INFLUENCE OF THE PHYSICAL-CHEMICAL FACTORS ON THE RESIDUALS MANAGEMENT FOR DRINKING WATER TREATMENT PLANTS

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ABSTRACT

A drinking water treatment plant produces large quantities of residuals as a result of treatment processes such as clarification, filtration and powdered activated carbon adsorption. Generated residuals mainly include suspended solids removed from raw water, chemical precipitates created by the treatment process and carrier water. Recently, more stringent regulatory changes have caused dramatic changes in the handling of residuals from water treatment plants. Limitations have been placed on the ability of drinking water treatment plants to discharge residuals to sanitary sewers or natural waterways. So, the impact of regulations has placed a greater careful consideration on the on-site treatment of these residuals.
The treatment, transportation and disposal of the sludge make up a major fraction of the total water treatment costs. The purpose of sludge treatment is to receive and concentrate these residuals and dispose of them. Residuals in liquid form may be pumped through pipelines or transported by tanker trucks. Alternatively, residuals in cake form may be trucked to a loading facility or final disposal location. However, as a comparison, the residuals disposal in the form of dense slurry by hydraulic transport through pipeline presents several beneficial advantages. It is environmental impact-free, demands substantially less space, makes possible full automation and needs a minimum of operating staff.
The optimized management of a sludge hydraulic transport system aims to the ability to obtain much higher solids concentration with minimized power consumption. One possibility to achieve these aims is based on change the physical-chemical environment of the slurries in a manner to produce sufficient level of the repulsive forces between the particles and depress the non-Newtonian behaviour resulted by high solids concentrations.

The aim of study is to present experimental investigation of the ability to obtain much higher solids concentration with minimized power consumption for the hydraulic transport system of dense suspensions by change the physical-chemical environment. The study will demonstrate the possibility to obtain optimized management of the residuals disposal for drinking water treatment plants by this concept.

Key Words: water treatment, residuals, sludge, optimization

1. INTRODUCTION

In conventional water treatment systems, coagulation, flocculation and sedimentation, followed by rapid gravity sand filtration are well-proven technology for the significant removal of colour and particulate matter including protozoa, viruses, bacteria, and other micro-organisms. Dissolved organic matters, many of which cause taste and odour in water, could also be removed by addition of powdered activated carbon, PAC, that have a porous structure and capability to adsorption.

As a result of these treatment processes large quantities of residuals are produced at the drinking water treatment plants. Generated residuals mainly include suspended solids removed from raw water, chemical precipitates created by the treatment process, powdered activated carbon, and carrier water.

Regulatory changes have caused dramatic changes in the handling of residuals from water treatment plants since the early 1970s. The Clean Water Act placed limitations on the ability of drinking water treatment plants to discharge residuals to sanitary sewers or natural waterways. This placed a greater emphasis on the on-site handling of process wastes, [1]. From economic and environmental standpoints, the residuals produced by different treatment processes can have significantly different treatment costs and disposal or reuse options for safe handling, [2]. The treatment, transportation and disposal of the sludge make up a major fraction of the total water treatment costs, [3].

Most water plant sludges can be further thickened in a gravity concentration tank because some dewatering systems will perform more efficiently with higher solids concentrations, [2]. Also, hydraulic transport of fine grained suspensions in pipes economically prefers dense slurries. Therefore, thickening can be economically attractive in that it reduces the sludge volume and results in a more concentrated sludge for hydraulically transporting or for further treatment by dewatering process.

Methods for transporting water treatment plant residuals are similar to other solids and sludge materials handling methods. Residuals in liquid form may be pumped through pipelines or transported by tanker trucks. Alternatively, residuals in cake form may be pumped or trucked to a loading facility or final disposal location, [1]. However, as a comparison, the residuals disposal in the form of dense slurry by hydraulic transport through pipeline presents several beneficial advantages. It is environmental impact-free, demands substantially less space, makes possible full automation and needs a minimum of operating staff, [4]. The optimized management of a sludge hydraulic transport system aims to the ability to obtain much higher solids concentration with minimized power consumption. One possibility to achieve this aim is based on change the physical-chemical environment of the slurries in a manner to produce sufficient level of the repulsive forces between the particles and depress the non-Newtonian behaviour resulted by high solids concentrations (in colloidal form), [5, 6].

The aim of study is to present experimental investigation of the ability to obtain much higher solids concentration with minimized power consumption for the hydraulic transport system of dense kaolin suspensions by change the physical-chemical environment. The study will demonstrate the possibility to obtain optimized management for the residuals disposal for drinking water treatment plants by this concept. The wealth of literature has been explored to study and present the nature and hydraulics of the drinking water plant residuals. The rheological characteristic and flow behaviour with an attention to methods of pressure loss reduction by modifications of the slurry physical-chemical characteristics have been also presented.

1.1 Nature of Residuals

The term residuals is now used to describe the range of process side-streams liquid, solid, or gaseous that can be produced by water treatment processes, [2]. However, 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. Solids generated during the water treatment process consist primarily of nearly all the suspended solids (turbidity) in the influent, algae, viruses and dissolved solids as well as all the chemical added that form precipitates including lime, iron- and aluminum-based coagulants and chemicals such as PAC added to remove organics or to weight sludge blankets. Knowledge of the properties and quantities of sludge produced is essential for the design of any process flow sheet. When compared to wastewater sludges little interest has been paid to the characterization and treatment of potable sludges, [3]. With increasing costs and environmental concerns and desires for beneficial reuse, it has become increasingly common when evaluating or designing the main water process to consider the residuals quality and characteristics and view residuals management as part of the overall process to be optimized when determining the most economical manner in which to meet a specific set of finished water quality goals. The quality and characteristics of the potable residuals are completely interrelated to the main treatment process and two different treatment processes achieving the same finished water goals can produce much different residuals. [2]. In general, settled iron sludges have a higher solids concentration than alum sludges, and the addition of polymer or lime increases the solids concentration of both.
Aluminum and iron coagulants result in inorganic sludges containing compounds such as aluminum hydroxide and ferric hydroxide along with clay, silts, and organic and inorganic matter precipitated by the coagulant. The nature of sludge produced is highly variable, depending on source water quality. Seasonal variations in source water also affect such characteristics of the sludge as its thickening density and dewaterability. The characteristics of coagulant sludges also vary with the proportion of material removed from the water. High-turbidity waters usually result in sludges that are more concentrated and less difficult to dewater; low-turbidity waters present a more difficult sludge processing problem, [1].
The physical properties of sludge had been divided into their macro and micro properties. Macro properties are such parameters as specific resistance, settling rates, and solids concentrations. The indices described could be considered macro properties. Micro properties include particle size distribution and density, [2]. When the micro and macro properties of about 80 water plant sludges were studied, coagulant sludges had a median particle diameter of 0.005 mm with a range of approximately 0.001 to

0.03 mm, [2]. Lime sludge had a similar range but the median diameter was 0.012 mm. The coagulant residuals had an average specific gravity of 2.32 and the lime residuals averaged 2.50. Also, whenever referring to the physical properties of sludge, it is important to know the suspended solids concentration of the solid/liquid mixture in order to assess the physical state, [2].

1.2 Rheological Characteristics and Flow Behaviour

The design of solids handling facilities requires hydraulic calculations for the sizing of pumps and piping. The Hazen-Williams formula is an empirical equation that is valid only for water (around room temperature and in the turbulent flow regime) and is not appropriate for process streams with solids concentrations higher than 2% to .%3. At solids concentrations above 2% to 3%, the flow stream becomes non-Newtonian, [1].
The basic difference between Newtonian and non-Newtonian fluids is that the behaviour of a Newtonian fluid undergoing shear can be completely defined by one variable, the viscosity, while for non-Newtonians the viscosity is dependent upon the rate at which the fluid is sheared; hence the use of a single value for viscosity is no longer appropriate. The rheogram of a Newtonian fluid is a straight line which passes through the origin and has a slope equals the viscosity, μ, which is constant at a given temperature and pressure. The non-Newtonian behaviour is more complicated. Some non-Newtonian fluid rheograms may not be a straight line while attaining the passing from origin (power-law fluids), and other may attain the straightness while doing offset from the origin having a yield stress (Bingham fluids).
The yielded pseudo-homogeneous model is a combination between the power law and Bingham models and is often approximates behaviour of wide range non-Newtonian which takes the form:

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

where τ_Y is the yield stress, n is the flow behaviour index, and k is the fluid consistency index.
Flocculated suspensions of fine particles that generally exhibit shear-thinning non-Newtonian flow characteristics can show extremely large variations in apparent viscosity over the cross-section when flowing in a pipe. The high apparent viscosity of the suspension in the low-shear regions in the core of the pipe is important in that it aids the suspension of the particles. At the same time, pressure gradients are at an acceptable level because the apparent viscosity of the suspension is low in the high shear-rate regions near the pipe walls. Since it is possible to operate at very high solids concentrations, the flow rate of transporting fluids is reduced, and thus the same solids throughputs may be achieved at very much lower velocities. Not only does this result in lower power requirements, but it also reduces wear attrition and alleviates problems of disposing of large volume of transporting fluid. The properties of such suspensions

make them highly suitable for the transport of coarse particle under conditions of laminar pipe flow. The favorable rheological properties of flocculated suspensions exhibiting non-Newtonian shear-thinning characteristics represent an advantage, [7].

1.3 Pressure Loss Reduction

Pumping power for a sludge hydraulic transport system is primarily determined by frictional pressure losses in the pipelines. To minimize both capital and operational costs for pumps, motors, gearboxes and other such system items, there is, therefore, 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 [8] 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 [9, 10] 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.

The power requirement reduction that is based on change of physical-chemical behaviour of the slurry was shown e.g. by Czaban [11]. He used a fluxing agent for modifying the viscosity of water, sand and cement mixture, i.e. for increasing the mixture fluidity. Changing physical-chemical environment of a suspension makes possible to optimize both 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 [12] and El-Nahhas et al [13, 14] confirm the possibility of substantial reduction of the yield stress and apparent viscosity of highly concentrated fine-grained kaolin slurries by a modification of their physical-chemical behavior. Addition of a peptizing agent, also called electrolyte or dispersion agent, to kaolin slurries produces sufficient level of the repulsive forces between the particles, i.e. peptization that results in significant decrease of the apparent viscosity and yield stress.

For potable water treatment residuals, as the same concept, if freshly prepared ferric hydroxide precipitate is treated with a small quantity of $FeCl_3$ (electrolyte) solution, a dark reddish brown colloidal solution of $Fe(OH)_3$ is formed. This process is reverse of coagulation. Similarly, a colloidal solution of $Al(OH)_3$ is obtained when freshly precipated $Al(OH)_3$ is treated with a small quantity of dilute HCl (acid added being insufficient to convert hydroxide completely into chloride), [15]. The peptizing action is due to the preferential adsorption of one of the ions of the electrolyte, which then gives to the colloidal particle a positive or negative charge. For example $Fe(OH)_3$ adsorbs Fe3+ ions from $FeCl_3$ (peptizing agent) and thereby gets a positive charge on the surface. Particles carrying similar charges get separated, yielding smaller sized colloidal particles. [15].

2. EXPERIMENTAL SETUP

2.1 Experimental Facilities

During the 2001 tests in the rheology laboratory at Hydrodynamic Institute, Academy of Science of Czech Republic (refer to [12] for more details), 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.

Also, 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.

2.1 Experimental Test Material

As kaolin slurry is often used as model slurry for investigation of the yield pseudoplastic suspension, and hence sludge, it was used for the present investigation. 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 little ratios of sodium carbonate (Na_2Co_3) as a dispersing agent.

3. RESULTS AND DISCUSSIONS

The rheological measurements that were carried out using the rate-controlled coaxial cylinder viscometer Haake RV-20 system were taken at a temperature, which was strictly kept constant, of 20 ± 0.1 ^{o}C. The flow curves (rheograms) of the tested slurries were obtained under continuous flow conditions by changing the shear rate (γ) stepwise from 0 to 1000 s^{-1}, by changing the speed of rotation of the spindle.

Figure 1 shows typical rheograms for the dense kaolin slurries that showed both a yield stress and rheogram curvature, indicating that these slurries have non-Newtonian behaviour and should be characterized by yield pseudoplastic rheological model (Equation 1).

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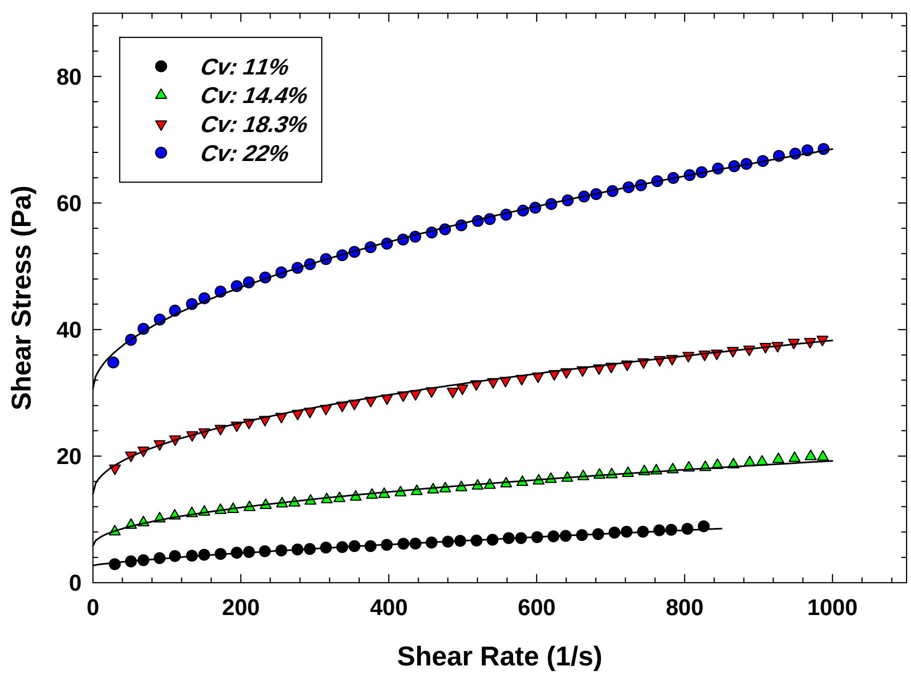

Fig. 1 Rheological Characteristics of Dense Suspensions as Measured by a Rotational Viscometer

An area in which sludges hydrotransport require a more careful treatment than single-phase fluids is that of the pressure gradient or energy gradient. The expression of frictional pressure loss as a hydraulic gradient, *i*, (in m water per m length of pipe) is so common in slurry pipelining. Moreover, for evaluating extra friction loss caused by the solids presence, we use the solids effect, also called excess head loss, (i-i_w), where

i_w is the friction gradient for carrier liquid alone (water) at the flow rate equal to the mixture flow rate.

Figure 2 presents the relation between solids effect (i-i_w) and mean flow velocity for different volumetric concentrations of dense kaolin slurries. It could be noted that at very low velocities the solids effect increases as the mean velocity increases because of yield stress and high apparent viscosity effects. For higher velocities in the laminar flow region, the solids effect (i-i_w) obviously decreases as the mean velocity increase till reaching a minimum value that could be sometimes negative value meaning that the hydraulic gradient of the mixture is less than that of water alone. This could confirm the principal mechanism of drag reduction for non-Newtonian slurries in turbulent flow region associated with thickening of the viscous sub-layer that has been described by Wilson & Thomas [16]. Also, this behavior means that in the laminar flow region, is characterized by the low-slope flat curve in the v-i plots, so the difference between the slurry hydraulic gradient and clear water hydraulic gradient decreases gradually with increasing the mean velocity. The flat slopes of v-i plots, which are typically found for laminar flow region, mean that slight increases in pressure gradient could be resulted by much increase in mean velocity and hence tend to be attractive economically.

The minimum reaching solids effect (i-i_w) value predicts the beginning of the laminar/turbulent transition region after which the flow behaviour is fundamentally changes. The solids effect in the turbulent region increases with increasing the mean velocity meaning that the mixture hydraulic gradient steeply increases.

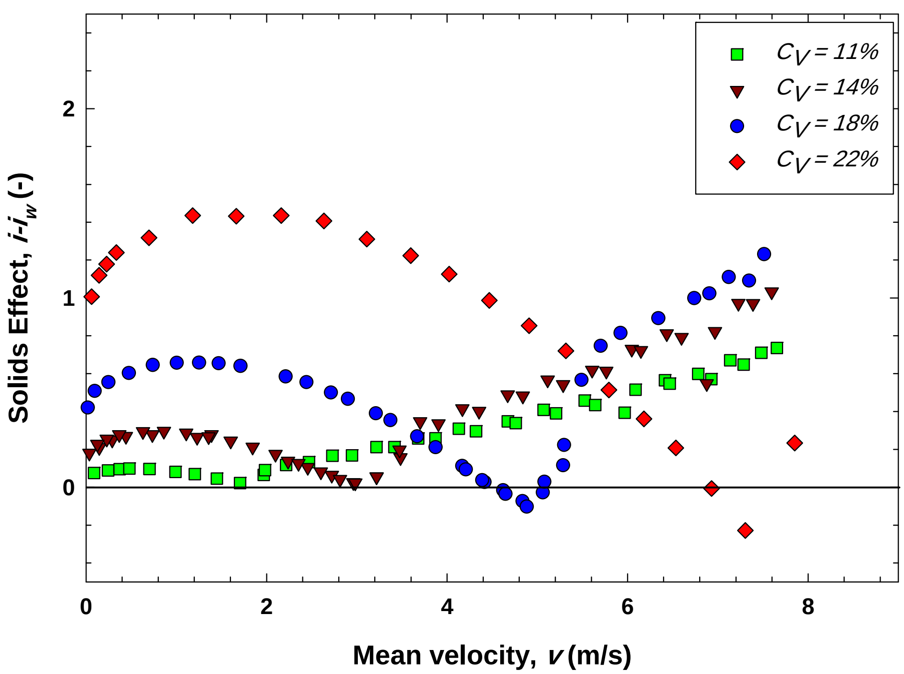

Fig. 2 Flow Behaviour of Dense Suspensions as Measured by Pipeline Test Loop

Referring to Figure 2, it can be also seen that, with increase of volumetric concentration, the transition between laminar and turbulent flow, predicted by the minimum reaching value of the solids effect (i-i_w) occurs at higher velocity.

Figure 3 shows the effect of addition of a dispersing agent, with different ratios, on the flow behavior of slurry with maximum possible naturally obtained volumetric concentration (C_v = 22%). It could be noticed that by addition of the dispersing agent with agent/kaolin mass ratio C_a = 0.05%, in laminar flow region, the solids effect and hence slurry hydraulic gradient is about 30 % reduced. A considerable decrease of laminar/turbulent transition velocity value could be observed. Increasing the dispersing agent/kaolin mass ratio up to C_a = 0.1%, the laminar/turbulent transition velocity had more decreased to about v ~ 3.0 m/s. A great reduction in the hydraulic gradient at the laminar flow region causes the solids effect to be slightly more than zero. After the transition region hydraulic gradient steeply go up and continues in turbulent region with a slope steeper than that in the laminar region for both natural kaolin and peptized kaolin with C_a = 0.05%. Increasing C_a to 0.15 % more reduction in the hydraulic gradient at laminar region could be observed making the solids effect has negative values meaning that slurry hydraulic gradient becomes lower than that of water alone. Laminar/turbulent transition point is situated at slurry velocity about v ~ 2.0 m/s. At turbulent region of the slurry with C_a = 0.15%, its flow behavior becomes more or less the same as that of slurry with C_a = 0.10%. Also, the benefit from dispersing process vanishes for velocities higher than 5 m/s.

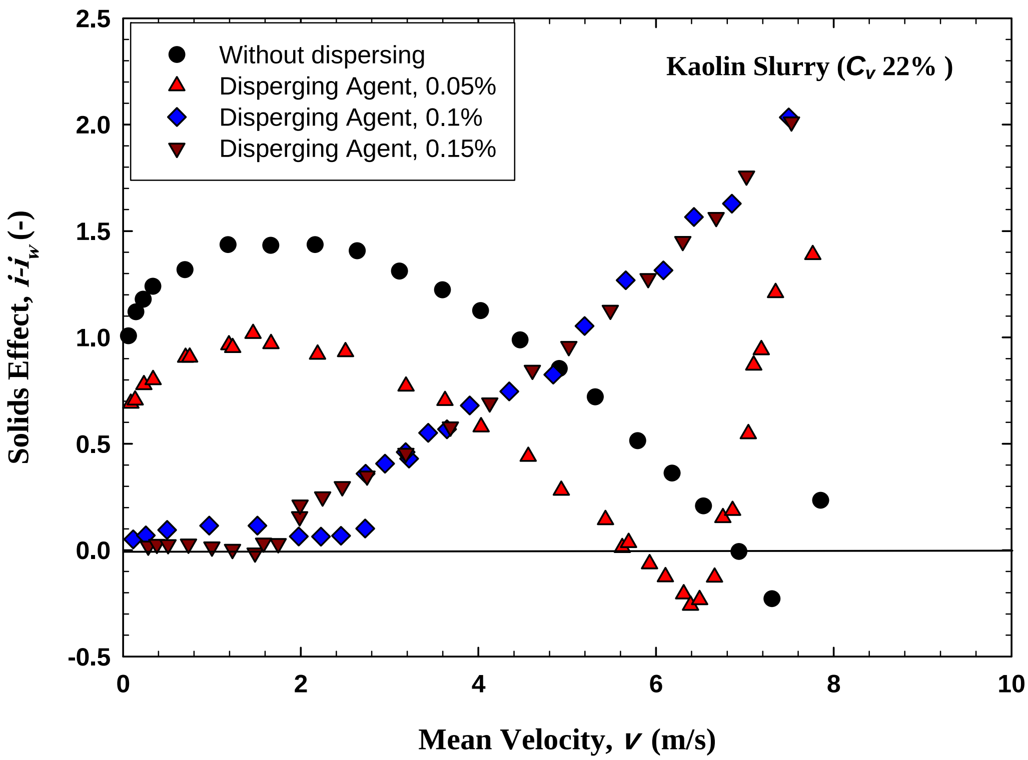

Fig. 3 Effect of Dispersing Agent Addition on Flow Behaviour of the Densest Suspension (C_v = 22%)

The value of the maximum naturally obtained concentration depends on the nature of solids hydro-mixture and mutual physical-chemical behaviour of solids crystal and water. Dispersing process could also serve to obtain higher concentration of slurries. Adding a dispersing agent to slurry, which reaches near the greatest slurry concentration makes the attraction forces in the slurry decrease, the repulsion forces prevail and the aggregates of solid particles are destroyed, also the inner structure of the slurry is changed. The slurry becomes peptized and therefore it is possible to have more solids content and increase the volumetric concentration.

Figure 4 compares the behaviour of the densest natural slurry (C_v = 22%) with that of a more concentrated slurry with concentration of C_v = 26% obtained by dispersing process with two peptizing agent/kaolin ratios C_a = 0.05% and 0.15%.

As shown in Figure 4, two obtained economic benefits of the dispersing effect could be noted. First, higher concentration slurry that is impossible to flow naturally in pipes is obtained by the addition of the dispersing agent. Second, the accompanied friction loss is reduced. Concentrated slurry of C_v = 26% obtained by dispersing process with a dispersing ratio, C_a = 0.05%, had lower friction loss than that of the natural suspension of lower concentration (22%) within a velocity range up to $v \approx 4$ m/s. Increasing the peptizing ratio to C_a = 0.15% vanishes the yield stress. The slurry wall shear stress is slightly higher than the corresponding one of the pure water within a velocity range up to $v \approx 3.6$ m/s.

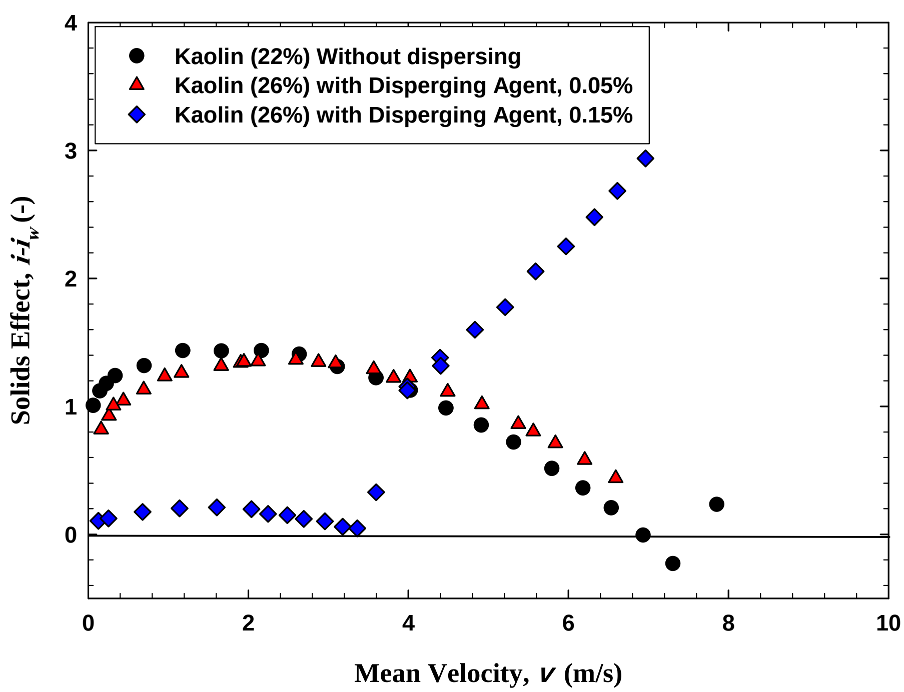

Fig. 4 Obtaining More Solids Concentration by Dispersing Agent Addition

CONCLUSIONS

The control of physical-chemical environment and of the inner structure of drinking water residuals could optimize both the energy and water consumption during its hydraulic transport. Adding dispersing agent to the suspensions significantly depresses non-Newtonian behaviour, caused by presence of colloidal particles, resulting in decreasing the apparent viscosity and yield stress. Accordingly, it lowers the frictional pressure losses and hence manages the pumping power consumption for pipeline transport and handling. Also, the dispersing process can help to reach much higher concentration of solids, and hence water saving. Effectiveness of the dispersing process depends on solids concentration, dispersing agent amount, and acting shear stress or flow velocity ranges.

NOMENCLATURE

		Units
C_a	agent/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]
i	hydraulic gradient of the mixture	[m water/m pipe]
i_w	hydraulic gradient of water at the same flow rate as the mixture	[m water/m pipe]
k	consistency index	[$kgm^{-1}s^{n-2}$]
n	flow behaviour index	[-]
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]
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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