WATER TREATMENT PLANT OPTIMIZATION BY CONTROLLING THE SUSPENDED SOLIDS PHYSICOCHEMICAL ENVIRONMENT

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ABSTRACT

Optimizing water treatment plant operation is a concept should be applied to all plants because some operational improvements can always be made. Optimization at a water treatment plant can be considered achieved when certain goals are being met to attain the most efficient use of the water treatment plant facilities. The most important goals are to reduce the water wastes, manage the energy consumption and achieve the chemical cost performance that means the chemical cost for obtaining an aimed treatment effect. Understanding and control of the physicochemical nature of water and colloidal suspensions play an important rule to obtain several goals for optimization. One of these optimization goals for the plant operation is the colloids removal improvement with economic coagulant dosing. This could be achieved by studying all parameters affecting particle-to-particle interaction. Taking these parameters into consideration can help to optimize the coagulant dosing required to remove the repulsive forces between particles allowing them to effectively form large flocs that settle fast and filter easily. On contrary of this, the opposite goal is to maximize the repulsive forces between the colloids in order to keep each particle discrete and prevent them from gathering into larger, causing faster settling agglomerates. This is mainly during sludge disposal to makeup a major fraction of carrier water and energy consumption.

The aim of study is experimentally demonstrate how the control of the physicochemical environment of the colloidal suspension can contribute the global optimization for the water treatment plant operation.

Keywords: water treatment, flocculation, stabilization, optimization

INTRODUCTION

Water treatment plant optimization is a continuous process to meet current and future regulations and provide water of superior quality. Water treatment plants deal with colloidal suspensions that can be as dense as sludge or as dilute as the turbidity particles in the raw surface water. Improved understanding the physicochemical environment of the colloidal suspension and control particle-to-particle interaction can help to optimize the water treatment plant operation in many different stages. Optimization can lead to the delivery of a higher quality product at a lower cost.

The characteristics of a suspension can be tailored according to which of attractive or repulsive force is aimed to prevail. One case we may want to maximize the repulsive forces between them in order to keep each particle discrete. Sludge hydrotransport via pipelines requires this particles disintegration to prevent the problems of settling and blockage. Another case, we have the opposite goal and want to separate the colloid from the liquid as a part of water treatment processes. Removing the repulsive forces allows them to form large flocs that settle fast and can be filtered easily.

Particle-to-Particle Interaction

Particle-to-particle interaction is a crucial element in determining the characteristics of colloidal suspensions. Most particles in water, mineral and organic, have electrically charged surfaces, and the sign of the charge is usually negative, [1]. If their surface charge is relatively high, then adjacent colloids will repel each other and will tend to maintain their individuality. The force of gravity is insignificant on such small colloids. As a result, highly charged colloids tend to remain discrete and in suspension. On the other hand, a colloid with little or no charge has little resistance to the natural tendency for fine particles to gather together into aggregates. Small clumps will form and, in turn, aggregate into larger flocs which settle quickly or form an interconnected matrix. This changes the physical characteristics of the suspension. Particle charge can be controlled by modifying the environment around the colloids. This can be done by varying the pH or the ionic species in solution. Another, more direct technique is to add flocculants or dispersants to the suspension. These are surface active agents which adsorb directly to the colloid and change its surface characteristics, including charge. Direct measurement of surface charge is not easy and the so called zeta potential is used instead. Zeta potential is the electrical voltage difference between the surface of each colloid and its suspending liquid. The potential is caused by the surface charge, so it is a fairly direct measure of the suspension characteristics.

Optimizing the Colloids Removal

Coagulation, flocculation and sedimentation are the successive processes for colloids removal. Coagulation is the destabilization of colloidal particles brought about by the addition of a chemical reagent known as a coagulant. Flocculation is the agglomeration of destabilized particles into microfloc, and later into bulky floccules which can be settled called floc. There are three important considerations for optimum coagulation to occur: pH of the processing water, duration of coagulation dispersion, and that no other chemical which directly react with coagulant be fed at the flash mixer, [2]. When feeding coagulant, the pH of the raw water is obviously important because the coagulation process requires an adequate amount of trivalent or even high ionic species in order to effectively reduce the electrical charge of the colloidal particles. The lower the pH, the better is the production of these species, [3].

When using alum sulfate as a coagulant, there is a strong relation between pH and performance, but there is no single optimum pH for specific water. Rather, there is an interrelation between pH and the type of aluminum hydroxide formed. This in turn determines the charge on the hydrous oxide complex. Another important aspect of pH is its effect on solubility of the aluminum (Al+3) ion, [4].

Optimum flocculation is mainly achieved under the conditions of proper coagulation, optimum pH range, proper level of mixing intensity and adequate net mixing time, [2].

Optimizing the sludge Hydrotransportation

The term sludge can be taken as describing any suspension of solid material in a liquid. In the context of water treatment processes the liquid phase of the sludge is aqueous whilst the solid phase will consist of any materials derived from the raw water together with the residues of any chemicals added in the treatment process.

Sludge is often difficult to dispose and its removal is almost always a significant item in operating costs. From the economic standpoint, the real aim is to limit the cost of sludge treatment and transport. Optimizing this procedure depends on the means of sludge disposal, energy requirements and costs, labor costs, conditioning reagent cost, etc. On the other hand, the protection of workers' health and of the environment calls for methods which will cause the least nuisance and still be economically feasible. The most economical and safe means for sludge disposal is transport it as a dense suspensions through pipelines.

Sludge suspensions are non-Newtonian fluids, so the value found for viscosity is quite relative and depends on the shearing stress applied, [5]. The yielded pseudo-homogeneous (Herschel-Bulkley) model is a combination between the power law and Bingham models and is often approximates behavior of wide range non-Newtonian fluids which takes the form:

$$\tau = \tau_Y + k\left(\frac{du}{dy}\right)^n = \tau_Y + k\gamma^n \tag{1}$$

where τ_Y is the yield stress, n is the flow behavior index, and k is the fluid consistency index.

Frictional pressure losses in the sludge piping system determine the required pumping power that affect the size of the capital items such as pumps, motors, gearboxes and other facilities. So there is an incentive to minimize the frictional pressure losses. The techniques for reducing the frictional pressure losses in homogeneous suspension pipe flow could be by either directly altering its rheological properties or changing the suspension physicochemical environment. Altering the rheological parameters could be made by using drag reducing additives like polymer, surfactant and fibre additives. Chung et al [6] experimentally showed that dilute polymer solutions can significantly reduce pressure gradients of not only water but also water-particles mixture flows in the higher Reynolds-number range; drag reduction is as much as 80%. However, in the lower Reynolds-number range, pressure drops and friction factors for both water and water-particles mixtures are greater with polymer than without. Chara et al. [7, 8] showed that the surfactant agents lose their drag reduction ability when being subject to high shear stress, but quickly regain their effectiveness when they are flowing in a region of lower shear.

On the other hand changing physical-chemical environment of a suspension makes possible to optimize energy and water requirements. The preparation of dense sludge involves the attainment of a high degree of particle stabilization and appropriate rheological properties, which could result in pressure loss reduction when flowing in pipes. El-Nahhas [9] and El-Nahhas et al. [10, 11] confirm the possibility of substantial reduction of the yield stress and viscosity of highly concentrated fine-grained kaolin slurries by a modification of their physical-chemical behavior.

The Aim of Study

The aim of study is experimentally demonstrate how the control of the physicochemical environment of the colloidal suspension can contribute the global optimization for the water treatment plant operation. The raw water turbidity removal was investigated under conditions that the colloids destabilization and flocculation is aided. These conditions were obtained by raw water acidification (to change its pH value) and by adding a powdered activated carbon dose.

On the other hand, a study about the possibility of pressure loss reduction of the dense kaolin suspensions (as sludge modeling) by changing their physical/chemical characteristics has been obtained. The physical/chemical characteristics were changed by the addition of a stabilizing agent with different amounts. The study demonstrates an ability to obtain higher concentration suspensions with a significant decrease in apparent viscosity, yield stress and pressure losses.

EXPERIMENTAL SETUP

For the study of colloids removal optimization, a bench-scale laboratory testing was carried out conducting with the standard jar test procedure that usually used in water treatment applications. For sludge hydraulic transportation study, sets of experiments were conducted by a pipeline test loop and rheological tests were obtained by a rate-controlled rotational viscometer for kaolin suspensions.

Bench-Scale Testing

Standard laboratory jar test procedure, usually used in water treatment applications, was carried out for evaluating coagulation and flocculation processes at the different cases. In this procedure, a suspension is dosed with different amounts of coagulant under standard mixing and sedimentation conditions. Usually there is a brief rapid mix period immediately after dosing. This is followed by a longer period of slow stirring during which flocs may be formed as a result of aggregation. These flocs are then allowed to settle for a standard period, after which a sample of the supernatant water is taken and its turbidity is measured. This residual turbidity gives a good indication of the degree of removal during sedimentation and hence of the effectiveness of the coagulation/flocculation process. For details of the test procedure reference could be made to Letterman [1].

The rate-controlled rotational viscometer "Haake RV-20" was used to measure the rheological characteristics of the suspensions of the different considered concentrations. It is consist of a cylinder rotating in a static measuring cup filled with the suspension sample. The rotor is driven at fixed or programmable speeds by a DC motor utilizing a feedback loop for very accurate speed control. The resistance of the sample to flow causes a very small movement in a torsion bar, mounted between the motor and driven shaft. This movement or deflection is detected by an electronic transducer. Signals proportional to the speed and torque are transmitted to the control unit and computer for processing and display.

Pipeline Loop Testing

An open-loop recirculation pipeline system was employed for studying the effect of physicochemical environment on the suspensions flow behaviour. Suspension was forced by a screw pump driven by an electric motor with a speed regulator from an open storage tank to delivery pipe. The flow rate could be changed stepwise by changing the rotor rotation speed. The upward branch of the piping loop is surrounded by a shell in which cooling water flows in a counter-flow direction to keep the slurry of different experiments in a narrow range of temperatures. The test section was located on the back branch of the pipeline and its length to diameter ratio exceeded 400. The storage tank was equipped with an agitator to prevent the slurry from settling. A stainless steel pipe of internal diameter, D = 17.5 mm was used for measurements. The pipe was equipped with three pressure tappings connected through solids pods to differential Hottingger-Baldvin pressure transducers and the readings were monitored by a computer. At the downstream end of the test pipes a box divider was mounted that allows diversion of the discharge to a plastic container for weigh testing. Since the divider arm was connected to an electric stopwatch, the mass flow rate was precisely measured. If the plastic container was replaced by a glass calibrated cylinder, the slurry density and hence the volumetric concentration could also be determined. This arrangement allowed checking of the concentration during each experimental run. Calibration experiments with clear water, which was periodically run, showed that the pipe used in the test section behaved as a smooth pipe.

Kaolin slurry is often used as model slurry for investigation of the yield pseudoplastic suspension, and hence sludge. So, for pipe loop tests, suspensions with different concentrations were prepared by the kaolin powder from Horni Briza (Czech Republic) The kaolin mean diameter is d_{50} = 2.8 μm and its density is ρ_s = 2549 kg/m^3. The suspension physicochemical environment was controlled by adding different ratios of sodium carbonate (Na_2Co_3).

RESULTS AND DISCUSSIONS

Sludge Hydrotransport Optimization

As discussed previously, sludge suspensions are non-Newtonian fluids and it could be described successfully by the Herschel-Bulkley model. Kaolin hydro-mixture is one of appropriate slurries for significant change of flow behaviour and rheological parameters due to the change of physical-chemical environment as it was shown e.g. by Vlasak et al. [12]. Therefore, kaolin slurry is often used as model slurry for investigation of the yield pseudoplastic suspension, and hence sludge.

Figure (1) shows the effect of adding sodium carbonate, as a deflocculating agent, with dosing of C_a = 0.05% and 0.15% on the rheological behavior of the highest concentration suspension (C_v = 22.6%). The rheological behavior is expressed by the shear stress/shear rate plots that are determined directly by the rotational viscometer Haake.

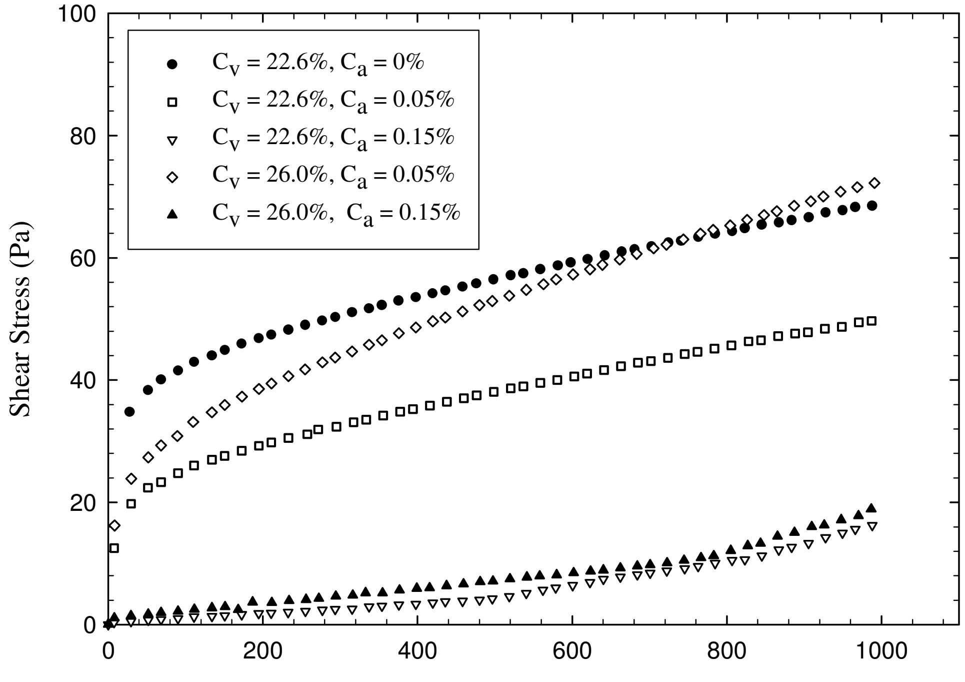

Figure 1 Rheograms of natural and deflocculated suspensions

The natural suspension (C_v = 22.6%, C_a = 0.0%) behaves as yielded pseudo-plastic fluid. when deflocculating it with a dose (C_a = 0.05%) it maintains the same behavior but with about 50% reduction in the yield stress.

When increasing the deflocculant dose up to C_a = 0.15% the suspension has a different behavior. It has semi-linear shear rate/shear stress relation with very small yield stress value, i.e. it can be approximated as a Newtonian fluid.

Due to the deflocculating agent activity the attraction forces in the suspension decrease, the repulsion forces prevail and the aggregates of solid particles are destroyed, the suspension becomes more liquefied and therefore it is possible to mix more solids to the suspension to concentrate it. Figure (1) also presents the rheological behavior of the deflocculated suspension with higher volumetric concentration of C_v = 26% that could not be reached naturally. The suspension (C_v = 26%, C_a = 0.05%) behaves as yielded pseudoplastic fluid. Increasing C_a up to 0.15%, the slurry has a semi-linear rheogram with very small yield stress, so it could be approximated as a Newtonian fluid.

Viscosity is another property that can be adjusted by varying the balance between repulsion and attraction. Figure (2) shows how deflocculating the slurry can affect the apparent viscosity of the studied suspensions. It could be noted that viscosity is considered a measurement of the intensity of the interparticulate forces. It also permits evaluation of the thixotropic nature of sludge. This property is very useful for assessing the possibility of collecting, transporting and pumping sludge.

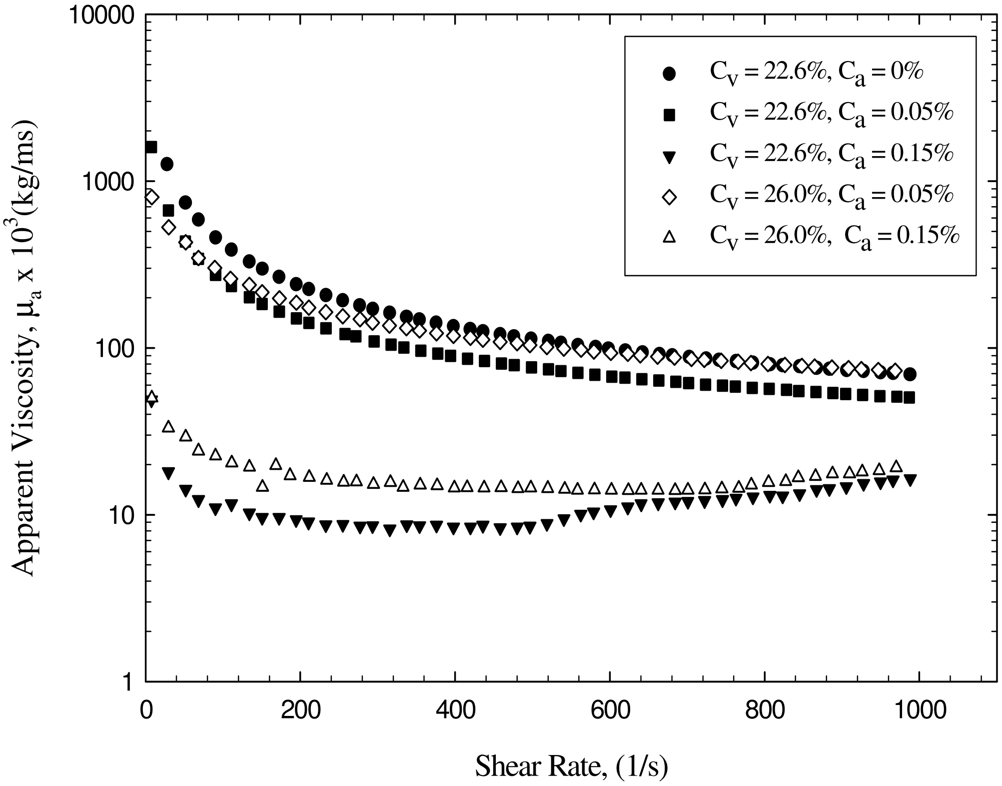

Figure 2 Apparent viscosity of natural and deflocculated suspensions

An area in which suspensions require a more careful treatment than single-phase fluids is that of the friction losses or transportation energy consumption. The suspensions discussed above were tested also by the experimental pipeline loop to prove the effect of suspension deflocculation on the friction losses and pipe flow behavior. The friction loss associated with the flow of suspension in a pipe is clearly represented in the form of the hydraulic gradient. The development of hydraulic gradient, *i* with increasing the mean velocity *V*, which represents a characteristic resistance curve, has been obtained and presented in Figure (3).

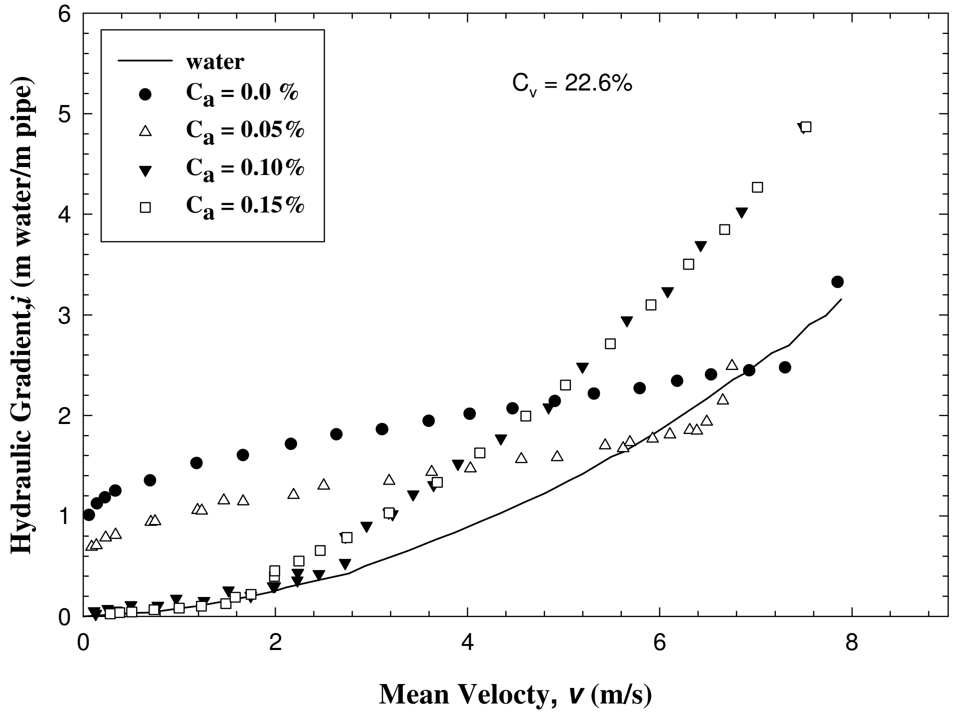

Figure 3 Resistance curves for natural and deflocculated suspensions

It could be noticed that deflocculating the suspension of volumetric concentration C_v = 22.6% with a dose C_a = 0.05% has reduced the hydraulic gradient in laminar flow region (about 30% reduction). A decrease of laminar/turbulent transition velocity value could be observed. The benefit from deflocculation process vanishes in the turbulent flow region for velocities higher than 5 m/s. For suspension of C_v = 26%, increasing the dose of the deflocculating agent from C_a = 0.05% to C_a = 0.15% causes a great reduction in the hydraulic gradient at the laminar region and the transient velocity. Benefit vanishes for mean velocities higher than about 4.4 m/s.

The above analyses confirm that deflocculating the suspensions can help to reach much higher concentration of solids and lower energy consumption for pipeline transport. It was demonstrated that presence of the deflocculant results in the significant decrease of the apparent viscosity and mainly of the yield stress that may be vanished. Efficiency of the process depends on solids concentration, deflocculant dose, and acting shear stress or flow velocity ranges.

When studying the suspension energy dissipation in a piping system, the specific energy consumption, *SEC*, could be a very useful parameter. It determines the energy required to transport a given quantity of solids over a given distance in a pipeline and it is given as:

$$SEC = 0.2778\frac{i\,g}{S_s C_v} \tag{2}$$

where *SEC* is in units of [kw.hr/tonne.km. The *SEC* has been plotted against solids throughput (the amount of dry solids delivered at the pipeline outlet over a time period) and shown in Figure (4).

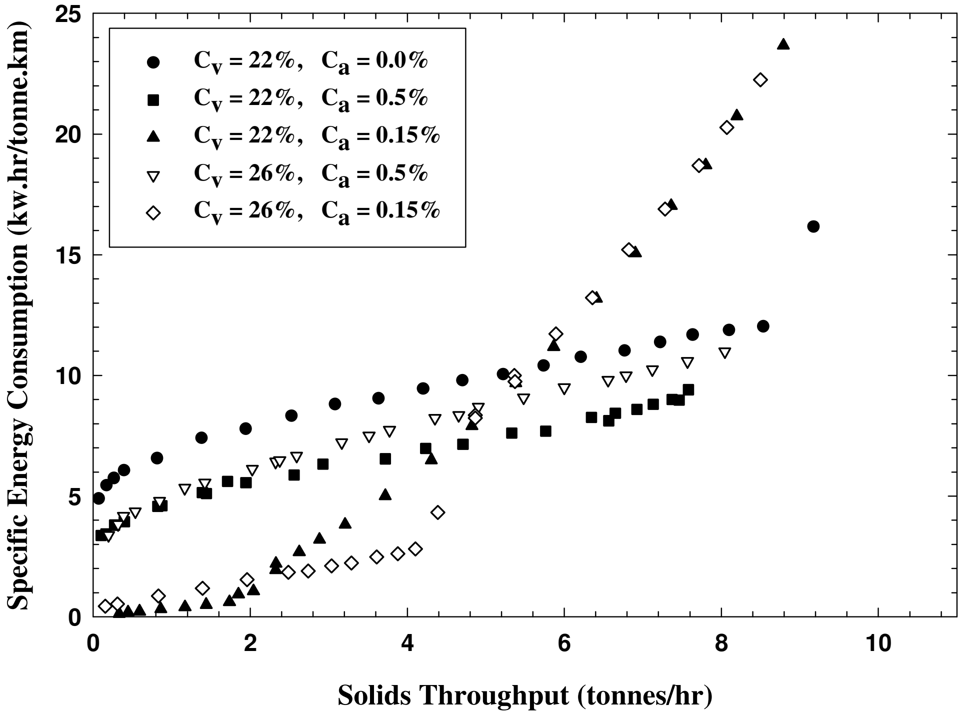

Figure 4 Specific energy consumption for natural and deflocculated suspensions

Colloids Removal Optimization

As shown previously, among the optimization requirements for colloids removal, it should take into consideration any other chemicals (rather than the coagulant) that could be added in the different stages of the processes. For instance, pre-chlorination that has acidic effect reduces the pH value of the raw water. To demonstrate the effect of pH value on the effectiveness of the coagulation and the flocculation, and hence the colloids removal, the raw water is acidified by adding a dose of concentrated sulfuric acid. This reduced the pH value from 7.8 to 6.8. Both natural and acidified raw water were tested conducting the jar test procedures. Figure (5) presents the effect of raw water pH value on the turbidity removal for different coagulant, which is alum sulfate, dose. It could be noticed that lowering pH value from 7.8 to 6.8 enhanced the colloids removal. This confirms the strong relation between pH and removal performance. Because there is no single optimum pH for specific water, periodic jar tests should be conducted to conclude the optimum processes performance.

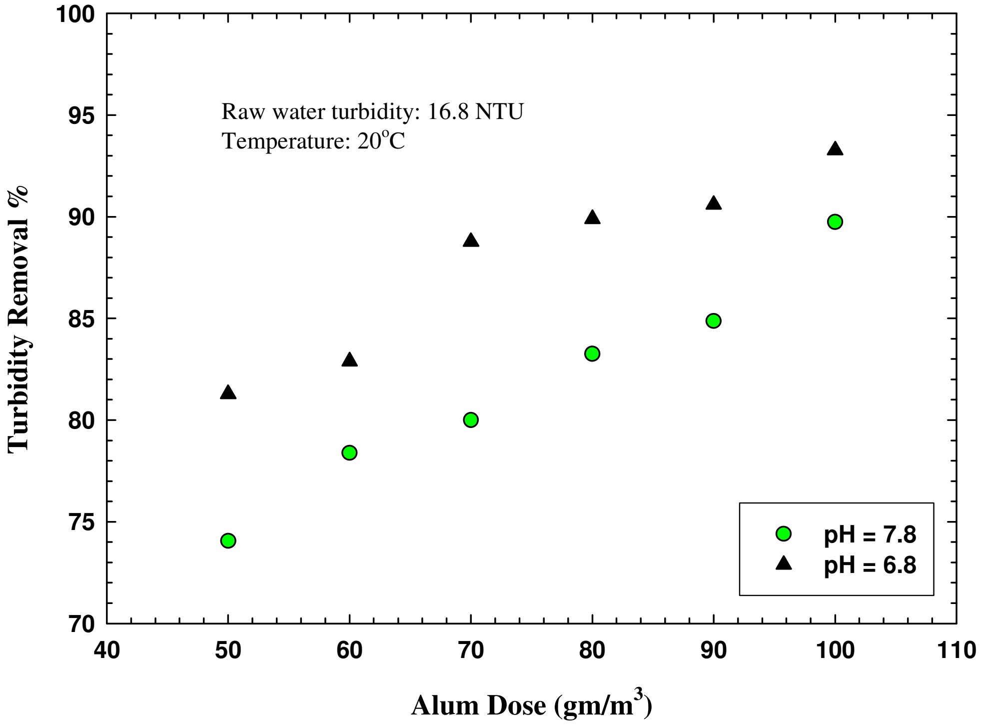

Figure 5 Effect of raw water pH value on the turbidity removal

Another chemical that could be added with or just before the coagulant addition is the powdered activated carbon, PAC. Activated carbon is a porous carbon structure having capability to adsorb dissolved organic matters many of which cause taste and odor in water. Figure (6) shows the effect of adding the powdered activated carbon, with 10 gm/m^3 dose, on the colloids removal at different alum doses.

The presence of powdered activated carbon among the colloidal particles improves the turbidity removal. The carbon particles are surrounded by an electric double layer due to electrostatic interactions. The ionic strength could be increased and the double layer thickness be compressed and therefore the flocculation enhancement be obtained.

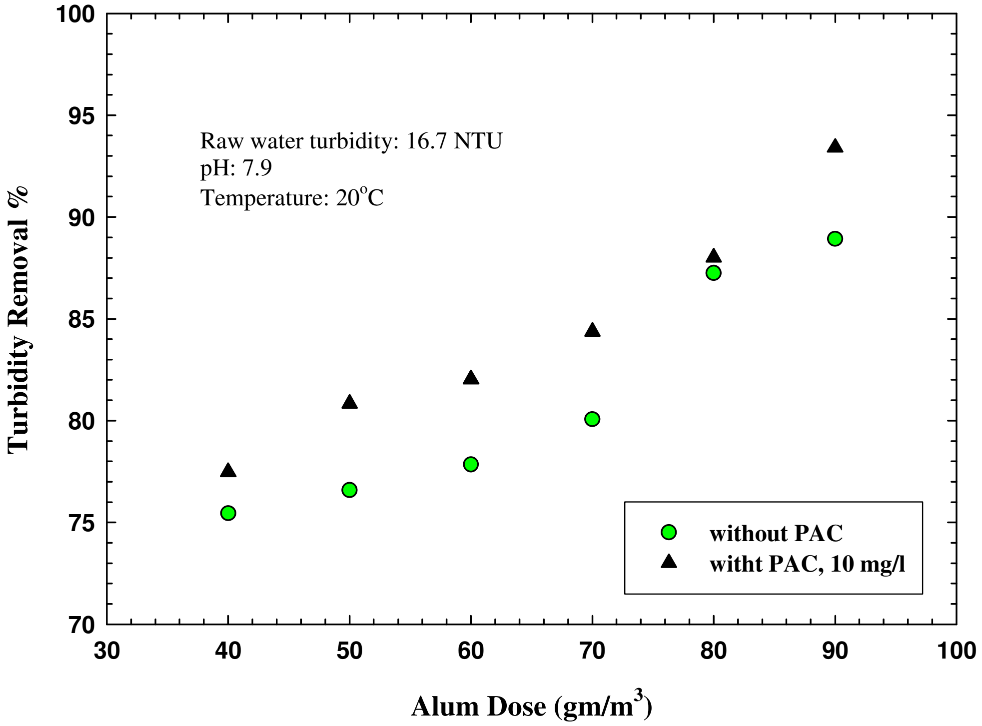

Figure 6 Effect of PAC presence on the turbidity removal

CONCLUSIONS

Global optimization for the water treatment plant operation can be obtained by understanding and control of physicochemical environment of the colloidal suspension. The characteristics of a suspension can be tailored by understanding the particle-to-particle interactions. The attractive forces should prevail for colloids removal to form large flocs, while it should be minimized keeping each particle discrete during sludge hydrotransport.

As increasing the solids concentration of non-Newtonian suspensions (as during sludge removal), flocculation of the colloidal particles results in increasing the yield stress, apparent viscosity and frictional losses. Addition a deflocculating agent to dense suspensions strongly depressed non-Newtonian behavior, resulting in decreasing the apparent viscosity, yield stress and frictional losses and hence energy consumption. It enabled also to reach much higher concentration of solids and saving waste water for hydrotransport.

Because the raw water pH value is a very important factor for adjusting the suspension physicochemical environment and colloids removal, it should take into consideration any additive effect that can alter this value either positively or negatively. This can led to obtain optimum turbidity removal and/or economic coagulant dose. The presence of powdered activated carbon among the colloidal particles also affects the suspension physicochemical environment. It enhances the flocculation performance and turbidity removal.

NOMENCLATURE

		Units
C_a	deflocculant/solids mass ratio	[-]
C_V	volumetric concentration	[-]
D	pipe internal diameter	[m]
d_{50}	diameter of which 50% (by mass) of the particles are finer	[m]
g	gravitational acceleration	[m/s^2]
i	hydraulic gradient	[m water/m pipe]
k	consistency index	[kgm^{-1}s^{n-2}]
n	flow behavior index	[-]
SEC	specific energy consumption	[kw.hr/tonne.km]
S_s	solids specific gravity	[-]
u	local fluid velocity in the pipe-axis direction	[m/s]
V	mean velocity	[m/s]
y	vertical distance in a pipeline cross-section	[m]
γ	shear rate	[1/s]
μ_a	apparent viscosity	[kg/ms]
ρ	density	[kg/m^3]
ρ_s	solid density	[kg/m^3]
τ	shear stress	[kg/ms^2]
τ_Y	yield stress	[kg/ms^2]

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