., 2002; Abdallah Qasaimeh, M.R., 2011; van de Ven, T.G.M., et. al., 2004; Mohammad Raji Abdallah Qasaimeh, 2022; Dr. Mohammad Raji Abdallah Qasaimeh, 2024). In general, when the objective is to investigate a selected factor we fix the all other factors and perform the experimental runs at different values of the factor under study. In all runs, the fines were added at different consistencies C_{fn} to 500 ml distilled water and stirred at process shear rate G_p fixed at $N = 206$ (r.p.m). After the maintenance of the homogeneous suspension, the 0.25 mg CF/gm fines was added first, followed with 0.12 mg PEO/gm fines. The fines suspension was transported via the transparent tube at shear rate (G_t) exerted by a pump was fixed at constant volume in all runs to pass the photo cell of the Photometric Dispersion Analyzer (PDA) (Gregory, J., 1984; Rank Brothers Ltd.) and get the ratio reading (a measure of floc size) versus time. Number of runs were performed at different values of C_{fn} while the all other parameters were kept constants.

Measurement of the Flocculation-Deflocculation Intensities

After CF addition, no PDA output signal was recorded denoting that CF does not flocculate particles. After PEO addition the signal was recorded (Fig. 2) as a ratio reading (R) with time (t) showing flocculation as an increase in floc size with time as a curve drawn by the pen of the

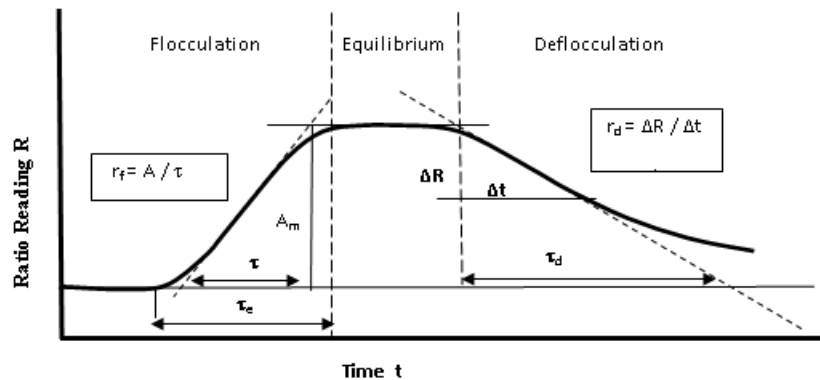recorder. At equilibrium, the vertical distance the pen moved on the curve is the maximum floc

Fig. 2: Flocculation and Deflocculation Intensity Readings.

size denoted by the amplitude A in arbitrary unit (A.U.). At initial flocculation (Fig. 2), we took the slope of the curve that denotes the initial rate of flocculation. The time needed to reach the size A at equilibrium is the characteristic time of flocculation (τ). The initial rate of flocculation was estimated using $r_f\ (= A/\tau)$ (Abdallah, Mohammad. R., 2002). After equilibrium time (τ_e), deflocculation started to appear as a decrease in floc size with time. The slope of the curve at initial deflocculation denotes the initial rate of deflocculation $r_d\ (= A/\tau_d)$, where (τ_d) is the time needed to reach the initial floc size, taken as the characteristic time of deflocculation (Abdallah Qasaimeh, M.R., 2011). All details are shown in figure 2.

RESULTS AND DISCUSSION

The main goal in flocculation is to produce the floc at the wanted specifications in mill. The unwanted flocs will be resulted when process factors are not controlled. In our previous works we studied number of affective factors in flocculation process using the CF-PEO retention aid. One (Abdallah, Mohammad. R., 2002) was the study of the former factors that affect the PEO entanglements and their effects on flocculation efficiency. We also studied the role of the effective shear rate and the affective CF-PEO dosages (Abdallah, Mohammad. R., 2002). In further works we studied the deflocculation phenomena (Abdallah Qasaimeh, M.R., 2011; Mohammad Raji Abdallah Qasaimeh, 2022; Dr. Mohammad Raji Abdallah Qasaimeh, 2024) and later the role of the CF concentration C (Mohammad Raji Abdallah Qasaimeh, 2022) and found the important affective parameters related to C (Dr. Mohammad Raji Abdallah Qasaimeh, 2024).

In this work our study was on the consistency of fines C_{fn}, where all the other parameters were kept constants, and the flocculation runs were performed in a beaker at different values of C_{fn}. In all runs, the used cofactor type and addition were the same. The PEO addition was the same and its quality has the same coil size δ. The fines used were extracted from the same pulps having radius a. The process shear rate G_p (N r.p.m), the tube shear rate G_t and the room temperature T were kept same and constants. For fixed parameters, the bond strength between CF-PEO complex and fines has the same value in all runs. Since the fines, CF, PEO, G_p and T were fixed constants and same in all runs, the value of k_{det} will also be constant and same
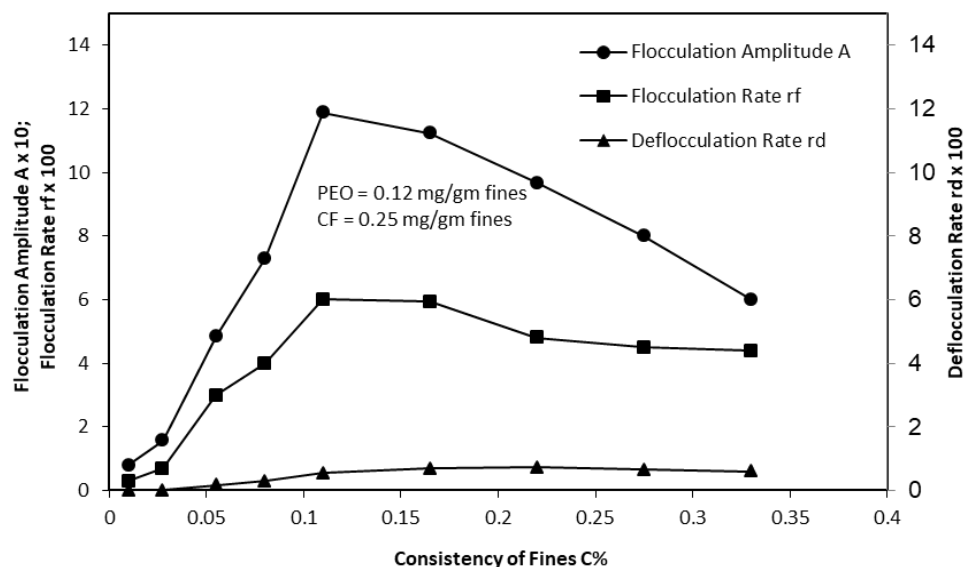

Fig. 3: The effect of the increase in fines consistency on the floc size, flocculation rate and deflocculation rate in flocculation of fines using the CF-PEO retention aid system.

(Varenners, S. and van de Ven, T.G.M., 1987). Experimental results (Fig.3) show the variation of the important parameters of the process versus the consistency C_{fn}. At low consistency, both floc size A and flocculation rate r_f have increased with the increase in C_{fn}, reaching maximum at around $C_{fn} = 0.11\%$. In this range $(0 < C_{fn} \leq 0.11\%)$, the floc size A and flocculation rate r_f have been enhanced with the increase in fines consistency C_{fn}. The maximum values of A and r_f continued in the period $(0.11\% < C_{fn} \leq 0.165\%)$. At higher values of $C_{fn}(>0.165\%)$, both the floc size A and the flocculation rate r_f started to decrease with the increase in consistency C_{fn}. No larger consistencies of fines $C_{fn}(>0.33\%)$ were used, since the PDA readings started to

overload resulting in significant errors in the results. In all runs, no flocs were present at initial time then no detachments occurred $(r_{\text{det}} = 0)$, thus $r_f = r_{att}$.

Deflocculation, the phenomena recorded after equilibrium in previous works (Abdallah Qasaimeh, M.R., 2011; Mohammad Raji Abdallah Qasaimeh, 2022; Dr. Mohammad Raji Abdallah Qasaimeh, 2024) is also recorded in this work in all runs. The rate of deflocculation r_d started to increase with the increase in the consistency C_{fn}, reached maximum at $C_{fn} = 0.11\%$, and then plateaued at higher values of C_{fn}. The consistency $C_{fn}(= 0.11\%)$ has been found the optimum value where the floc size A, the flocculation rate r_f and the deflocculation rate r_d are maximum. For more, low fines consistency was used in previous work to avoid the overloading of the PDA reading at high PEO dosages (Abdallah, Mohammad. R., 2002; Rank Brothers Ltd). In this work, the maximum consistency did not exceed the $C_{fn} (\leq 0.33\%)$ and no PDA overloading was recorded in all runs. For more, as deflocculation was recorded in this work, the kinetic dynamics have been studied to find out the flocculation rate constants (k_f), the deflocculation rate constant (k_d) and the reverse equilibrium constant (K_{-equi}). These parameters have been plotted (Fig. 4) and determined. Although the k_d has small values with the increase in C_{fn} and always smaller than k_f, the significant increase in the K_{-equi} with the increase in C_{fn}
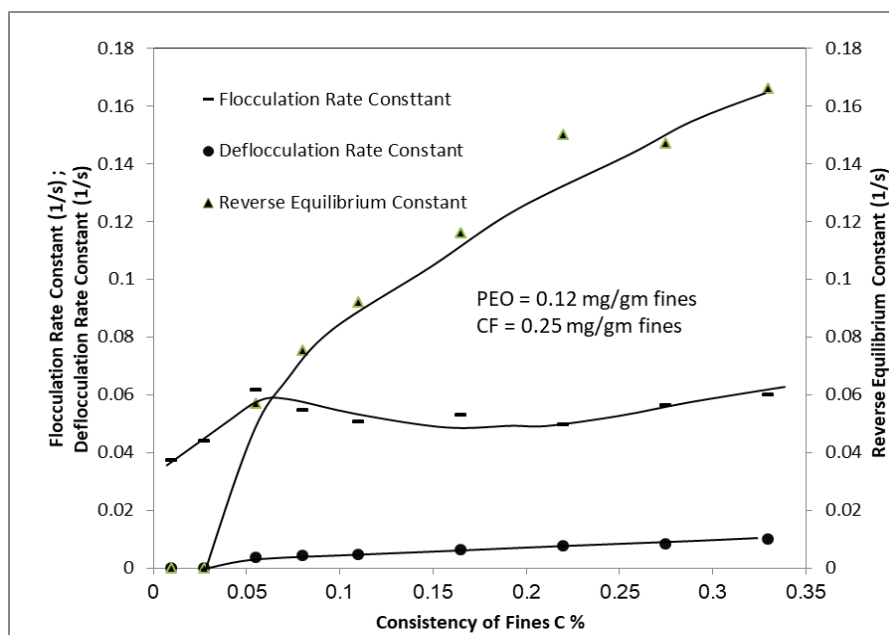

Fig. 4: The variations of flocculate rate constant, deflocculate rate constant and reverse equilibrium rate constant with the increase in fines consistency.

(Fig. 4) shows how much the deflocculation was enhanced with the increase in C_{fn}. These increases in k_f, k_d and K_{-equi} with the increase in C_{fn} can be ascribed to changes in some parameters in fines flocculation. One important parameter is the increase in collision frequency with the increase in C_{fn}. The second parameter is the change in the suspension viscosity μ, referred to the number of researchers in literature who reported the increase in the suspension viscosity with the increase in the suspension concentration. Einstein worked on Newtonian fluids containing neutrally buoyant of non-interacting spheres to investigate their effects on fluids viscosity and derived a relationship (Martin et. al., 2017). The presence of the equal size spheres in suspension was found to increase the viscosity relative to that of pure liquid (μ_o) to give $\mu = \mu_o (1 + B_o \phi)$ (Mueller et. al., 2010). where (ϕ) is the volume fraction of the spheres and (B_o) is a constant. According to Einstein the $B_o = 2.5$ and assigned in between 1.5 and 5 by others (Mueller et. al., 2010). Since fines are heterogeneous non-spheres and most often small rods, some corrections will modify the B_o value and the Einstein derived relationship can be more modified for fines. The object of this work is not the B_o value that can be larger or less, but is the increase in the viscosity with the increase in the fines consistency. This behavior can also be related to Power law model $(\mu = K \ G^{n-1})$, which shows the directly proportional of μ with the consistency index (K), but the inversely proportional with shear rate G, where (n) is the flow behavior index (Ghazaleh Ghanaatpishehsanaei, 2023). In this work, the shear rate G was kept constant and the main affective factor on viscosity was the consistency C_{fn}. Now based on the viscosity increase with the consistency, the resulted varying rate constants k_f, k_d and K_{-equi} (Fig.4) can be attributed to the viscosity increase of the fines suspension with the increase in C_{fn}. All the rate constants (Fig.4) have shown significant increases at low consistency values up to $C_{fn} (\leq 0.05\%)$. With the increase in C_{fn}, both collision frequency (ω) and viscosity μ will increase and show contrary effects. The ω will enhance the all rate constants, while the μ in the form of viscous forces will counteract the attachment causing k_f to decrease and k_d and K_{-equi} to increase. Viscosity and collision (the consistency effects) show clearly the effects (Fig. 4) at $C_{fn} (>0.05\%)$, the k_f plateaus and then slightly decreases; the k_d increases; but K_{-equi} increases significantly. In other words, enhancement in deflocculation or increments in k_d and in K_{-equi}:

Table 1: The mathematical model showing the values of the attachment rate constants that fit Longmuir equation and Smoluchowski isotherm in each zone with experimental results.

	Fitting of Smoluchowski isotherm and Longmuir equation $r_f = k_{att} \, C_{fn}^2 \quad (A.U./s)$		
Zone	Consistency C_{fn} (%) $\dfrac{gm\ fines}{100\ ml\ Water}$	Consistency square C_{fn}^2 $(\dfrac{gm\ fines}{100\ ml\ Water})^2$	The k_{att} $\dfrac{A.U\ /\ s}{(\dfrac{gm\ fines}{100\ ml\ Water})^2}$
1	$0.01 < C_{fn} \leq 0.0548$	$0.0001 < C_{fn}^2 \leq 0.003003$	994
2	$0.0548 < C_{fn} \leq 0.11$	$0.003003 < C_{fn}^2 \leq 0.0121$	331.43
3	$0.11 < C_{fn} \leq 0.22$	$0.0121 < C_{fn}^2 \leq 0.0484$	-33.06
4	$0.22 < C_{fn} \leq 0.330153$	$0.0484 < C_{fn}^2 \leq 0.109001$	-6.84818

with the increase in C_{fn} can be attributed to the increase in the ω among the fines and to the increase in μ of the suspension since they both increase with the increase in C_{fn}. In other words, the increase in μ mainly at $C_{fn} \, (\geq 0.05\%)$, or the increase in the counter viscous forces, works to dissipates the power of mixing that enhances the attachments of the fines in the suspension.
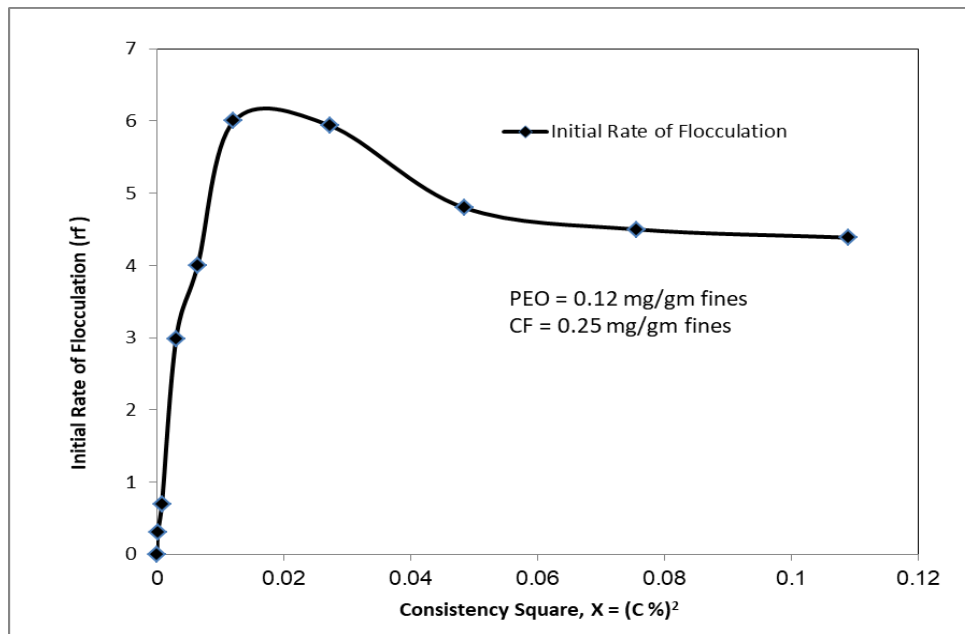

Fig. 5: The relation of initial rate of flocculation with the square of the fines consistency.

In verification of the flocculation runs with Longmuir and Smoluchowski isotherm $(r_f = k_{att} \, C_{fn}^2)$, we have plotted the experimental values of the initial rate of flocculation r_f versus the C_{fn}^2 and found the values of k_{att} (the slope of the curves) and how change. With the

increase in C_{fn}^2, results (Fig. 5) show that the r_f increases drastically, then significantly reaching maximum, and then started to decrease. To analyze these results, we subdivided the consistency scale into four zones: $0.01 < C_{fn} \le 0.0548$; $0.0548 < C_{fn} \le 0.11$; $0.11 < C_{fn} \le 0.22$; $0.22 < C_{fn} \le 0.330153$ and tabulated them as shown in Table 1 (Column 2). The square of the consistencies C_{fn}^2 are tabulated in Column 3. The attachment rate constants k_{att} are estimated from the linear slope of each curve zone (Fig. 5) and tabulated in Column 4.

Results of the analysis of the r_f variation versus C_{fn}^2 show a drastic linear increase having $k_{att} = 994$ within the zone $(0.01 < C_{fn} \le 0.0548)$, followed with a second high increase having $k_{att} = 331.43$ within the zone $(0.0548 < C_{fn} \le 0.11)$. This increase in r_f can be attributed to the increase in the collision frequency ω resulted from the increase in C_{fn}; here the square of C_{fn} indicates the binary attachments. In contrary, these collision attachment forces are countered with the viscous forces, which are low at low values of C_{fn}, but increase with the increase in C_{fn}. When r_f reached maximum $(r_f \approx 6)$ within $(0.0121 \le C_{fn}^2 \le 0.0272)$, the collision forces balance with the viscous forces, making r_f to plateau. With more increase in consistency $C_{fn} > 0.0272$, the counter viscous forces become dominant and overcome the collision forces, showing negative slopes (negative k_{att}), thus causing a decrease in flocculation rate r_f. The resulted values of k_{att}.
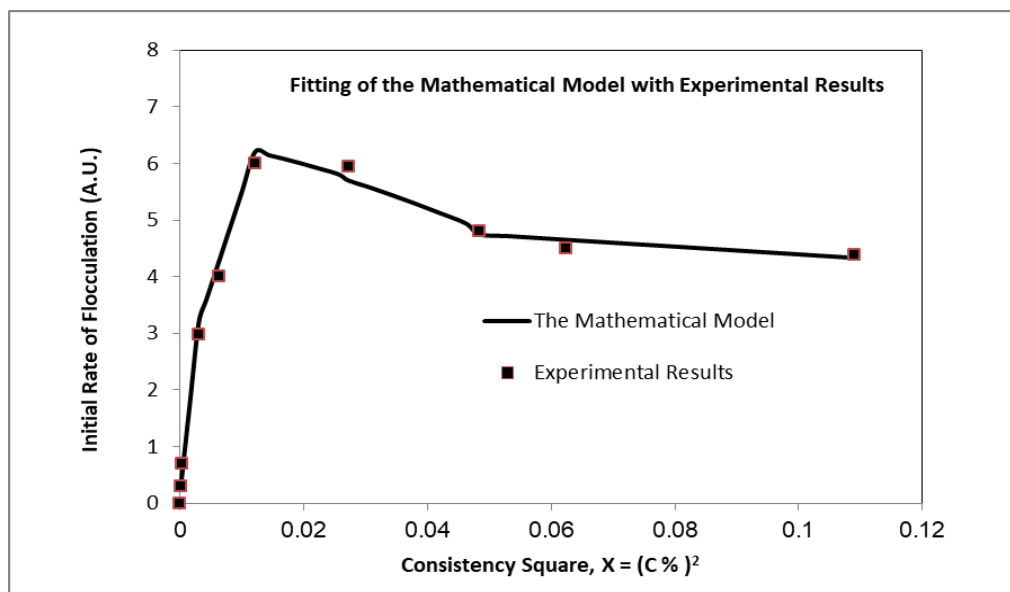

Fig. 6: Fitting of the mathematical model of initial rate of flocculation of the fines that satisfies Longmuir equation and Smoluchowski with the experimental results.

in the four zones (Table 1) represent the mathematical model supposed to fit Longmuir equation and Smoluchowski isotherm using $r_f = k_{att} \, C_{fn}^2$. The values of r_f using the model for each zone, and the experimental values of r_f are plotted (Fig. 6) versus the square consistency $X(= C_{fn}^2)$. Results show that the values of r_f using the model have fit the values of the experimental results with acceptable deviations in the average range of $(\pm 5\%)$.

CONCLUSION AND RECOMMENDATIONS

We have investigated the effects of the fines consistency on fines flocculation. The rate constants of flocculation, the deflocculation and the reverse equilibrium constants were determined at different consistencies and plotted showing the consistency effect. The flocculation of fines was verified and found applying to Longmuir equation and Smoluschowski isotherm, giving different values of the attachment rate constant at different consistency zones. These results are useful to be a guide to mills to choose the suitable consistency with its parameters and avoid the loss of power and cost due to the high viscous forces at high consistencies that oppose attachments.

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