Arsenic removal from high-arsenic water by enhanced coagulation with ferric ions and coarse calcite

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Abstract

Arsenic removal from high-arsenic water in a mine drainage system has been studied through an enhanced coagulation process with ferric ions and coarse calcite (38–74 μm) in this work. The experimental results have shown that arsenic-borne coagulates produced by coagulation with ferric ions alone were very fine, so micro-filtration (membrane as filter medium) was needed to remove the coagulates from water. In the presence of coarse calcite, small arsenic-borne coagulates coated on coarse calcite surfaces, leading the settling rate of the coagulates to considerably increase. The enhanced coagulation followed by conventional filtration (filter paper as filter medium) achieved a very high arsenic removal (over 99%) from high-arsenic water (5 mg/l arsenic concentration), producing a cleaned water with the residual arsenic concentration of 13 μg/l. It has been found that the mechanism by which coarse calcite enhanced the coagulation of high-arsenic water might be due to attractive electrical double layer interaction between small arsenic-borne coagulates and calcite particles, which leads to non-existence of a potential energy barrier between the heterogeneous particles.

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1. Introduction

In Mexico, hundreds of years of mining activities for gold, silver and metallic sulfide minerals left a considerable quantity of tailings, some of which have a high arsenic content. Owing to rain, wind and other natural effects, the arsenic dispersed into the nearest water courses or agricultural fields in the forms of arsenate ion (As (V)) and arsenite ion (As (III)), leading to a high arsenic concentration in the water courses around the mines. For example, in Matehuala city, state of San Luis Potosí, water from mine drainage systems contained up to 7 mg/l As (Razo-Soto et al., 2005). As it has been reported, serious health problems, such as cancers, skin alteration, etc., have been linked to arsenic ingestion even at a low concentration (20–50 μg/l) (O’Connor, 2002). The Secretary of Health (SAA) of Mexico recently has implemented a new maximum contaminant level (MCL) for arsenic in drinking water of 20 μg/l. Accordingly, the high arsenic water from mine drainage systems would be a great environmental concern through the contamination of shallow groundwater and surface water around the areas. The water has to be treated to remove arsenic effectively, in order to minimize the environmental effects.

Arsenic removal from water is an important subject worldwide, which has recently attracted great attentions. A variety of treatment processes has been developed for arsenic elimination from water, including coagulation (precipitation) (Wickramasinghe et al., 2004; Hering et al., 1997), adsorption (Wang et al., 2002; Zhang et al., 2003; Katsoyiannis and Zouboulis, 2002), ion exchange (Korngold et al., 2001), membrane filtration (Sato et al., 2002), electrocoagulation (Kumar et al., 2004; Arienzo et al., 2002), biological process
(Katsoyannis and Zouboulis, 2004), iron oxide-coated sand (Thirunavukkarasu et al., 2003), high gradient magnetic separation (Chiba et al., 2002) and natural iron ores (Zhang et al., 2004), manganese greensand (Thirunavukkarasu et al., 2005), etc. There are numerous review papers for the arsenic removal technologies, some of which were recently made by Jiang (2001), Bissen and Frimmel (2003), Dambies (2004) and USEPA (2000). Coagulation and adsorption processes are most promising for arsenic removal from high-arsenic water because of the low cost and high efficiency, and are widely used in the developing world. But, they have not been shown to deeply eliminate arsenic from water and to produce clean water with a very low arsenic concentration, say 10 μg/L. However, membrane filtration process could lower arsenic concentration in water from 48 to 1–2 μg/L (Bissen and Frimmel, 2003), and ion exchange process could remove arsenic to levels lower than 5 μg/L for water with initial arsenic concentration of 87 μg/L (Wang et al., 2002), which are currently used in the developed world. The other processes are still at a laboratory or pilot scale.

Coagulation process is traditionally realized by adding ferric or aluminum ions (Hering et al., 1996). In this process, fine particles in water first aggregate into coagulates because added ferric or aluminum ions strongly reduce the absolute values of zeta potentials of the particles. Then, arsenic ions (arsenate or arsenite) precipitate with the ferric or aluminum ions on the coagulates, and thus concentrate in the coagulates. After that, the coagulates are separated from water through filtration, eliminating arsenic from the water. The coagulates are termed arsenic-borne coagulates. Coagulation with ferric ions for arsenic removal can be traced back to the late 1960s in Taiwan to treat deep well water with naturally elevated arsenic concentrations (Shen, 1973). Gulledge and O’Connor (1973) also reported that arsenic could be readily removed from water to a high degree by conventional water treatment using ferric or aluminum ions as coagulants. Since then, there have been a lot of reports on coagulation process for arsenic removal. It has been found that the coagulation is much more effective for the removal of As (V) than As (III). In the case when only As (III) is present, oxidation to convert As (III) to As (V) is needed prior to coagulation. The effective pH for arsenic removal was reported to be 5–7 with aluminum ions, and 5–8 for ferric ions (Song and Logsdon, 1978). Besides iron and aluminum compounds, manganese, calcium and magnesium compounds are also of effective coagulants for eliminating arsenic from water in neutral medium (Raje and Swain, 2002; Jiang, 2001). Arsenic removal from water achieved by coagulation process depends on initial arsenic concentration in water (Thirunavukkarasu et al., 2005; Jiang, 2001). The arsenic removal could reach 99% (Jiang, 2001). Recently, it was reported that modified coagulation/filtration could give a residual arsenic concentration of 2 μg/L or less for treated well water (Han et al., 2003).

The arsenic removal is also dependent on the pore size of the membrane filter disks used for coagulation process (Han et al., 2003), since coagulates smaller than the pore can pass through the filter and remain in water. As it is known, in filtration, larger the filter pores, lower the capital and operation costs, and higher the separation efficiency. Therefore, there is a great significance in enlarging arsenic-borne coagulates in order to improve coagulation/filtration process for arsenic removal. However, there is little information in this regard, although there are numerous reports on coagulation process for arsenic removal from water.

Usually, coagulations are enhanced by adjusting pH and electrolyte concentration to reduce the absolute values of zeta potentials of particles, and by optimizing coagulation kinetics. Besides, it can also be realized by adding appropriate coarse particles, in which fine particles in suspensions coat coarse particles in the form of multilayers. Such coagulates consist of fine particles and coarse particles. This phenomenon was observed early in mineral flotation systems, and was termed “slime coating” (Fuerstenau et al., 1979; Somasundaran, 1980). The coarse particle enhancement of coagulation of fine particles not only strongly reduces particle numbers in suspensions, but also greatly increases coagulate size. The mechanism of the coarse particle effect might be attributed to the increase of aggregation rate, because collision rate between coarse particle and fine particle is much higher than that between fine particles themselves (Song and Lopez-Valdivieso, 2002). The commercial uses of this effect appeared in a flotation circuit for the purification of kaolin early in 1960s, in which anatase fines aggregated with coarse calcite, followed by the flotation of the coated calcite to remove the anatase from kaolin (Green and Duke, 1962).

In the present study, we attempted to make use of the coarse particle effect to improve the coagulation process for arsenic removal from water. The objective is to develop a new cost-effective technique for eliminating arsenic from high-arsenic water in the mine drainage located in Matehuala city, Mexico. The possibility and effectiveness of this new enhanced coagulation process were determined while ferric sulfate was used as coagulant and calcite was used as the coarse particle. In order to understand the coarse particle effect in the enhanced coagulation, the zeta potentials of arsenic-borne coagulates and calcite particles were determined, and the settling rates of arsenic-borne coagulates before and after coating coarse calcite were measured. In addition, arsenic-borne coagulates were observed by using a scanning electronic microscope (SEM) and an atomic force microscope (AFM).

2. Experimental

2.1. Materials

The high-arsenic water sample used in this work was originally collected from the Cerrito Blanco channel, located in Matehuala city, state of San Luis Potosi, Mexico. The water was first sieved with a 400 mesh screen, and then was filtered with an Ahlstrom Grade 610 filter paper (2.5 μm aperture) to remove solid contaminants. The water past the filter paper was used for the tests, which gave the initial arsenic concentration of 5071 μg/l. The chemical composition and some properties of the water sample were listed in Tables 1 and 2, respectively.

Ferric sulfate (Fe2(SO4)3·5H2O) (J. T. Baker, analytic purity) was used as coagulant; hydrochloric acid (HCl) (Fremont,
analytic purity) and sodium hydroxide (NaOH) (J. T. Barker, analytic purity) was used to adjust pH. Calcite used in this work was obtained from the mine of Minera de Las Curvas, Mexico. The chunk mineral was first crushed with a hammer, and then purified by hand sorting. After that, the mineral was ground with a porcelain mortar, followed by a size classification with screens to obtain two size fractions of 52–74 μm and 38–44 μm, which were determined to contain 99.2% and 99.0% CaCO₃, respectively.

2.2. Arsenic removal by coagulation with ferric ions

High-arsenic water (200 ml) was first mixed with a given amount of Fe₂(SO₄)₃ in a flask, and then was adjusted for pH with HCl or NaOH by using a potential meter (Orion 720-A). After that, it was stirred on a magnetic agitator (Digital hot plate/stirrer 04644) at 240 rev/min for 30 min, while temperature was kept at 30 ± 0.2 °C. Arsenic-borne coagulates were formed during the agitation. After that, the suspension was filtrated through a Millipore white GSWP membrane (0.22 μm aperture). The filtrate was sent for arsenic analysis. Each test was duplicated. The arithmetic average result of the two tests was reported in this paper.

2.3. Arsenic removal by enhanced coagulation with ferric ions and coarse calcite

High-arsenic water (200 ml) was first mixed with a given amount of Fe₂(SO₄)₃ and coarse calcite in a flask, and then pH-adjusted and stirred in the same way as mentioned above. After that, the suspension was filtrated through an Ahlstrom Grade 610 filter paper (2.5 μm aperture). The filtrate was sent for arsenic analysis. Each test was duplicated. The arithmetic average result of the two tests was reported in this paper.

2.4. Arsenic analysis

Arsenic concentration in water or filtrates was determined by using a Perkin-Elmer Aanalyst 100 atomic absorption spectrometer coupled to a Perkin-Elmer FIAS 100 flow injection system. Water or filtrate (20 ml) was first mixed with 2 ml mixture of KI (10%) and ascorbic acid (5%) and 1 ml concentrated hydrochloric acid at 75 °C for 5 min. This treatment was to reduce As (V) to As (III) and to dissolve solid particles in the water or filtrates. Then, the solution was cooled to room temperature, from which a 10 ml solution was taken for the analysis of As (III) concentration with the instruments. Each analysis for arsenic concentration was duplicated. The arithmetic average of the two analysis results was reported in this paper. As soon as arsenic concentrations were obtained, arsenic removal (E) was calculated by the following expression:

\[
E = \frac{C_0 - C}{C_0},
\]

where \(C_0\) and \(C\) are the arsenic concentration of the high-arsenic water sample and a filtrate from arsenic removal tests, respectively.

2.5. Turbidity measurement

Turbidity of the high-arsenic water treated by coagulation was determined by using a Bausch & Lomb Spectronic 20 spectrophotometer. First, coagulation was applied to water. Then, 20 ml of the suspension was transferred to a tube for turbidity measurement. Light transmissivity as a function of settling time was obtained from this measurement, which could provide information on settling rate of coagulates. At the same settling time, a larger light transmissivity indicates a higher settling rate, or stronger coagulation. Each measurement was tripled. The arithmetic average of the three measurement results was reported in this paper.

2.6. Microscope study

Coagulates from coagulations were observed by using a Quesant Qscope 250 AFM and a Philips Microspec WDX SEM in this work. AFM images and SEM micrographs of coagulates were photographed. The samples for the observations were prepared by putting a drop of coagulated suspension on a metal dish for SEM study or on a mica for AFM study, and then drying in room temperature. Before the SEM study, the sample on the dish was coated by gold. In addition, an EDAX energy dispersive spectrometer (EDS) attached to the SEM was used to determine the existence of arsenic in coagulates.

2.7. Zeta potential determination

A micro-electrophoresis meter (Riddick) was used to measure the zeta potentials of arsenic-borne coagulates from the
coagulation mentioned above and calcite fines in aqueous solutions. The electrophoresis mobility of over 20 particles was determined, and the average value was transformed to zeta potential using the Smoluchowski equation.

2.8. Particle size analysis

A Shimadzu SALD-1100 laser diffraction particle size analyzer with semiconductor laser as the light source was used to measure the size distributions of arsenic-borne coagulates from the coagulation mentioned above in this study. This instrument reports optical diameter instead of the equivalent Stokes diameter. In order to protect coagulates from breaking, ultrasonic was not applied to the suspensions during the measurements. The measurement was tripled. The arithmetic average of the three measurement results was reported in this paper.

3. Results and discussions

3.1. Arsenic removal by coagulation with ferric ions

Fig. 1 illustrates arsenic removal from the high-arsenic water as a function of pH by coagulation with 100 mg/l ferric sulfate and micro-filtration with the membrane. Error analysis for the results of arsenic elimination presented in the graph was made on the basis of the standard error of the coagulation/filtration tests and arsenic analysis. The error was also presented in the graph in the form of an error bar. As it can be seen, in the acidic range, very high arsenic removal, about 99%, was achieved, while in the alkaline range, the arsenic removal declined sharply with the increase of pH. This result is in a good agreement with those obtained by coagulation with ferric ions for low-arsenic concentration water (20–100 μg/l), as reported elsewhere (Hering et al., 1996; Gulledge and O’Connor, 1973). Obviously, coagulation/micro-filtration process is very effective in eliminating arsenic from high-arsenic water at acidic to neutral pH.

Fig. 2 shows the size distribution of arsenic-borne coagulates from the coagulation of high-arsenic water with 100 mg/l ferric sulfate at pH 5. Error analysis for the weight percentage of each size fraction showed that the maximum error was ±0.6%. Since the error bars were too small to draw, only the arithmetic average values of cumulative undersize were presented in the graph. As it is noted, the coagulates were very fine, ranging between 0.5 and 20 μm. There were about 17% (weight percentage) coagulates smaller than 2.5 μm, and about 83% coagulates smaller than 10 μm. Obviously, filtration with the membrane (0.22 μm aperture) is qualified for a perfect separation of the coagulates from water. However, filtration with the filter paper (2.5 μm aperture) would lead to low arsenic removal, because 17% coagulates would pass through the paper into filtrates. In addition, this result suggests that the separation of the coagulates from water cannot be realized by gravitational sedimentation, as the coagulates are in colloidal size range.

The AFM image of coagulates from the coagulation of the high-arsenic water with 100 mg/l ferric sulfate at pH 5 is given in Fig. 3. It clearly shows the three dimensions of
arsenic-borne coagulates. The coagulates have irregular shape, and a size of 0.5–4 μm.

3.2. Arsenic removal by enhanced coagulation with ferric ions and coarse calcite

Enhanced coagulation with ferric ions and coarse calcite followed by filtration with filter papers (2.5 μm aperture) was tested to eliminate arsenic from the high-arsenic water. Fig. 4 illustrates arsenic removal from the water as a function of calcite addition at pH 6 and 100 mg/l ferric sulfate addition. The error bars obtained from the standard error analysis of coagulation/filtration tests and arsenic analysis were also given in the graph. Without coarse calcite, the arsenic removal was only 85%, which was in correspondence with the cumulative oversize of arsenic-borne coagulates as shown in Fig. 2. Such a low arsenic removal should be attributed to small arsenic-borne coagulates passing through the filter papers. As the increase of coarse calcite addition, the arsenic removal increased until it reached about 99%. This increase was very sharp in the small calcite addition range, but was mild after 2.5 g/l calcite addition. Indeed, the coagulation of high-arsenic water could be greatly enhanced by adding coarse calcite particles and, thus, arsenic can be effectively removed from the water by filtration in a large pore filter medium. Also, it can be observed from this graph that 38–44 μm calcite enhanced arsenic removal more strongly than 52–74 μm calcite at the same amount of addition. The mechanism might be due to the larger surface area on smaller particles, leading to more coatings of arsenic-borne coagulates on calcite surfaces.

The effect of pH on arsenic removal from the high-arsenic water by coagulation with 100 mg/l ferric sulfate and 5 g/l coarse calcite and filtration with the filter papers is shown in Fig. 5. The error bars of arsenic removal for the points appeared in the graph were ±0.2% to ±0.7%. They were not presented in the graph because most of the bars overlapped with the corresponding points. As it is noted, the arsenic removal vs. pH curve in the presence of coarse calcite is very similar to that without calcite as shown in Fig. 1. High arsenic removal was achieved in the range of pH 5–7. At the alkaline pHs, the arsenic removal declined sharply with increasing pH. Again, this graph also showed that 38–44 μm calcite improved arsenic removal from the high-arsenic water by enhanced coagulation more strongly than 52–74 μm calcite.

At pH = 5, the enhanced coagulation and filtration with filter papers produced treated water with the residual arsenic concentration of 13.2 μg/l, which is less than the Mexican MCL for arsenic in drinking water. Compared with the results as shown in Fig. 1, it is noted that the maximum arsenic removal achieved by the enhanced coagulation was almost the same as that produced by coagulation with the same amount of ferric sulfate and filtration with membrane. It indicates that the role played by coarse calcite in the enhanced coagulation might be solely to increase the size of arsenic-borne coagulates.

For high-arsenic water treatment, another effective process is adsorption (Jiang, 2001; Bissen and Frimmel, 2003; Dambies, 2004; USEPA, 2000). Many kinds of materials, such as activated alumina, activated carbon, granulated ferric hydroxide, zero-valent iron, natural iron minerals and metal-loaded polymers, etc., are used as the adsorbent. Ahn et al. (2003) studied arsenic removal from high-arsenic water in a mine tailing containment system by using waste steels and zero-valent iron, and produced treated waters with the residual arsenic concentrations of 44 and 3 μg/l arsenic from waters initially containing 4137 and 1400 μg/l arsenic, respectively. Jiang (2001) reported that by activated carbon adsorption 96% of arsenic can be removed from water with initial arsenic concentration of 300 μg/l, and by coagulation with ferric ions 99% of arsenic can be removed from water with initial arsenic concentration of 1100 μg/l. Clearly, the enhanced coagulation process with ferric ions and coarse calcite showed a very high efficiency for arsenic removal from high-arsenic water.

The results presented in this paper were obtained from batch tests in laboratory. If the enhanced coagulation process is applied to treat the high-arsenic water in pilot or plant scale, the arsenic removal might be less than 99.5% that was achieved in batch scale, and the residual arsenic
concentration of cleaned water might be greater than the Mexican MCL for arsenic in drinking water (20 μg/l As) and much greater than the World Health Organization (WHO) guideline value (10 μg/l As). Therefore, the enhanced coagulation process may be used as primary treatment for the high-arsenic water from the mine drainage system. Another process (which could be conventional coagulation, adsorption, ion exchange, etc.) has to be followed to deeply remove arsenic from water in order to meet the Mexican MCL or WHO guideline value.

3.3. Mechanisms of the enhanced coagulation

Coagulates from the enhanced coagulation were photographed by using a SEM. Fig. 6 gives two SEM micrographs. In the images, the large particles which were similar to cubes were of calcite, and the small irregular particles were of arsenic-borne coagulates. As it can be observed, the calcite surfaces (right sides and lateral sides) were coated by a lot of small coagulates, some of which were very fine (less than 1 μm). Because of the coating, the small arsenic-borne coagulates behave similar to the coarse calcite in gravitational sedimentation and filtration, and thus are easily removed from water. In addition, EDS attached to the SEM was used to chemically analyze the small coagulates on the calcite surfaces in the images. Numerous points on the coagulates were chosen. Arsenic was found in the coagulates, ranging from 0.8% to 5.3% As. Indeed, they were of arsenic-borne coagulates.

The enhanced coagulation was also studied through sedimentation tests. Fig. 7 illustrates the light transmissivity of the high-arsenic water treated by coagulation with 100 mg/l ferric sulfate at pH 7 as a function of settling time, in the absence and presence of coarse calcite (38–44 μm). Error analysis for three tripled measurements showed that the standard error for light transmissivity ranged from 0 to ±0.8%. Such small error bars were difficult to be clearly presented, so that only arithmetic average values of light transmissivity appeared in the graph. As it is noted, without calcite, the light transmissivity increased very slowly with increasing settling time, indicating a slow coagulate sedimentation. Clean water in the sedimentation tube (100% light transmissivity) was obtained after 22 h settling. However, 5 g/l coarse calcite coagulates settled down much more rapidly, leaving clean water in the tube after 14 min. These results suggest that coarse calcite considerably enhanced the coagulation of the high-arsenic water, and greatly increased the sedimentation of arsenic-borne coagulates.

According to Stokes equation of sedimentation, the terminal settling velocity of a particle in a liquid is proportional to the square of the diameter of the particle. So, the coarse calcite should have a much higher settling rate than small arsenic-borne coagulates. If small coagulates coat on coarse calcite particles, they would settle down in the same velocity (or a little bit higher) as the calcite particles. This is the mechanism by which the sedimentation of arsenic-borne coagulates was considerably improved by adding coarse calcite particles.

Fig. 8 shows light transmissivity of the high-arsenic water treated by enhanced coagulation with 100 mg/l ferric sulfate and 5 g/l coarse calcite as a function of settling time at various pH. As it can be seen, the settling rate of arsenic-borne coagulates decreased with the increase of pH. Light transmissivity of 100% appeared after 9 min at pH = 6, compared with 29 min at pH = 9. These results might be attributed to that coarse calcite had a stronger ability to carry small arsenic-borne coagulates at pH = 6 than at pH = 9. In other
Overbeek, 1948). According to this theory, the potential energy between two heterogeneous particles equals that of two homogeneous particles, which may be obtained by (Israelachvili, 1992)

\[
V_{h} = \frac{A_{123}}{R_{o}} \left( \frac{1}{C_{16}/C_{17}} + \frac{1}{C_{18}/C_{19}} \right),
\]

where \(A_{123}\) is the Hamaker constant of particles 1 and 2 in medium 3, which may be obtained by (Israelachvili, 1992)

\[
A_{123} = \left( \sqrt{A_{11} - \sqrt{A_{33}}} \right) \left( \sqrt{A_{22} - \sqrt{A_{33}}} \right),
\]

where \(A_{11}, A_{22}\) and \(A_{33}\) are the Hamaker constants of particles 1, 2 and medium 3 in vacuum.

In the case of this work, the Hamaker constants of the arsenic-borne coagulates and calcite are larger than water, i.e. \(A_{11} > A_{33}\) and \(A_{22} > A_{33}\). So, \(A_{123} > 0\), and thus \(V_{h} < 0\) according to Eqs. (4) and (3), indicating an attractive interaction of van der Waals between the two heterogeneous particles. In the range of pH 4.9–9.3, \(\psi_{1} < 0\) (arsenic-borne coagulates), and \(\psi_{2} > 0\) (calcite), leading to \(\tan \left( \frac{e\psi_{1}}{kT} \right) < 0\) and \(\tan \left( \frac{e\psi_{2}}{kT} \right) > 0\), and thus \(V_{R} < 0\) according to Eq. (1). It means that the electrical double layer interaction was also attractive between the two heterogeneous particles. Therefore, in the pH range, the total potential energy of interaction between the arsenic-borne coagulate and the calcite particle was attractive at every distance. In other words, there was no potential energy barrier between the two particles. A strong coagulation should employ to the arsenic-borne coagulates and calcite particles. This is the mechanism by which small arsenic-borne coagulates coated on coarse calcite, as shown in Figs. 6 and 8.

In addition, there are interests to understand the impacts of other factors on arsenic removal from the high-arsenic water by the enhanced coagulation process, e.g., ions, organic carbon and ionic strength in initial water, chemisorption of arsenate ions on calcite surfaces, etc., which are our current and future research interests. Another further work in this regard is to build up a pilot system for the enhanced coagulation process to eliminate arsenic from the high-arsenic water in the mine drainage system. The state government of San Luis Potosi has approved financial support for the pilot-scale tests.

The experimental results from this study have shown that the enhanced coagulation process is a very cost-effective technique for arsenic removal from high-arsenic water.
Because of the high settling rate, the arsenic-borne coagulates from the enhanced coagulation can be first concentrated from water by gravitational sedimentation, and then separated from water by filtration with a large-pore filter medium, producing a very low arsenic concentration of cleaned water. Compared with conventional coagulation/filtration process for arsenic removal, the enhanced coagulation process features lower capital and operation costs, simpler in operation and lower task in maintenance. Since coagulation is a commonly and widely used process for water treatment worldwide, it will not be hard to realize the practical uses of the enhanced coagulation process. Coarse calcite may be added together with ferric sulfate and other chemical reagents, which would not bring great difficulty. For the steps of conditioning, sedimentation and filtration, the enhanced coagulation could be the same as conventional coagulation/filtration process. However, the disposal of the sludge from the enhanced coagulation process has to be studied to meet the Mexican regulation for toxic waste disposal, which will be our further research subject together with the pilot-scale studying.

4. Conclusions

(1) Coagulation/filtration for arsenic removal from a high-arsenic water with ferric ions as the coagulant could be considerably enhanced by adding an appropriate amount of coarse calcite (38–74 μm). This enhancement may be attributed to the coating of small arsenic-borne coagulates on calcite surfaces, improving the gravitational sedimentation and filtration of the coagulates greatly.

(2) The coating of small arsenic-borne coagulates on coarse calcite may be due to the attractive electrical double layer interaction between the coagulates and coarse calcite because of the reverse zeta potential of the two particles, which leads to non-existence of a potential energy barrier between the two particles.

(3) The enhanced coagulation with ferric ions and coarse calcite and conventional filtration (filter paper as filter medium) achieved a very high arsenic removal (over 99%) from a high-arsenic water in mine drainage system (5 mg/l As), giving the residual arsenic concentration of 13 μg/l.

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