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Application of fly ash for flouride adsorption

ABSTRACT

The suitable characteristics of fly ash from thermal power plants make it a proper adsorbent for removing various pollutants from water and aqueous solutions. Valorization and utilization of fly ash can reduce the use of conventional adsorbents. The paper presents an overview of the possibility of using raw and modified fly ash to remove fluorides from water and aqueous solutions, as well as the influence of different process parameters (sorbent dose, contact time, pH value, temperature, etc.) on the value of adsorption capacity and adsorption efficiency of used sorbent. Fly ash can be used as an effective sorbent for the removal of fluoride, both in raw and modified form, with given optimal process parameters. Raw fly ash shows better adsorption properties when performing the experiment in a column, with a higher dose of sorbent and longer contact time, in an acidic environment (pH = 2-3), compared to batch experiments. Various authors have modified fly ash by treatment with certain chemical agents (HCl, Ca $(OH)_2$*…) or by synthesis of zeolite based on fly ash. Modification of fly ash improves its adsorption properties, so in slightly acidic conditions (pH = 6), for a relatively short contact time (10-30 min), in batch conditions, significant adsorption efficiency (~90%) can be achieved.*

Keywords: *fly ash, adsorption, fluorides, wastewater.*

1. INTRODUCTION

Due to the rapid industrialization and the increase in the global population, water resources are being contaminated. Pollutants in water are often very harmful for living organisms, furthermore, they affect the entire ecosystem, so their removal and reduction of concentrations within the legal limit values is necessary.

The content of dissolved or suspended matter in untreated water can affect its use. Numerous chemical elements and compounds are essential for the growth of living organisms. Their presence in drinking water in minor concentrations does not pose a risk to human health. Concerning that fact, fluorides are a good example. For instance, water with high fluoride concentration is not suitable for drinking, while low concentrations are advisable in drinking water. According to the World Health Organization the maximum allowable concentration of fluoride in drinking water is 1.5 mg/L [1]. The World Health Organization has classified fluoride as a contaminant, which can contribute to a wide range of health issues [2]. According to the US Environmental Protection Agency, the maximum allowable concentrations of fluorides in drinking water are slightly higher and amounts of 2 mg/L (for the prevention of enamel fluorosis) and 4 mg/L (for the prevention of skeletal fluorosis) [3]. The presence of fluoride in water is very important for protecting teeth from caries and bone strengthening, but higher levels can have detrimental effects on health. High fluoride content in water can lead to several health problems such as damage of the tooth and the bone structure (dental and skeletal fluorosis), various neurological complications, and cancers [4-6].

Anthropogenic activities are the dominant source of fluoride in the environment, although the geological distribution of fluorine-containing minerals is also significant [7]. The most important natural sources of fluoride are fluorite, fluorapatite, and cryolite minerals, while anthropogenic sources include untreated wastewater and improper disposal of industrial waste.

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Fly ash is industrial waste from the combustion of coal in thermal power plants and other industrial furnaces. It consists of fine abrasive particles of unburned coal compounds that flue gasses carry from the furnace. Inadequate disposal of fly ash or direct release into the air can cause multiple environmental problems. To prevent the release of particles into the atmosphere, they are separated from the flue gasses by electrostatic precipitators [8]. To reduce the costs of its disposal and the negative impact of fly ash on the environment, numerous studies on the possibilities of its use have been conducted [9]. Since fly ash is considered as useful by-product, its market has been growing, especially in the construction industry, as a substitute for the original materials. The estimations of growth are from USD 3.4 billion in 2018 to USD 4.5 billion by 2023, at a Compound annual growth rate (CAGR) of 6.0% [10]. During the other forecasting period, from 2016-2026, the fly ash market is estimated to register CAGR of 4% [11]. The CAGR of 5.83% is estimated for the period of 2019-2027 [12]. As a dominant market region, Asia Pacific region is growing with a fastest CAGR, followed by North America.

Numerous studies have shown that fly ash, due to its chemical and mineral composition and high porosity, can be successfully used as a "low-cost" adsorbent for the removal of various types of organic and inorganic pollutants from aquatic systems [9,13]. The adsorption capacity of fly ash may increase after physical and/or chemical treatment (modification).

The paper presents an overview of research on the possibility of using raw (original) or activated fly ash in the adsorption of fluoride from water. The obtained results are compared, and the process conditions and main characteristics of the used materials are shown. This paper aims to offer a starting point for further research, which can be focused on the upgrading of achieved results so far in the investigation of the use of fly ash in water treatment.

2. FLUORIDE IN WATER

Fluorine is a very reactive element. It mainly occurs in the form of various compounds. Fluorine compounds can be in solid, liquid, and gaseous forms, and occur as organic and inorganic substances [14].

Fluorides are present in all aquatic ambients in concentrations ranging from minimum (mg/L, µg/L, trace amounts) to those exceeding the maximum limit values. In some African and Asian countries, such as Pakistan, Thailand, and Sri Lanka, over 60% of the population is exposed to very high concentrations of fluoride in drinking water [15, 16]. To ensure the quality of the recipients, because of the excessive fluoride concentration in wastewater there is a need for defluoridation [9].

The fluoride content in groundwater can be the result of the movement of water within the soil, dissolving minerals present in the rocks, but also of anthropogenic origin. High fluoride concentration in the surface water is mainly the result of anthropogenic activities, such as the discharge of untreated wastewater into the environment and improper disposal of various industrial wastes [17, 18]. Fluorides have a very wide application in the industry. They are used in the production of aluminum, refrigeration techniques, plastics, dental hygiene products, herbicides, pesticides, metallurgy, etc. High fluoride content can be found in wastewater generated in coal power plants, fluorine production, semiconductor industry, glass and ceramics industry, electroplating processes, rubber production, phosphate fertilizer production, and aluminum smelters. The concentration of fluoride in industrial wastewater is generally higher compared to natural water and ranges from tens to thousands of mg/L [19].

Intake of fluoride in low concentrations, from 0.5 to 1mg/L has a positive effect on human health [20, 21]. Adding fluoride to the water supply system to improve the dental health of the population is a practice supported by many international organizations and institutions. However, in addition to the benefits of fluoride intake, when it comes to high fluoride concentrations negative effects on human health have been found [22].

Fluorides belong to a very reactive group of compounds, which are quickly absorbed from the digestive system and have the ability of bioaccumulation and long-term deposition in teeth and bones. Fluorides can cause numerous acute and chronic diseases. The most common acute health problems caused by fluoride poisoning are abdominal pain, diarrhea, vomiting, sweating, limb pain, etc.; while chronic health problems range from aesthetic such as changes in teeth and bones, to development of mental disabilities, and even death. Some of the most common diseases caused by excessive fluoride intake are weight loss, dental and skeletal fluorosis, osteoporosis (bone fractures), arthritis, hypocalcemia (low calcium in the blood), hyperkalemia (excess potassium in the blood) which will affect the spine, brain damage and soft tissue damage, dysfunction of the nervous system and thyroid gland. Excessive fluoride intake can lead to cancer, neurological and cerebrovascular effects, and other diseases [7, 23, 24].

2.1. Technologies for removing fluoride from water

One of the main challenges in fluoride removal from water is to develop an efficient, and "low cost" method. Defluoridation techniques, in general, can be divided into 2 groups: (a) membrane methods and (b) surface adsorption techniques. The most commonly used membrane methods are: reverse osmosis and electrodialysis. Adsorption techniques include adsorption on different materials [25].

Adsorption is a very common method for defluoridation of water [26]. According to the chemical and mineral composition, adsorbents can be based on oxides and oxy-hydroxides of aluminum, calcium, iron (Fe), and other metal oxides, carbon, natural, and biomaterials (biosorbents), agricultural waste, construction residues, nanomaterials, as well as industrial waste materials. Different types of sorbents were tested for fluoride removal, such as alumina, bauxite, red mud, fly ash, clay, and activated carbon [5, 25].

For the removal of fluoride from wastewater, mainly used methods are divided into two groups: (a) precipitation methods, based on the addition of chemicals to water, and (b) adsorption methods, where fluoride is removed by adsorption or ion exchange reaction on a suitable substrate capable of regeneration and reuse. Conventional methods for fluoride removal (membrane filtration, coagulation, chemical precipitation) have many disadvantages in terms of required time, environmental impact, as well as energy consumption. Coagulation and precipitation produce huge amounts of sludge, and membrane filtration methods are high-cost [21]. The adsorption process is increasingly attracting attention due to the simplicity of its use, the suitability of adsorption materials, and economical application costs [27].

3. FLY ASH PROPERTIES

Fly ash is a residue from the combustion of coal in thermal power plants and blast furnaces. It consists of fine particles that may contain heavy metals and, therefore, is classified as hazardous waste [28].

Fly ash particles mostly come from unburned mineral components (silt and clay) found in coal deposits. After exposure to high temperatures, silt, and clay (mainly consisting of silicon dioxide and alumina) are melted and combined to form amorphous micron-sized spherical particles based on Si-Al (SiO_2 and Al_2O_3) carried by the flue gas stream. Other elements can condense on these amorphous particles [29]. As the fly ash particles move away from the boiler in the gas stream, the molten aluminosilicate spheres are cooled and solidified, trapping many elements within the cooled matrix and also serving as a solid surface for adsorption of other suspended particles. Usually, these amorphous spheres include Ca, Na, Fe, Mg, K, and Ti, with minor quantities of other elements sorbed on its surface, such as As, B, Ba, Cd, Cr, Cu, F, Mo, Ni, Pb, S, and Zn. The typical empirical composition of fly ash is: 10Si + 5Al + 0.5Ca + 0.5Na + 0.4Fe + 0.2Mg + 0.2K + 0.1Ti + 0.05S + more than 15 other elements in traces [30, 31]. Elements within a spherical matrix are relatively insoluble when melted in a matrix, while surface-bound compounds are often in the form of soluble salts that can be easily washed off the surface.

Based on the chemical composition of fly ash (the result of coal combustion), there are class F and class C [32]. Also, the characteristics of fly ash depend on the type of used equipment. The concentrations of major and minor elements in the ash vary depending on the coal origin. Some physical and chemical characteristics of fly ash are shown in Table 1.

Table 1. Characteristics of fly ash [33, 34, 35, 36, 37]

Tabela 1. Karakteristike letećeg pepela [33, 34, 35, 36, 37]

Constituent	Class F		Class C	
	Range	Typical	Range	Typical
SiO_2 (%)	38-65.43	54.9	20.09-40.36	39.9
Al_2O_3 (%)	17.74-29.45	25.8	16.91-21.76	16.7
CaO (%)	0.2-9.31	8.7	12.65-27.66	24.3
Fe_2O_3 (%)	3.3-25.29	6.9	3.4-10.11	5.8
SO_3 (%)	0.21-3.07	0.6	0.86-3.5	3.3
Loss on ignition (LOI) (%)	0.2-3.4	2.8	0.17-0.90	0.5
Specific surface area (cm^2/g)	13012-5770	-	11963-19646	-

4. QUANTITIES AND DISPOSAL

At the end of the 20th century, the annual emission of fly ash from coal was estimated at 500 million tons, which was about 75-80% of the total ash produced [38]. The growing demand for energy around the world has led to an increase in the use of coal, and thus to the production of large amounts of fly ash. The major producers of fly ash are India, China, America, and Germany. Data for the European Union (EU15) members show that only in 2016 about 40 million tons of ash were generated from coal combustion, and the largest share in production has fly ash (63.8%) [39].

Such large amounts of fly ash must be stored either in tanks or in landfills and lagoons, which requires high costs and becomes a serious environmental problem. Disposal of fly ash on the ground, in addition to the demand for large areas, poses a danger due to the leaching of heavy metals and the spread of particles by the wind which can cause environmental pollution. Due to the negative impact on the environment and human health, efforts are being made to reduce its disposal, through its valorization. For that reason, researchers are trying to find new possibilities for the use of this waste material.

5. USE OF FLY ASH

Until recently fly ash was treated as waste and a source of air and water pollution. Nevertheless, fly ash is a resource material that has proven its advantages. There are various options for using fly ash. In general, it can be used in the following ways [9,13]:

- In the production of construction materials and as a construction material,
- As a material for the synthesis of zeolite,
- As a soil amendment,
- As a backfill material for underground mining,
- As a sorbent for flue gas pollutants,
- As a sorbent for water pollutants.

At the end of the 20th century, the worldwide use of fly ash ranged from a minimum of 3% to a maximum of 57%, and the average use was only 16% of total produced fly ash [38]. Today, about 60% of the total amount of generated fly ash is used for various purposes [40]. Within the European Union, the total amount of fly ash used in 2016 was about 11.4 million tons [39]. Considerable amounts of fly ash have been used in the construction material industry, primarily in the production of portland cement and concrete, and the construction of roads and embankments [28,29,41]. The use of fly ash in the construction industry accounts for about 40% of its total annual emissions, and the backfilling of mine stopes at about 35% [34].

5.1. Application of fly ash in water treatment

In addition to the possibilities of commercial use, fly ash due to its chemical and physical properties finds potential application in the treatment of various pollutants from wastewater. The main components that contribute to its adsorption capacity are alumina, silicon dioxide, iron oxide, calcium oxide, magnesium oxide, and carbon. Significant physical properties of fly ash are porosity, particle distribution, and specific surface area. Also, the alkaline nature of fly ash makes it a good neutralizing agent. Numerous studies have been conducted to investigate the use of fly ash for the adsorption of various pollutants from aqueous solutions. Fly ash is a suitable adsorbent for pollutants in wastewater and drinking water. Depending on its composition and characteristics, it can be subjected to a certain pre-treatment before application to increase its sorption capacity [9, 13, 33, 42].

In wastewater treatment, fly ash can be effectively used to reduce the values of parameters such as pH, total organic carbon (TOC), total suspended particles (TSS), and total dissolved particles (TDS), due to its high porosity and adsorption capacity [42]. Some studies show the successful use of fly ash in the treatment of wastewater from the dye and pigment industry [43], as well as domestic wastewater [44]. Fly ash can be used to remove heavy metals from water, such as Cu, Pb, Zn, Mn, Cd, Cr, and Ni [9, 45]. Apart from that, fly ash can be used in the adsorption of organic and inorganic pollutants from wastewater, including phosphorus, fluoride, boron, phenols, pesticides, and other compounds [9, 46].

6. APPLICATION OF FLY ASH BASED ADSORBENTS FOR FLUORIDE ADSORPTION

Various types of industrial by-products and wastes have been tested as adsorbents for fluoride removal from water, including fly ash. Raw and modified fly ash used for fluoride adsorption is the subject of numerous studies. For such purpose, solutions of different initial fluoride concentrations were used. A summary of the process conditions, achieved adsorption capacity (or efficiency), and type of adsorption is given in Table 2.

At the end of the last century, Chaturvedi et al. investigated the use of fly ash to remove fluoride from wastewater in batch conditions, depending on the concentration, contact time, temperature, and pH value of the solution. They showed that the removal of fluoride has better efficiency with low initial fluoride concentrations, at high temperatures, and in acidic conditions. The initial fluoride concentration has a significant impact on process efficiency. In this case, the Langmuir isotherm better describes the adsorption process [33].

Table 2. Summary of the optimal process parameters in the adsorption of fluoride from water and aqueous solutions using different adsorbents based on fly ash

Tabela 2. Pregled optimalnih parametara procesa adsorpcije flourida iz vode i vodenih rastvora korištenjem različitih adsorbenasa na bazi letećeg pepela

Adsorbent	Column and/or batch testing	t (℃)	Initial concentration of fluoride ions	pH	Contact time	Adsorbent dose	Adsorption capacity (qmax)	Efficiency (%)	Adsorption isotherm	Order of reaction	Ref.
Fly ash, sieved	batch	50 ℃	15 mg/L	6.5	120 min	10 g/L	23.33 mg/g	~94 %	Langmuir	FO	[33]
Fly ash	column (400x45 mm)	20 ℃	0-100 mg/L	-	120 h	450 g	-	100 %	-	-	[47]
Fly ash	batch	room temp.	10 mg/L	2-3	120 min	-	-	~80 %	Freundlich	-	[48]
Zeolite NaP1 based on FA	batch	room temp.	<7 mg/L	6	10-20 min	10 g/L	-	92.27%	Langmuir	-	[49]
FA modified with Mg	batch	45 ℃	100 mg/L	3	60 min	2.5 g/L	6 mg/g	-	Langmuir	PSO	[50]
FA treated with CaOH	batch	50 ℃	10 mg/L	7	120 min	3 g/L	10.86 mg/g	> 80%	Langmuir	PSO	[51]
Fly ash modified with HCl	batch	31±5 ℃	5 mg/L	2.5	30 min	0.5 g/L	-	82.0 %	-	-	[52]
FA zeolite	batch	-	5 mg/L	6	30 min	0.024 g/L	-	~90 %	Langmuir	-	[53]
Fly ash, sieved	batch	30 ℃	5 mg/L	2	180 min	2.5 g/L	5.70 mg/g	-	Langmuir	PSO	[54]
Cenosphere FA - modif. with lime mude	batch	27 ℃	11 mg/L	5	-	1.9 g/L	7.37 mg/g	~90 %	Langmuir	PSO	[55]
Fly ash	batch	-	50 mg/L	5	4h	5 g/L	-	67.2 %	Freundlich	PSO	[56]

FA zeolite	batch	25 ℃	50 mg/L	5.5-6.5	2h	≥12.5 g/L	18.12 mg/g	~100 %	Langmuir	PSO	[57]
NaOH/Fe-MFA FA-modif.	batch	-	-	2	2 h	2 g/L	18.6 mg/g	92 %	Langmuir	PSO	[58]

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Recent research has confirmed the fact that in batch conditions, the adsorption of fluoride from aqueous solutions using fly ash is highly affected by the acidic environment [54, 56]. Chakraborty et al. achieved maximum adsorption capacity under strongly acidic conditions, lower initial fluoride concentrations (5 mg/L), and higher temperatures. They showed good correspondence of process with Langmuir's isotherm model and pseudo-second-order for kinetics [54]. Chandraker et al achieved optimal conditions for fluoride removal in a slightly acidic environment and with a high initial fluoride concentration (50 mg/L). The adsorption corresponded to Freundlich's isotherm model and pseudo-second-order kinetics [56].

The acidic conditions and increase of the contact time were suitable for the removal of fluoide using fly ash in batch conditions. It was shown by Nemade and the authors, and the process fitted well with Freundlich's isotherm model [48].

Experiments conducted in columns filled with fly ash have shown that the adsorption efficiency of fluoride ions is higher with high initial fluoride concentrations [47].

Various methods for modification of fly ash can improve its sorption properties. Some of these modifications include the synthesis of zeolite from fly ash or modification of its structure with chemical treatment.

Investigation of the adsorption characteristics of zeolite NaP1 synthesized from fly ash for removal of fluoride from water found that the initial concentration and the contact time have a major impact. The best efficiency was achieved at a fluoride concentration of 7 mg/L and a contact time of 20 minutes. Adsorption on NaP1 zeolite corresponds to Langmuir's model [49]. Panda and Kar have confirmed the efficient use of synthetic zeolite based on fly ash in the sorption of fluoride from water. Synthesized zeolite showed better adsorption characteristics than the original unmodified fly ash [53]. Chen et al. showed that fly ash based zeolite (AHZ - aluminum hydroxide loaded zeolite) shows good selectivity for fluoride adsorption in the presence of competitive ions. The adsorption reaction corresponds to the Langmuir model and the kinetics of the pseudo-second-order. Aluminum hydroxide is the main component that contributes to fluoride adsorption [57].

Langmuir's model proved to be suitable for the adsorption of fluoride from aqueous solutions using fly ash loaded with magnesium, and the kinetics corresponded to the pseudo-second-order reaction. The modified fly ash proved to be an effective fluoride adsorbent under acidic conditions, and the maximum adsorption was obtained at pH 3. Coexistent ions had a significant influence on the removal of fluoride [50]. The high sorption efficiency (82%) of fluoride from an acidic medium (pH 2.5) was also confirmed with chemically treated fly ash. The chemical treatment was based on the modification of fly ash with hydrochloric acid [52].

Calcium hydroxide-modified fly ash is an effective adsorbent for removing fluoride from neutral aqueous solutions. Maximum removal efficiency (> 80%) was observed at pH 7. Removal efficiency increased with increasing temperature indicating process spontaneity and endothermic response. The adsorption equilibrium is fitted better with the Langmuir isotherm. Equilibrium data show that monolayer adsorption corresponds to the pseudo-second-order model [51].

Fly ash modified with lime mud from the paper pulp was characterized by a microporous structure with a large specific surface area and high calcium content. The influence of process parameters on the removal of fluoride from aqueous solutions is as follows: pH > adsorbent dose > F^- concentration > temperature. The highest efficiency was achieved in a slightly acidic environment (pH 5) and a temperature of 27.0°C. Adsorption of fluoride shows the reaction correspondence with pseudo-second-order and Langmuir’s isotherm model, which indicates chemisorption and monolayer adsorption [55].

Modification of raw fly ash with NaOH and $FeCl_3$ gave a high-efficiency sorbent (around 92%) for the adsorption of fluorides from synthetic aqueous solutions. The maximum adsorption capacity was achieved in a very acidic environment (pH = 2). The adsorption of fluorides, under the given conditions, corresponded to the Langmuir model of the isotherm, and the kinetics of chemisorption corresponded to the model of the pseudo-second-order [58].

Generally, an acidic medium is suitable for the adsorption of fluoride on fly ash. In acidic conditions, the surface of the adsorbent is highly protonated and has a higher affinity for negatively charged ions due to the stronger attractive force between the positively charged surface and the negatively charged fluoride ions [50, 52].

7. CONCLUSIONS

In waste management, before the final disposal, it is beneficial to include the valorization of the waste materials. To remove various pollutants from water and aqueous solutions, more industrial products, such as fly ash, are being investigated as adsorbents.

Various authors have investigated the possibility of adsorption of flourides from water and aqueous solutions using fly ash, in unmodified and modified form. Process parameters such as pH value, temperature, contact time, sorbent dose, and others were varied to determine the optimal conditions for performing the adsorption process on a particular adsorbent. Based on the presented results of the authors, it can be noticed that in most cases the adsorption of flourides corresponds to the Langmuir model of the isotherm, which indicates the development of monolayer chemisorption. The adsorption kinetics using different fly ash based adsorbents mainly followed the pseudo-second order model. In addition to the influence of process parameter values, the adsorption efficiency and the adsorption capacity differed depending on whether unmodified or modified fly ash was used. The highest efficiency of flouride adsorption (100%) was achieved in experiments performed on raw (original) fly ash in a column at a high dose of adsorbent (450 g) and a longer contact time (120 hours). Unmodified fly ash achieved better efficiency of adsorption of flourides from water and aqueous solutions (~80%) in acidic medium (pH = 2 - 3) in batch conditions, at a contact time of 120 min. Modification of fly ash improves the adsorption characteristics of fly ash, whereby a significant adsorption efficiency (~90%) is achieved in a slightly acidic conditions (pH = 6) with a shorter contact time (10 - 30 min) in batch conditions than with raw fly ash.

Based on the review of literature references presented in the paper, it can be concluded that fly ash is a suitable and efficient adsorbent for removing fluoride from water and aqueous solutions, both in raw and modified form, in acidic and slightly acidic conditions.

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IZVOD

UPOTREBA LETEĆEG PEPELA ZA ADSORPCIJU FLOURIDA

Odgovarajuće karakteristike letećeg pepela iz termoelektrana čine ga pogodnim adsorbensom za uklanjanje različitih polutanata iz vode i vodenih rastvora. Njegovom valorizacijom i iskorištenjem može se smanjiti upotreba konvencionalnih adsorbenasa. U radu je predstavljen pregled mogućnosti upotrebe sirovog i modifikovanog letećeg pepela za uklanjanje fluorida iz vode i vodenih rastvora, kao i uticaj različitih procesnih parametara (doza sorbenta, kontaktno vrijeme, pH vrijednost, temperatura i drugi) na vrijednost adsorpcionog kapaciteta i efikasnosti adsorpcije korištenog sorbenta. Leteći pepeo se može koristiti kao efikasan sorbent za uklanjanje fluorida, i u sirovom i u modifikovanom obliku, pri određenim optimalnim parametrima procesa. Sirovi leteći pepeo pokazuje bolja adsorpciona svojstva pri izvođenju eksperimenta u koloni nego pri šaržnim uslovima, pri upotrebi veće doze sorbenta i dužem vremenu kontakta, u kiseloj sredini (pH = 2-3). Različiti autori su modifikovali leteći pepeo tretmanom određenim hemijskim sredstvima (HCl, $Ca(OH)_2$…) ili sintezom zeolita na bazi letećeg pepela. Modifikacijom letećeg pepela se poboljšavaju njegova adsorpciona svojstva, tako da se u slabo kiseloj sredini (pH = 6), za relativno kratko kontaktno vrijeme (10-30 min), u šaržnim uslovima, postiže značajna efikasnost adsorpcije (~90%).

***Ključne riječi**: leteći pepeo, adsorpcija, fluoridi, otpadna voda.*

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