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COD REMOVAL FROM LANDFILL LEACHATE USING FENTON OXIDATION AND COAGULATION

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Abstract

The treatment of old municipal landfill leachate by Fenton oxidation, coagulation as well as coagulation combined with the Fenton oxidation was carried out on a laboratory scale. It has been found that organic pollutants in leachate could be successfully removed by Fenton oxidation. The most advantageous dose of H_2O_2 and Fe^{2+}/H_2O_2 ratio were 1350 mg/L and 0.2, respectively at pH 3 and reaction time of 45 minutes. In these operating conditions, the COD removal efficiency reached 61%. However, a 73.1% removal of COD was attained after 26 hours of Fenton oxidation. In coagulation process, the efficiency was within the range of 39-45.8% using PIX as a coagulant at dose of 500 mg/L (pH 5 and 30 min of reaction time). The best result of COD removal (65.3%) was obtained in the combined treatment system including a coagulation process, followed by a Fenton oxidation. In this case, COD removal by coagulation was 45.8% while by Fenton oxidation only 19.5%. Therefore more experiments need to be done towards optimisation of such combined system. It concerns particularly the second treatment stage by Fenton oxidation. It was concluded that the Fenton oxidation or combined coagulation-Fenton oxidation system are very efficient and promising methods for treatment of non-biodegradable landfill leachate.

Streszczenie

Prowadzono oczyszczanie odcieków ze starej kwatery składowiska odpadów komunalnych za pomocą odczynnika Fentona, procesu koagulacji, jak również koagulacji połączonej z utlenianiem odczynnikiem Fentona w skali laboratoryjnej. Wykazano, że zanieczyszczenia organiczne zawarte w odciekach były efektywnie usuwane za pomocą utleniania odczynnikiem Fentona. Najkorzystniejsza dawka H_2O_2 i stosunek Fe^{2+}/H_2O_2 wynosiły odpowiednio 1350 mg/L i 0.2 przy pH 3 i czasie reakcji 45 minut. W tych warunkach stopień obniżenia wartości ChZT wynosił 61%. Po 26 godzinach efektywność ta zwiększyła się do 73.1%. W procesie koagulacji, efektywność obniżania ChZT zawierała się w granicach 39-45.8% przy zastosowaniu dawki PIX-u równej 500 mg/L przy pH 5 i czasie reakcji 30 minut. Najlepszy wynik obniżenia wartości ChZT (65.3%) uzyskano w układzie kombinowanym (koagulacja-odczynnik Fentona). W tym przypadku efektywność obniżenia wartości ChZT w procesie koagulacji wynosiła 45.8%, natomiast w procesie Fentona jedynie 19.5%. Dlatego niezbędne są dalsze badania nad optymalizacją takiego układu kombinowanego, a w szczególności drugiego stopnia oczyszczania odczynnikiem Fentona. Wyniki badań wykazały, że zastosowanie odczynnika Fentona bądź układu kombinowanego stanowi efektywny i obiecujący sposób oczyszczania odcieków niepodatnych na biodegradację.

Keywords: **Landfill leachate; Fenton reagent; Coagulation; Advanced oxidation.**

1. INTRODUCTION

Leachates from municipal solid waste landfill sites are often defined as hazardous and heavily polluted wastewaters. Leachates may contain large amounts of organic matter (biodegradable, but also refractory to biodegradation), where humic-type constituents make an important group [1], as well as ammonia-nitrogen, heavy metals, chlorinated organic and inorganic salts [2]. Landfill leachates have been identified as potential sources of ground and surface water contamination, as they may percolate through soils and subsoils, causing extensive pollution of streams, creeks and water wells, if they are not properly collected, treated and safely disposed [3, 4].

Landfill leachate is generated as a result of precipitation, surface run-off, and infiltration or intrusion of groundwater percolating through a landfill [2]. Therefore, the characteristics of landfill leachates are the combined result of number of complex factors, including soil properties, weather conditions, municipal solid waste composition, landfill age, and landfill operation. The organic matter present in old landfill leachates is usually well stabilized, so biological treatment is ineffective for such effluents [5].

The composition and concentration of contaminants are mainly influenced by the age of landfill [4, 6]. Biological processes are quite effective, when applied to relatively younger (i.e. recently produced) leachates, containing mainly volatile fatty acids, but they are less efficient for treatment of older (i.e. more stabilized) leachates [7]. Biorefractory contaminants, contained mainly in older leachates, are not amenable to conventional biological processes, whereas the high ammonia content might also be inhibitory to activated sludge microorganisms [8]. Furthermore, a supplementary addition of phosphorus is often necessary, as landfill leachates are generally phosphorus-deficient [4, 7]. Consequently, the biological treatments become ineffective for the treatment of old landfill leachates [9, 10].

To treat these old or refractory landfill leachates, many physical/chemical (chemical oxidation, chemical precipitation, coagulation-flocculation, activated carbon adsorption and membrane processes) and biophysical processes have been used [2, 7, 9, 11-15]. Coagulation and flocculation is a relatively simple technique that may be employed successfully in treating old landfill leachates [7, 9, 16]. However, this treatment only leads to moderate removals of COD and TOC, and it has its drawbacks: sludge is produced, and in some cases, when traditional chemical coagulants are used, an increase on the concentration of aluminium or iron, in the liquid phase, may be observed [5]. Therefore, coagulation/precipitation is not appropriate for a full treatment of leachate, due to its limited efficiency for removal of organic content. However, coagulation/precipitation can be an efficient pretreatment prior to biological or membrane treatment, or an effective post-treatment for the leachate [4, 7], as well as can be used as one of the elements of a technological setup for the purification of leachates from municipal solid waste landfills [13].

One available technology widely used to treat landfill leachate in recent years is Fenton's oxidation process ($H_2O_2 + Fe^{2+}$) [17], which has the advantages of both oxidation and coagulation processes [9, 18]. Among the different technologies reported in literature for the treatment of highly contaminated effluents, Fenton's reagent is characterized by its cost effectiveness, simplicity and suitability to treat aqueous wastes showing a variable composition [19, 20]. The Fenton reagent has been found to be effective in degradation of various industrial wastewater components [21-28].

The Fenton reaction can be effectively exploited to treat landfill leachate, and may be particularly appropriate for mature leachate. Fenton processes are applicable to the treatment of highly toxic leachate and exhibit noticeably faster kinetics as compared with biological treatment processes. Fenton treatment also achieves considerably higher efficiency of removal of organic compounds from leachate, compared with other physical/chemical technologies including coagulation and activated carbon adsorption. In particular, Fenton treatment effects chemical destruction rather than pollutant transfer from one phase to another, in contrast with membrane filtration and with other separation processes. Importantly, capital costs and energy requirements of Fenton treatment can be expected to be very low compared with other advanced oxidation processes [29].

In the Fenton process, coagulation and oxidation both contribute to the removal of pollutants from leachate, and their relative importance depends on leachate characteristics and reaction conditions. The relative importance of oxidation and coagulation depends primarily on the H_2O_2/Fe^{2+} ratio. Chemical coagulation predominates at a lower H_2O_2/Fe^{2+} ratio, whereas chemical oxidation is dominant at higher H_2O_2/Fe^{2+} ratios [30]. Generally, an initial pH between 2.0 and 4.5 favours the Fenton reaction [29].

Fenton treatment can be implemented alone or in tandem with other technologies for leachate treatment. Several flow sheets reported for Fenton-based leachate treatment schemes are shown in Figure 1 [29]. These flow sheets can be roughly grouped into four categories: direct Fenton treatment of raw leachate, Fenton pretreatment prior to biological treatment, Fenton treatment preceded by physical/chemical treatment, occasionally followed by bio-

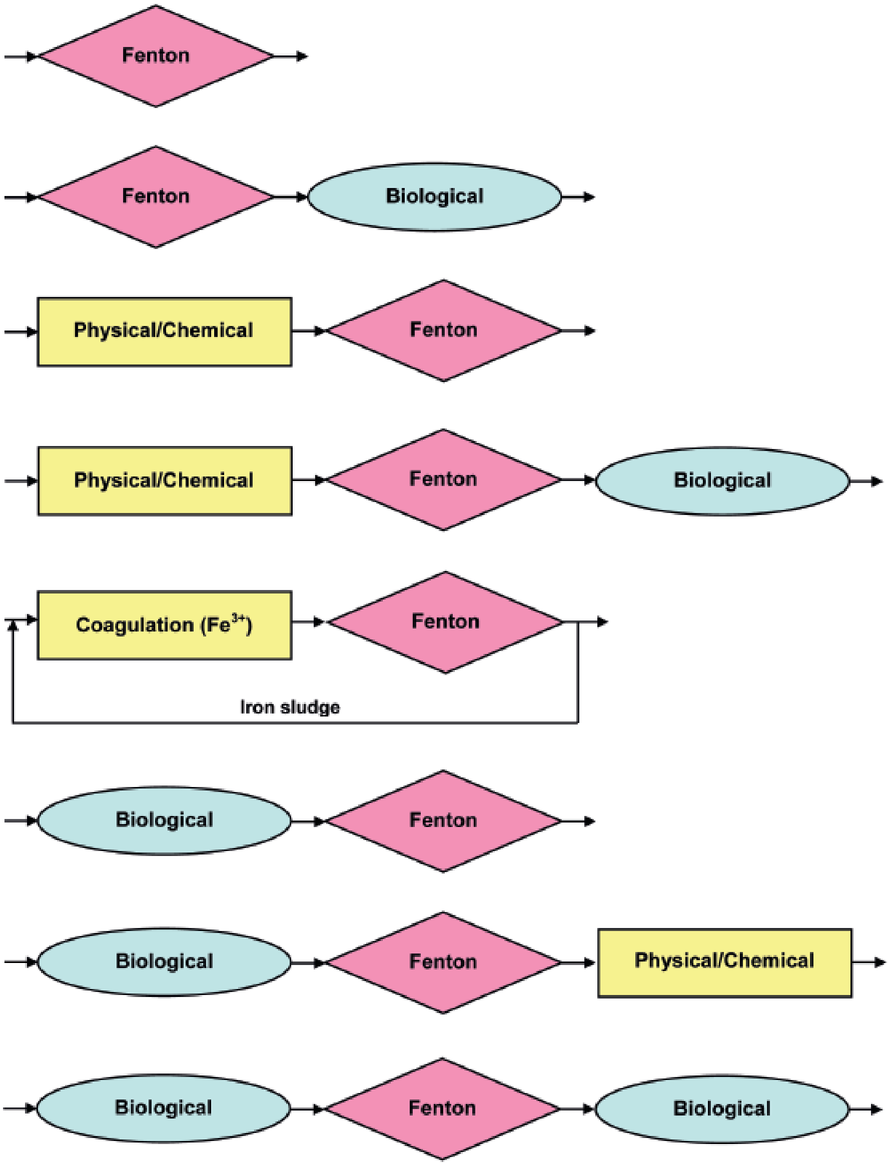

Figure 1.
Flow sheets for Fenton treatment of landfill leachate [29]

logical treatment, and Fenton treatment preceded by biological treatment, occasionally followed by physical/chemical or biological treatment.

In this paper, COD removal efficiency from old municipal landfill leachate has been examined using Fenton oxidation as well as coagulation process. In the Fenton oxidation, the effects of several process conditions such as dosage of H_2O_2, Fe^{2+}/H_2O_2 ratio, pH and reaction time were investigated. Moreover, the effect of different dosages of PIX ($FeClSO_4$) in coagulation process was studied. Additionally, a coagulation process combined with the Fenton oxidation was also used.

2. MATERIALS AND METHODS

Landfill leachate: Leachate was collected from the municipal solid waste landfill in southern Poland. Its characteristics were: dark brown colour, poor clarity, COD in the range from 932 to 1325 mg/L, $BOD_5/COD = 0.2$ and pH 6.7-7.3 (average pH = 7.0). Taking into account the low value of the BOD_5/COD

ratio, this leachate was classified as “old” and non-biodegradable.

Experimental procedure: The Fenton oxidation experiments were performed in ambient temperature in glass reactors with a magnetic stirrer. The following parameters were examined and optimized: H_2O_2 concentration, Fe^{2+}/H_2O_2 weight ratio, pH and time. The procedure was as follows: 0.5 L of leachate was put into reactors of 1-litre volume, and then acidified with H_2SO_4 to the selected value, since a Fenton reagent is effective in acidic pH range. After that, various doses of 30% H_2O_2 and solid $FeSO_4 \cdot 7H_2O$ were added. After appropriate time the leachate was neutralized with 5% solution of NaOH up to about pH 8.5. Then, the samples were centrifuged at 3000 rpm (2.5 min) and analysed.

Coagulation studies were performed in a conventional jar-test apparatus (Flocculator SW1) equipped with 6 beakers of 1 L volume. The experimental procedure consisted of three subsequent stages: the initial rapid mixing lasted 2 min at 120 rpm, the following slow mixing for 30 min at 30 rpm, while the final settling step lasted for another 1 hour. Chemical reagent used as coagulant was PIX 110 ($FeClSO_4$) at pH 5. After the settling period, the supernatants were withdrawn from the beaker and analysed.

In the combined method, experiments were performed using a coagulation process, followed by a Fenton oxidation. The optimal operating parameters, that were determined earlier, were used for each process.

Analytical methods: COD_{Cr} in leachate was determined in accordance with Polish Standard [31], while pH was measured by pH-meter (pH 196, Poland). In the samples of leachates treated by Fenton oxidation, concentration of residual H_2O_2 was analysed by iodometric method before the COD measurement. The presence of H_2O_2 increase the COD value since it acts as a reductant, especially in the chromate based analysis of COD [32, 33]. The initial dark brown colour of raw leachate was not an obstacle in determination of H_2O_2 because, after Fenton process, the leachate was discolouring. However, in no case the presence of residual H_2O_2 was found in leachate after Fenton oxidation and neutralization. Therefore, there was no need to calculate COD as difference between the total COD measured and the COD due to residual H_2O_2.

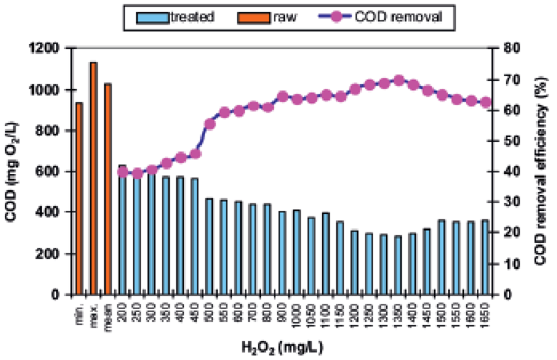

Figure 2.
Effect of the H_2O_2 dosage on the COD removal efficiency (Fe^{2+}/H_2O_2 ratio = 0.3, pH 3, reaction time 90 min.)

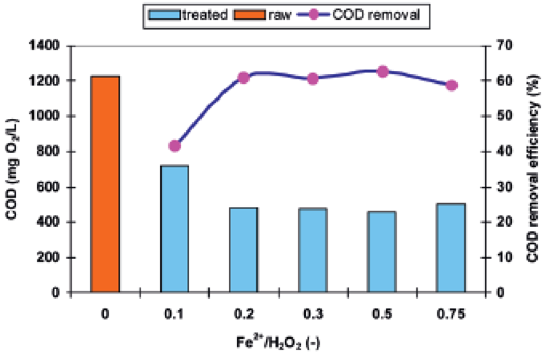

Figure 3.
Effect of the Fe^{2+}/H_2O_2 dosage on the COD removal efficiency (H_2O_2 conc. 1350 mg/L, pH 3, reaction time 120 min.)

3. RESULTS AND DISCUSSION

3.1. Fenton oxidation

Preliminary batch tests were conducted to determine the optimum dose of H_2O_2 (Fig. 2). The COD values were determined after 90 minutes of the Fenton oxidation. The experiments were performed in the wide range of 200-1600 mg H_2O_2/L. As the dosage of H_2O_2 changed from 200 to 1350 mg/L, COD removal efficiency increased from 39.8 to 69.7% (COD value 631 and 282 mg O_2/L respectively). However, above the dose of 1350 mg H_2O_2/L a slight decrease in COD removal was observed. These phenomena could be explained by the excess of hydrogen peroxide concentration, behaving as a hydroxyl radical’s scavenger in the Fenton reaction, according to the following reaction [34]:

$$OH^{\bullet} + H_2O_2 \rightarrow H_2O + HO_2^{\bullet}$$

Therefore, further experiments concerning the optimisation of pH and Fe^{2+}/H_2O_2 ratio were continued at H_2O_2 dose of 1350 mg/L.

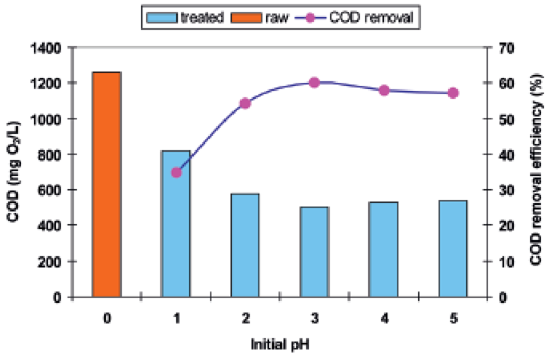

Figure 4.
Effect of the initial pH reaction on the COD removal efficiency (H_2O_2 conc. = 1350 mg/L, Fe^{2+}/H_2O_2 ratio = 0.2, reaction time = 120 min.)

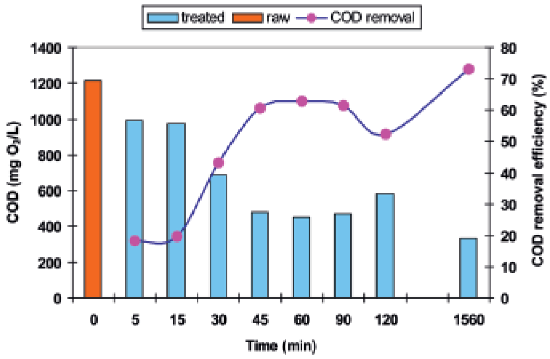

Figure 5.
Effect of the reaction time on the COD removal efficiency (H_2O_2 conc. = 1350 mg/L, Fe^{2+}/H_2O_2 ratio = 0.2, pH 3)

In order to investigate the optimum $FeSO_4$ dosage, five different Fe^{2+}/H_2O_2 ratios were tested using constant H_2O_2 concentration of 1350 mg/L (Fig. 3). The reaction time was extended to 120 min. These results show that with an increase in Fe^{2+}/H_2O_2 ratio in the range of 0.1–0.2 COD removal efficiency significantly increases from 42% to 61%. However, above Fe^{2+}/H_2O_2 ratio of 0.2, only slight changes in COD removal were observed and COD value kept almost the same level about 457-506.2 mg/L. Therefore, Fe^{2+}/H_2O_2 ratio of 0.2 was chosen for further experiments.

Hydrogen peroxide was most stable in the range of pH 3-4, but the decomposition rate was rapidly increased with increasing pH above 5. In a pH reaction higher than 5, the COD removal efficiency by oxidation was rapidly decreased, not only by decomposition of hydrogen peroxide but also by deactivation of a ferrous catalyst with the formation of ferric hydroxo complexes [9, 35]. Therefore, in order to estimate the pH effect on COD removal, the experiments were conducted at pH values varying between 1 and 5. As presented in Figure 4, COD removal efficiency was shown to be maximum (60.1%) around a reaction of pH 3, and it rapidly decreased with decreasing pH below 2. This inhibitory effect could be explained by an observation that excessive hydrogen ions are the dominant $OH^\bullet$ radical scavenger according to the following reaction [22, 34, 36]:

$$OH^\bullet + H^+ + e^- \rightarrow H_2O$$

As the pH changed from 3 to 5, the COD removal efficiency was only slightly decreased from 60.1% to 57.3%.

A very important factor was also the reaction time. Figure 5 shows the changes of COD as a function of reaction time during 26 hours of the Fenton oxidation. The results demonstrated that COD removal efficiency was rapidly increasing within the first 45 minutes of reaction time. Maximum efficiency of COD removal (62.9%) was observed after 60 min. After this time, COD removal was diminished to 61.4% and 52.3% after 90 and 120 min. respectively. These phenomena could be explained by the formation of by-products more resistant to oxidation. Degradation by-products of Fenton's reaction were not identified in this study. When the reaction time was extended up to 26 hours, COD removal efficiency was reached 73.1%, probably as a result of oxidation of these by-products. This supposition is based on the other observations that high efficiency of COD removal from leachates and industrial wastewater (using Fenton reagent or coagulation) was not always followed by significant reduction of their toxicity to an acceptable level [13, 22, 32]. Prolongation of reaction time caused distinct toxicity reduction to low level [32]. However, because between 45 and 60 min., the change of COD became insignificant, 45 minutes' reaction time was chosen as economically accepted in this study.

3.2. Coagulation process

The aim of the coagulation process was to determine possible efficiency of COD removal from landfill leachate. As a coagulant, the PIX 110 ($FeClSO_4$) was used at pH 5, because optimum pH range for PIX is 4.5-5.5. Several coagulant doses were tested without adding any polymers to improve flocculation quality. The results are presented in Figure 6.

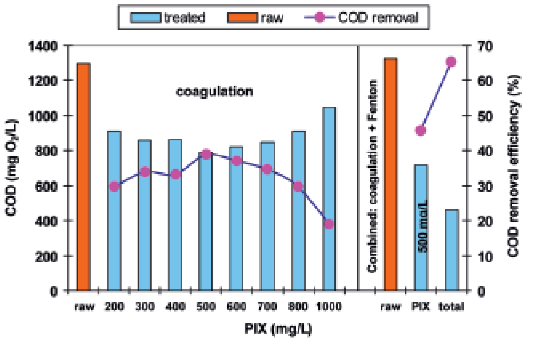

Figure 6.
The effectiveness of COD removal by coagulation (pH 5, reaction time = 30 min.) and combined coagulation–Fenton oxidation system (PIX dose = 500 mg/L, H_2O_2 conc. = 1350 mg/L, Fe^{2+}/H_2O_2 ratio = 0.2, pH 3, reaction time = 45 min.)

With increasing PIX dose, the COD removal efficiency increased gradually, giving a maximum (39%) at 500 mg/L and next decreased beyond this dose. This COD removal decrease (above dose of 500 mg/L) can be explained by the acidic character of PIX. When the dose of PIX was increased, pH decreased continually (pH was not adjusted during coagulation) and thus optimum pH range for coagulant was not maintained. This remains in agreement with the observations by Amokrane *et al.* [7] and Kang and Hwang [9]. According to Amokrane *et al.* [7], also with increasing PIX dose, the dark brown colour of raw leachate turned, after sludge separation, to a clear brown, then to yellow and became clear yellow for the coagulant dose near the optimal value.

On the basis of insufficient efficiency of the COD removal in coagulation process performed alone, it can be stated that for more effective treatment of leachate, the coagulation should be integrated with a Fenton oxidation.

3.3. Fenton oxidation combined with a coagulation process

The combined tests were performed using a coagulation process, followed by a Fenton oxidation. In the coagulation process (1st stage), the PIX dose of 500 mg/L was added at pH 5. These optimal parameters were determined earlier, when coagulation process was carried out alone. In the Fenton oxidation (2nd stage), also earlier determined parameters were used: H_2O_2 dose = 1350 mg/L, Fe^{2+}/H_2O_2 ratio = 0.2, pH 3 and 45 minutes' reaction time.

As presented in Figure 6, COD removal efficiency 45.8% and 19.5% was observed after coagulation and Fenton oxidation process respectively. The overall COD removal efficiency in combined process reached 65.3%. This efficiency was higher than after coagulation and Fenton oxidation performed alone. This relatively little increase in COD removal, observed by Fenton oxidation in the combined treatment system (19.5%) in relation to Fenton oxidation performed alone (61%) was probably because of effective COD removal by the coagulation process. In the presented experiments, the combined methods were performed using the optimal operating parameters that were determined earlier for each process alone. In such combined method, the effectiveness of the first stage is an important parameter that influences the second one and consequently the efficiency of the total process.

4. CONCLUSIONS

The application of coagulation and Fenton oxidation for non-biodegradable, old leachate collected from a sanitary landfill were examined in this study. The optimal operation conditions and results received for particular treatment systems are presented in Table 1. It has been found that organic pollutants in leachate could be successfully removed by Fenton oxidation. The COD removal efficiency reached 61%, using the following optimum operational conditions: H_2O_2 = 1350 mg/L, Fe^{2+}/H_2O_2 ratio = 0.2, initial pH = 3.0 and reaction time = 45 min. When the reaction time was extended up to 26 hours, COD removal efficiency reached 73.1%.

In coagulation process, the addition of PIX coagulant (500 mg/L at pH = 5.0 and reaction time = 30 min.) to landfill leachate resulted only in 39% reduction of COD. Further improvement of the coagulation efficiency could be probably obtained by adding polymers to improve flocculation quality. Applying other coagulants should also be taken into consideration to this effect.

The best results of COD removal (65.3%) were obtained in the combined treatment system including a coagulation process, followed by a Fenton oxidation. In this case, COD removal by coagulation was 45.8% while by Fenton oxidation only 19.5%. Therefore more experiments need to be done towards optimisation of such combined system. It concerns particularly the second treatment stage by Fenton oxidation. In such optimisation process the changes of toxicity should be also taken into consideration.

On the basis of the above results it can be stated that the Fenton oxidation or combined coagulation-Fenton oxidation system are very promising methods for treatment of non-biodegradable landfill leachate. Moreover, the effectiveness of Fenton oxidation and combined coagulation-Fenton system can be probably improved by the stepwise addition of both hydrogen peroxide and ferrous iron.

REFERENCES

[1] *Kang K.H., Shin H.S., Park H.*; Characterization of humic substances present in landfill leachates with different landfill ages and its implications. Wat. Res. Vol.36, No.16, 2002; p.4023-4032

[2] *Wang Z.P., Zhang Z., Lin Y.J., Deng N.S., Tao T., Zhuo K.*; Landfill leachate treatment by a coagulation–photooxidation process. J. Hazardous Mater. Vol.95, No.1/2, 2002; p.153-159

[3] *Mott H.V., Hartz K.E., Yonge D.R.*; Landfill leachates. J. Environ. Eng. Vol.113, No.3, 1987; p.476-485

[4] *Tatsi A.A., Zouboulis A.I., Matis K.A., Samaras P.*; Coagulation-flocculation pre-treatment of sanitary landfill leachates. Chemosphere, Vol.53, 2003; p.737-744

[5] *Silva A.C., Dezotti M., Sant'Anna G.L. Jr.*; Treatment and detoxification of a sanitary landfill leachate. Chemosphere, Vol. 55, 2004; p.207-214

[6] *Lopez A., Pagano M., Volpe A., Di Pinto A.C.*; Fenton's pre-treatment of mature landfill leachate. Chemosphere, Vol. 54, 2004; p.1005-1010

[7] *Amokrane A., Comel C., Veron J.*; Landfill leachates pre-treatment by coagulation flocculation. Wat. Res. Vol. 31, No. 11, 1997; p.2775-2782

[8] *Li X.Z., Zhao Q.L., Hao X.D.*; Ammonium removal from landfill leachate by chemical precipitation. Waste Management, Vol. 19, 1999; p.409-415

[9] *Kang Y.W., Hwang K-Y.*; Effects of reaction conditions on the oxidation efficiency in the Fenton process. Wat. Res. Vol. 34, No. 10, 2000; p.2786–2790

[10] *Medez R., Lema J.M., Blazquez R., Pan M., Forjan C.*; Characterization, digestibility and anaerobic treatment of leachates from old and young landfills. Wat. Sci. Technol. Vol.21, 1989; p.145-155

[11] *Enzminger J.D., Robertson D., Ahlert R.C., Kosson D.S.*; Treatment of landfill leachates. J. Hazardous Mater. Vol.14, 1987; p.83-101

[12] *Lisk D.J.*; Environmental effects of landfill. Sci. Total Environ. Vol.100, 1991; p.415-468

[13] *Wąsowski J., Słomczyńska B., Słomczyński T.*; Technological and toxicological aspects of the coagulation of leachates from municipal solid waste landfill. Archives of Environ. Protection, Vol.32, No.2, 2006; p.41-54

[14] *Morawe B., Ramteke D. S., Vogelpohl A.*; Activated carbon column performance studies of biologically treated landfill leachate. Chem. Engin Process, Vol.34, 1995; p.299-303

[15] *Di Palma L., Ferrantelli P., Merli C., Petrucci E.*; Treatment of industrial landfill leachate by means of evaporation and reverse osmosis. Waste Managm. Vol.22, 2002; p.951-955

[16] *Pieczykolan B., Barbusiński K., Płonka I.*; Preliminary tests of COD removal from landfill leachate using coagulation-flocculation processes. Architecture-Civil Engineering-Environment, Vol.2, No.4, 2009; p.131-136

[17] *Barbusiński K.*; Fenton reaction – controversy concerning the chemistry. Ecological Chemistry and Engineering S., Vol.16, No.S3, 2009; p.347-358

[18] *Zhang H., Choi H.J., Huang C.-P.*; Optimization of Fenton process for the treatment of landfill leachate. J. Hazardous Mater. Vol. B125, 2005; p.166-174

[19] *Bidga R.J.*; Fenton's chemistry: an effective advanced oxidation process. Environ. Technol. Vol.17, 1996; p.34-39

[20] *Rivas F.J., Beltran F., Gimeno O., Carvalho F.*; Fenton-like oxidation of landfill leachate. J. Environ. Sci. Health, Vol.A38, No.2, 2003; p.371-379

[21] *Barbusiński K., Filipek K.*; Use of Fenton's reagent for removal of pesticides from industrial wastewater. Polish J. Environ. Stud. Vol.10, No.4, 2001; p.207-212

[22] *Barbusiński K.*; Coke plant wastewater treatment by Fenton reagent. Archives of Environ. Protection, Vol.32, No.3, 2006; p.21-28

[23] *Barbusiński K.*; Intensyfikacja procesu oczyszczania ścieków i stabilizacji osadów nadmiernych z wykorzystaniem odczynnika Fentona (Using Fenton's reagent for intensification wastewater treatment and activated sludge stabilisation). Monografia Inżynieria Środowiska z. 50, Wydawnictwo Politechniki Śląskiej, Gliwice, 2004 (in Polish)

[24] *Casero I., Sicilia D., Rubio S., Pérez-Bendito D.*; Chemical degradation of aromatic amines by Fenton's reagent. Wat. Res. Vol.31, 1997; p.1985-1995

[25] *Huston P.L., Pignatello J.J.*; Degradation of selected pesticide active ingredients and commercial formulations in water by the photo-assisted Fenton reaction. Wat. Res. Vol.33, 1999; p.1238-1246

[26] *Kitis M., Adams C.D., Daigger G.T.*; The effects of Fenton's reagent pretreatment on the biodegradability of nonionic surfactants. Wat. Res. Vol.33, 1999; p.2561-2568

[27] B*arbusiński K.*; The full-scale treatment plant for decolourisation of dye wastewater. Architecture-Civil Engineering-Environment, Vol.2, No.2, 2009; p.89-94

[28] *Lin S.H., Lin C.M., Leu H.G.*; Operating characteristics and kinetic studies of surfactant wastewater treatment by Fenton oxidation. Wat. Res. Vol.33, 1999; p.1735-1741

[29] *Deng Y., Englehardt J.D.*; Treatment of landfill leachate by the Fenton process. Wat. Res. Vol.40, 2006; p.3683-3694

[30] *Neyens E., Baeyens J.*; A review of classic Fenton's peroxidation as an advanced oxidation technique. J. Hazardous Mater. Vol.98, No.1-3, 2003; p.33-50

[31] Polish Standard PN-74/C-04578

[32] *Barbusiński K.*; Toxicity of industrial wastewater treated by Fenton's reagent. Polish J. Environ. Stud. Vol.14, No.1, 2005; p.11-16

[33] *Kang Y.W., Cho M.-J., Hwang K.-Y.*; Correction of hydrogen peroxide interference on standard chemical oxygen demand test. Wat. Res. Vol.33, No.5, 1999; p.1247-1251

[34] *Tang W.Z., Huang C.P.*; 2.4-dichlorophenol oxidation kinetics by Fenton's reagent. Environ. Technol. Vol.17, 1996; p.1371-1378

[35] *Bidga R.J.*; Consider Fenton chemistry for wastewater treatment. Chem. Engineering Progress, Vol.91, No.12, 1995; p.62-66

[36] *Barbusiński K., Majewski J.*: Discoloration of azo dye Acid Red 18 by Fenton reagent in the presence of iron powder. Polish J. Environ. Stud. Vol.12, No.2, 2003; p.151-155