Chromium-containing wastewater treatment by means of using galvanocoagulators

Andrey Busarev¹[0000-0002-7063-2519], Runar Abitov¹[0000-0001-6138-6419] and Aleksandr Selyugin¹[0000-0003-2427-3698]

¹Kazan State University of Architecture and Engineering, Kazan, Russia
E-mail: kgasu.viv@gmail.com

Abstract. In this study, a galvanocoagulator was used for the treatment of chromium-containing wastewater. Its principle of operation is based on the use of processes for reducing Cr(VI) ions to the Cr(III) state using a galvanic pair "copper – iron" without applying an external electric field. In this case, the reduction of hexavalent chromium ions to trivalent occurs due to the oxidation of iron ions, which, when dissolved, pass into the solution. To speed up the process of iron dissolution, compressed air is supplied to the galvanocoagulator. The conversion of Cr(VI) and Cr(III) into insoluble compounds is performed by adding alkali solutions. The resulting suspension is removed from the water by settling and filtering methods. As a result of research, the possibility of effective treatment of chromium-containing wastewater using the method of galvanocoagulation was established; the technological parameters of the galvanocoagulator were determined. The hydraulic size of the suspension formed after processing of chromium-containing effluents in a galvanocoagulator is determined, which allows designing treatment facilities for the removal of heavy metal hydroxides by settling.

Keywords: wastewater, hexavalent chromium, treatment facilities, galvanocoagulator, research, hydraulic size of the suspensions.

1 Introduction
In the process of galvanic production, chromium-containing wastewater is formed, containing hexavalent chromium and trivalent chromium ions, as well as trivalent iron ions. In addition, strong mineral acids are present in chromium-containing wastewater. As a result, an active reaction of the wastewater medium is 2.5–5. Chromium-containing wastewater negatively affects living organisms: in addition to the general toxicity of heavy metals, hexavalent chromium can be a chemical mutagen. Chemical, physicochemical, biological and mechanical treatment methods are used for treatment of chromium-containing effluents.

When their consumption is up to 100 cubic meters/day, chemical reduction of hexavalent chromium ions is used. To do this, chromium-containing effluents are treated with solutions of bisulphite or sodium sulphite, iron vitriol.

Adsorption is a widely used method for removing Cr(VI) ions from water. A promising direction is the use of sorbents from various natural materials for this purpose. In the work [1], as a sorbent for removing Cr(VI)ions from water, a microalgae carbon was studied, which showed a high efficiency of removing hexavalent chromium. The authors of the work [2] used particles of cerium-doped iron oxides to remove Cr(VI) ions from water. The process allowed to obtain iron oxides from a wide surface area and certain textural characteristics, and increased the ability to remove chromium from aqueous solutions using a mechanism combining adsorption and photoreduction of Cr(VI). Work [3] is devoted to the study of peat as a sorbent for removing hexavalent chromium from water. The peat was modified by adding sulfuric acid. It was found that an increase in temperature leads to a better sorption capacity, and an increase in pH leads to a decrease in it. In the work [4], a new multilayer nanocomposite consisting of graphene oxide nanowires, manganese dioxide, iron oxide nanoparticles, and polypyrrole was used to remove hexavalent chromium ions from the water. It was used by the
adsorption-reduction method. Research has shown the high potential of a new composite. In studies [5], a composite obtained by modifying the crystalline phases of iron oxides together with chitosan was used as a sorbent. This composite has shown quite high efficiency. The aim of the research [6] was to select an inexpensive biosorbent for water purification from Cr(VI) ions. This sorbent was obtained by carbonizing a mixture of wheat straw and the Eupatorium adenophorum plant. The effect of pH, contact time, sorbent dosage and water temperature on the efficiency of hexavalent chromium removal at pH 1, which was 99.9 %, was studied. The authors of the work [7] used gooseberry seeds (Phyllanthus acidus) as a biosorbent for removing Cr(VI) ions from the water. This biosorbent performed well at pH 2 and 60 minutes contact time with water.

In the work [8], a new method for modifying the phyllostachys pubescens powder, which was treated with copper sulfide, was proposed. The resulting composite showed excellent efficiency in removing Cr(VI) and Cr(III) ions from water. Analysis of the adsorption mechanism showed that the main purification mechanism for Cr(III) is ion exchange, and for Cr(VI) is oxidation-reduction.

In studies [9], microporous activated carbon prepared from almond shell powder and activated with orthophosphoric acid was used to remove Cr(VI). It was found that the removal of Cr(VI) is 100 % at an initial pH of 2. In the work [10], a magnetically modified nanocomposite material graphene oxide/chitosan/ferrite (GCF) was synthesized and used to remove Cr(VI) from an aqueous solution. It can be used as a suitable adsorbent for removing hexavalent chromium from wastewater. The authors of [11] investigated the adsorption removal of hexavalent chromium from an aqueous solution using natural zeolite, clinoptilolite, in the form of a hollow fibrous ceramic membrane. The sample of it was produced by extrusion based on phase inversion followed by sintering. It was found that this material had potential as a single-stage removal of Cr(VI) by membrane adsorption for wastewater treatment. In the work [12] the authors synthesized a new form of aniline-formaldehyde condensate polymer carrier, which reduces residual hexavalent chromium concentration less than 1 mg/L dose of polymer 2 g/L; the maximum removal of total chromium was observed in the pH range 3–8.

In the study [13], activated carbon was obtained from commercial sources using potassium hydroxide as an activator. It showed a higher adsorption capacity and better regeneration rates when removing chromium, and could be used as a promising adsorbent for its removal from wastewater. The authors of [14] studied the removal of Cr(VI) from an aqueous solution using modified natural bentonite as a cheap material based on it. Natural bentonite was modified by a two-stage modification, activation by acid followed by iron pillariization.

When cleaning chrome-containing effluents by ion exchange, they are first fed to anionite filters, and then fed to H–cationite filters. When ionite is regenerated, flushing effluents are formed with a low pH and high content of chromium and iron ions, which are very difficult to dispose of.

During biological treatment of chromium-containing effluents, Cr(VI) is restored to the Cr(III) state in bioreactors. The resulting chromium hydroxide is separated from the effluent by mechanical methods. The authors [15] studied the bioremediation of hexavalent chromium and nitrates in a batch SBR–reactor.

Currently, electrochemical reduction of Cr(VI) ions is widely used, with the treatment of chromium-containing effluents in electrocoagulators. The reduction of hexavalent chromium ions in them is carried out by dissolving steel anodes at pH 3–6. The authors of the work [16] used electrocoagulation technology of electrical reduction to purify chromium-containing effluents, in which Cr(VI) in wastewater was reduced to Cr(III) and Fe(II) ions formed as a result of dissolution of steel electrodes in acidic conditions. Research results have shown that the recovery efficiency is almost independent of the current strength, and increases with increasing reaction time and acid concentration. In work [17], the method of sinusoidal alternating current coagulation (SACC) was used to reduce energy consumption and increase the efficiency of Cr(VI) removal. The effect of pH, current density, initial Cr(VI) concentration and reaction time on its removal was studied. Compared to the pulsed coagulation of direct current, SACC can significantly reduce concentrated polarisation and prevent passivation of iron electrodes, in order to reduce energy consumption and improve the efficiency of hexavalent chromium removal. In work [18], an aluminium anode was used to generate
types of metal coagulants, while the cathode material was replaced with a monopolar graphite cathode to reduce energy consumption and processing costs. As a result, it was found that the power consumed in the optimised state was low for the monopolar arrangement of the graphite cathode compared to the aluminium cathode for removing hexavalent chromium.

In work [19], the results of a study of the removal of hexavalent chromium from wastewater by electrocoagulation in an electrochemical reactor using an iron electrode are presented. Working parameters such as current density, runoff pH, number of electrodes and their materials were studied. The results showed that this process can lead to the conversion of Cr(VI) to Cr (III) with a yield of 100 % and 95,95 % in a relatively short reaction time and at low cost. The article [20] investigated the treatment of chromium-containing effluents in an electrochemical reactor with soluble steel electrodes. The new design of the anode increases its surface area, which provides a high rate of removal of chromium from the water in a very short time. In the work [21], experimental studies of purification of chromium-containing effluents by electrocoagulation using the resulting precipitate as a raw material for obtaining inorganic pigments were conducted. Electrocoagulation was performed in a batch reactor with iron electrodes. Sludge containing a large amount of iron and chromium can be used for the production of ceramic pigments. In the works [22,23], the influence of various electrical factors on the wastewater treatment process was studied.

Promising equipment for the treatment of chrome-containing waste water are galvanocoagulators, the principle of operation of which is based on the use of an iron-copper galvanic pair placed in chrome-containing drains. The process of restoring Cr(VI) ions to the Cr(III) state, in contrast to electrocoagulants, occurs without the imposition of an external electric field due to the difference in electrochemical potentials. Iron is polarised anodically and, being oxidised, passes into the wastewater, reducing Cr(VI) ions. Copper is not consumed. In drum-type galvanocoagulators, the rate of oxidation of Fe(II) ions increases due to the contact of the galvanic pair with air oxygen when the drum rotates.

For the treatment of chromium-containing wastewater of electroplating production, Kazan State University of Architecture and Engineering, together with Saint Petersburg State University of Architecture and Civil Engineering, developed a vertical galvanocoagulator for the recovery of Cr(VI) ions, in which this process is carried out by the action of an galvanic pair "iron-copper" electroplating pair without electricity costs. The galvanocoagulator contains a loading layer consisting of copper and iron shavings. When chromium-containing effluents are filtered through the loading layer, Cr(VI) ions are reduced to the Cr(III) state by electrochemical oxidation of iron. To accelerate the redox reaction, compressed air is supplied to the galvanocoagulator. Periodically, the load is removed from the galvanocoagulator; the remaining iron shavings are removed; the copper scrap is washed and mixed with a new portion of iron scrap. After the reduction of hexavalent chromium, the active reaction of the chromium-containing wastewater medium is corrected in order to form Hg(OH)₃ and Fe(OH)₃ hydroxides. To do this, solutions of lime Ca(OH)₂ or sodium hydroxide (NaOH) were added to the chromium-containing effluents. The active reaction of wastewater after alkalization increases to 8.5–9. Separation of insoluble iron and chromium hydroxides from waste water is carried out by settling in thin layer settling tanks followed by filtration in filters with granular loading.

2 Materials and methods
At the first stage of research, an experimental installation was developed to study the processes of treating chromium-containing wastewater in a galvanocoagulator, the scheme of which is shown in Figure 1.
Figure 1. The Scheme of the experimental installation: 1 – container for source water; 2 – galvano-coagulator; 3 – container for treated effluents; 4 – circulation pipeline; 5 – supply of wastewater for treatment; 6 – discharge of treated water; 7 – air supply.

The load of the electrocoagulator consists of a mixture of steel and copper shavings: the ratio of the iron mass to the mass of copper in the load is 4:1. In container 1, a model solution was prepared based on tap water, to which solutions of potassium bichromate (K$_2$Cr$_2$O$_7$), chromium sulphate (Cr$_2$(SO$_4$)$_3$) and iron chloride (FeCl$_3$) were added. Sulphuric acid was used to acidify the model solution.

When conducting research, the installation worked as follows. After preparing the model solution, the P-1 pump was switched on, the flow of which was measured in a volumetric way using a measuring cylinder and a stopwatch. While regulating the flow of the P-1 pump, the model solution was circulated through the pipeline 4. The supply of the P-1 pump must ensure the contact time of the chromium-containing effluents with the loading of the galvano-coagulator for five minutes. After the end of regulating the supply of the pump P-1, chromium-containing effluents were fed through the pipeline 5 to the galvano-coagulator 2. Pipeline 5 was equipped with the device for sampling PR-1 which was used to take samples of the source water to determine the concentration of Cr(VI), Cr(III) and Fe(III) ions in it.

After filling the galvano-coagulator, the treated chromium-containing effluents were fed through the pipeline 6 to the container 3. Compressed air was supplied to the galvanocoagulator by the K-1 compressor through the air duct 7. The air flow was regulated using a rotameter R-1. Pipeline 7 was equipped with the device for sampling PR-2, by means of which samples of chromium-containing effluents treated in a galvanocoagulator were taken after 10, 15, 30, 60, 120 and 240 minutes to determine the content of Cr(VI), Cr(III) and Fe(III) ions in them. The concentration of iron, hexavalent and trivalent chromium ions was determined by photometric method. The temperature of chromium-containing effluents was determined using a mercury thermometer with a division price of 0, 1 °C; the active reaction of the medium was determined using a pH meter of the pH–340 type. The sequence of actions described above was repeated for the contact time of chromium-containing effluents with the loading of the galvanocoagulator 7, 5, 10 and 15 minutes.

At the second stage of research, the hydraulic fineness of suspended substances representing flakes of iron and trivalent chromium hydroxides was determined for the calculation of settling tanks that are part of the chrome-containing wastewater treatment plant. To determine the hydraulic fineness of the suspension when calculating settling tanks, it is necessary to construct a dependence curve $P=f(U)$, where $U$ is the hydraulic fineness of the suspension (mm/s), $P$ is the amount of sediment that fell when settling waste water in the cylinder (%). The hydraulic fineness (mm/s) was calculated using the formula:

$$u = \frac{H}{t}$$ (1)
where \( H \) is the height of the water layer in the cylinder (mm), \( t \) is the setting time, (s).

The value of \( P \) (%) was calculated using the formula:

\[
P = \frac{M_0 - M}{M_0} \times 100\% \tag{2}
\]

where \( M_0 \) is the mass of suspended substances in the cylinder before settling (mg), \( M \) is the mass of suspended substances remaining in the cylinder after settling the waste water during time \( t \) (mg).

The value of \( M_0 \) (mg) were calculated using the formula:

\[
M_0 = \frac{\pi d^2}{4} \times H \times C_0 \times 10^3 \tag{3}
\]

where \( d \) diameter of the cylinder for settling waste water (m), \( C_0 \) is the concentration of suspended substances in the cylinder before settling (mg/L).

The value \( M \) (mg) was calculated using the formula:

\[
M = \frac{\pi d^2}{4} \times H \times C \times 10^3, \tag{4}
\]

where \( C \) is the concentration of suspended substances in the cylinder after settling the waste water for time \( t \) (mg).

The model solution was processed in a galvanocoagulator. Then the chromium-containing effluents were alkalinized with a 10 % NaOH solution until their pH reached 8.5–9. A sample of wastewater was taken, in which the concentration of suspended substances \( (C_0) \) was determined. Six glass cylinders with a height of 500 mm, placed in a water bath with an attached thermostat, were filled with caustic treated waste water up to a mark at a height of 300 mm. The thermostat maintained a temperature of \( +20 \) °C in the water bath. A sample was taken from cylinder 1 after 1 minute using a siphon, in which the concentration of suspended substances was determined. The same sample was taken from cylinder 2 in 5 minutes, from cylinder 3 in 10 minutes, from cylinder 4 in 20 minutes, from cylinder 5 in 30 minutes, and from cylinder 6 in 60 minutes.

The concentration of suspended substances in the waste water samples was determined by the weight method. The settling time was measured using a stopwatch. Hydraulic fineness was determined by eq. (1), and the amount of sediment is according to eqs. (2), (3) and (4).

3 Results and Discussion

The results of studies on the treatment of chromium-containing effluents with a galvanocoagulator are presented in Table 1.
Table 1. Results of the research on the treatment of chromium – containing effluents in galvanocoagulator.

| The time of contact (min) | The sampling time (min) | Ion concentration (mg/L) | In the source water | In the treated water |
|--------------------------|-------------------------|---------------------------|---------------------|---------------------|
|                          |                         | Cr<sup>6+</sup> | Cr<sup>3+</sup> | Fe<sup>3+</sup> | Cr<sup>6+</sup> | Cr<sup>3+</sup> | Fe<sup>3+</sup> |
| 1                        | 2                       | 3                  | 4                  | 5                  | 6                  | 7                  | 8                  |
|                          |                         | 10                 |                    |                    |                    |                    |                    |
|                          |                         | 15                 |                    |                    |                    |                    |                    |
|                          |                         | 30                 |                    |                    |                    |                    |                    |
|                          |                         | 60                 |                    |                    |                    |                    |                    |
|                          |                         | 120                |                    |                    |                    |                    |                    |
|                          |                         | 240                |                    |                    |                    |                    |                    |
| 5                        |                         |                    |                    |                    | 51                 | 15                 | 5                  |
|                          |                         |                    |                    |                    | 25                 | 40                 | 188                |
|                          |                         |                    |                    |                    | 23                 | 43                 | 190                |
|                          |                         |                    |                    |                    | 21                 | 45                 | 192                |
|                          |                         |                    |                    |                    | 21                 | 45                 | 192                |
|                          |                         |                    |                    |                    | 20                 | 46                 | 191                |
|                          |                         |                    |                    |                    | 20                 | 46                 | 192                |
| 7,5                      |                         |                    |                    |                    | 49                 | 14                 | 5                  |
|                          |                         |                    |                    |                    | 18                 | 45                 | 193                |
|                          |                         |                    |                    |                    | 15                 | 48                 | 199                |
|                          |                         |                    |                    |                    | 13                 | 50                 | 201                |
|                          |                         |                    |                    |                    | 13                 | 49                 | 199                |
|                          |                         |                    |                    |                    | 14                 | 49                 | 200                |
|                          |                         |                    |                    |                    | 12                 | 51                 | 200                |
| 10                       |                         |                    |                    |                    | 50                 | 16                 | 6                  |
|                          |                         |                    |                    |                    | 8                  | 58                 | 195                |
|                          |                         |                    |                    |                    | 5                  | 61                 | 198                |
|                          |                         |                    |                    |                    | 2                  | 64                 | 203                |
|                          |                         |                    |                    |                    | 1                  | 65                 | 206                |
|                          |                         |                    |                    |                    | 0                  | 66                 | 204                |
|                          |                         |                    |                    |                    | 0                  | 66                 | 204                |
| 15                       |                         |                    |                    |                    | 51                 | 15                 | 5                  |
|                          |                         |                    |                    |                    | 3                  | 63                 | 205                |
|                          |                         |                    |                    |                    | 1                  | 65                 | 207                |
|                          |                         |                    |                    |                    | 0                  | 66                 | 208                |
|                          |                         |                    |                    |                    | 0                  | 65                 | 208                |
|                          |                         |                    |                    |                    | 0                  | 66                 | 208                |

The results of studies to determine the hydraulic fineness of suspended substances are presented in Tables 2 and 3, as well as in Figure 2.
Table 2. Results of studies to determine the concentration of suspension after settling.

| No experiences | Concentration of the suspension before settling (mg/L) | Concentration of the suspension after settling for a time (mg/L) |
|----------------|--------------------------------------------------------|---------------------------------------------------------------|
|                |                                                        | 1 min | 2 min | 5 min | 10 min | 20 min | 50 min |
| 1              | 498                                                    | 444   | 375   | 190   | 119    | 86     | 51     |
| 2              | 504                                                    | 437   | 363   | 176   | 115    | 76     | 41     |
| 3              | 502                                                    | 456   | 386   | 200   | 131    | 100    | 61     |

Table 3. Results of the research on determination of hydraulic size.

| The mass of the suspension М₀(mg) | Parameters                                           | Time (min) |
|----------------------------------|------------------------------------------------------|-------------|
|                                  | Weight of the suspension after settling for a time, M(mg/L) | 1 | 2 | 5 | 10 | 20 | 50 |
| 294                              | 262                                                  | 221         | 112 | 70 | 51 | 30 |
|                                  | Amount of sediment P (%)                             | 11          | 25  | 62 | 76 | 83 | 90 |
|                                  | Hydraulic size U (mm/s)                              | 5           | 2.5 | 1  | 0.5| 0.25 | 0.1 |
| 297                              | 258                                                  | 214         | 104 | 68 | 45 | 24 |
|                                  | Amount of sediment P (%)                             | 13          | 28  | 65 | 77 | 85 | 92 |
|                                  | Hydraulic size U (mm/s)                              | 5           | 2.5 | 1  | 0.5| 0.25 | 0.1 |
| 296                              | 269                                                  | 228         | 118 | 77 | 59 | 36 |
|                                  | Amount of sediment P (%)                             | 9           | 23  | 60 | 74 | 80 | 88 |
|                                  | Hydraulic size U (mm/s)                              | 5           | 2.5 | 1  | 0.5| 0.25 | 0.1 |

From the results of the studies in Table 2: the process of recovery of ions of Cr(VI) in the chromium-containing effluent temperature 19.9 to 20.1 °C and pH equals to 3.9 and 4.1 is in galvanocoagulation quite stable; the contact time of the chromium-containing effluent with download galvanocoagulation providing complete reduction of hexavalent chromium should be at least 10 minutes; the output time of the galvanocoagulator to the operating mode is 15–30 minutes; the concentration of hexavalent chromium ions after treatment of chromium-containing effluents in the galvanocoagulator can be reduced from 49–51 mg/L to 0–25 mg/L; the concentration of Fe(III) ions after treatment of chromium-containing effluents in the galvanocoagulator increases from 5–6 mg/L to 188–209 mg /L.

Figure 2. Dependence P=f (U)
Analysis of the research results from Tables 2 and 3 and Figure 2 indicates that the hydraulic size of suspended substances formed after treatment of chromium-containing wastewater in a galvanocoagulator obtained in the course of the research can be assumed to be equal to 0.5 mm/s.

4 Conclusion
Conclusions drawn from this study can be summarized in the following statements.
1. As a result of experimental studies, the possibility of removing hexavalent chromium from wastewater in a galvanocoagulator was established, and the working parameters of the electrocoagulation process were determined.
2. To calculate the settling equipment that is part of the plant for the treatment of chrome-containing wastewater, the hydraulic size of suspended substances representing flakes of iron hydroxides and trivalent chromium is determined.
3. Galvanocoagulation is an efficient and energy-saving process for removing hexavalent chromium from electroplating wastewater.

References
[1] Daneshvar E, Zarrinnmehr, M J, Kousha M, Hashjin A M, Saratale G D, Maiti A, Vithanage M and Bhatnagar A 2019 Hexavalent chromium removal from water by microalgae-based materials: Adsorption, desorption and recovery studies Bioresource Technology 293 (12) pp 438–451 DOI: 10.1016/j.biortech.2019.122064
[2] Da Silva Neto J S, Madeira V S, Rodrigues G, Da Silva J A and Moreira M F 2019 Chromium (VI) removal using cerium doped iron oxide nanoparticles Materials Research Express 6 (11) pp 675–684 DOI: 10.1088/2053-1591/ab4b9e
[3] Li H, Hou R, Chen Y and Chen H 2019 Removal of hexavalent chromium from aqueous solutions using sulfonated peat Water (Switzerland) 11 (1980) pp 1–15 DOI: 10.3390/w11101980
[4] Liu W, Yang L, Xu Sh, Chen Y, Liu B, Li Zh and Jiang, Ch 2018 Efficient removal of hexavalent chromium from water by an adsorption – reduction mechanism with sandwiched nanocomposites RSC Advances 8 (27) pp 15087–93 DOI: 10.1039/C8RA01805G
[5] Chagas P M B, Caetano A A, Tireli A A, Cesar P H S, Corrêa A D and Guimarães I R 2019 Use of an Environmental Pollutant From Hexavalent Chromium Removal as a Green Catalyst in The Fenton Process Scientific Reports 9 (1) pp 1–15 DOI: 10.1038/s41598-019-49196-9
[6] Song D, Pan R, Tariq A, Azizullah A Sun F, Li Z and Xiong Q 2016 Adsorptive removal of toxic chromium from waste – water using wheat straw and Eupatorium adenophorum PLos ONE 11 (12) pp 1–15 DOI: 10.1371/journal.pone.0167037
[7] Aravind J, Sudha G, Kanmani P, Devisri A J, Dhivyalakshmi S and Raghavprasad M 2015 Equilibrium and kinetic study on chromium (VI) removal from simulated waste water using gooseberry seeds as a novel biosorbent Global Journal of Environmental Science and Management 1 (3) pp 233–244 DOI: 10.7508/gjesm.2015.03.006
[8] Ai T, Jiang X and Liu Q 2018 Chromium removal from industrial wastewater using Phyllostachys pubescens biomass loaded Cu-S nanospheres Open Chemistry 16 (1) pp 842–852 DOI: 10.1515/chem-2018-0073
[9] Rai M K, Giri B S, Nath Y, Bajaj H, Soni S, Singh R P, Singh R S and Rai B N 2018 Adsorption of hexavalent chromium from aqueous solution by activated carbon prepared from almond shell: Kinetics, equilibrium and thermodynamics study Journal of Water Supply: Research and Technology – AQUA 67 (8) pp 724–737 DOI: 10.2166/aqua.2018.047
[10] Samuel M S, Shah S S, Subramaniyan V, Qureshi T, Bhattacharya J and Pradeep Singh N D 2018 Preparation of graphene oxide/chitosan/ferrite nanocomposite for Chromium (VI) removal from aqueous solution International Journal of Biological Macromolecules 119 (11) pp 540–547 DOI: 10.1016/j.ijbiomac.2018.07.052
[11] Adam M R, Salleh N M, Othman M H D, Matsuura T, Ali M H, Puteh M H, Ismail A F, Rahman M A and Jaafar J 2018 The adsorptive removal of chromium (VI) in aqueous solution by novel natural zeolite based hollow fibre ceramic membrane Journal of Environmental Management 224(10) pp 252–262 DOI: 10.1016/j.jenvman.2018.07.043

[12] Terangpi P, Chakraborty S and Ray M 2018 Improved removal of hexavalent chromium from 10 mg/L solution by new micron sized polymer clusters of aniline formaldehyde condensate Chemical Engineering Journal 350(10) pp 599–607 DOI: 10.1016/j.cej.2018.05.171

[13] Chu B, Yamoto M, Amano Y and Machida M 2018 Adsorption, reduction and regeneration behavior of high surface area activated carbon in removal of Cr(VI). Desalination and Water Treatment 136(12) pp 395–404

[14] Taher T, Palapa N R, Mohadi R and Lesbani A 2019 Adsorption behavior of Cr (VI) from aqueous solution by Fe-pillared acid activated Indonesian bentonite AIP Conference Proceedings 2194 pp 1–9 DOI: 10.1063/1.5139856

[15] Jin R, Liu Y, Liu G, Tian T, Qiao S and Zhou J 2017 Characterization of Product and Potential Mechanism of Cr(VI) Reduction by Anaerobic Activated Sludge in a Sequencing Batch Reactor Scientific Reports 7(1) pp 1–12 DOI: 10.1038/s41598-017-01885-z

[16] Peng H, Leng Yu, Cheng Q, Shang Q, Shu J and Guo J 2019 Efficient removal of hexavalent chromium from wastewater with electro – reduction Processes 7(1) pp 1–12 DOI: 10.3390/pr7010041

[17] Xu T, Zhou Y, Lei X, Hu B, Chen H and Yu G 2019 Study on highly efficient Cr(VI) removal from wastewater by sinusoidal alternating current coagulation Journal of Environmental Management 249(11) pp 279–288 DOI: 10.1016/j.jenvman.2019.109322

[18] Singh H, Sonal S and Mishra B K 2018 Hexavalent chromium removal by monopolar electrodes based electrocoagulation system: Optimization through Box-Behnken design Journal of Water Supply: Research and Technology – aqua 67(2) pp 147–161 DOI: 10.2166/aqua.2017.135

[19] Cheballah K, Sahmoune A, Messaoudi K, Drouiche N and Lounici H 2015 Simultaneous removal of hexavalent chromium and COD from industrial wastewater by bipolar electrocoagulation Chemical Engineering and Processing: Process Intensification 96(10) pp 94–99 DOI: 10.1016/j.cep.2015.08.007

[20] El–Taweel Y A, Nassef E M, Elkheriyan I and Sayed D 2015 Removal of Cr(VI) ions from waste water by electrocoagulation using iron electrode Egyptian Journal of Petroleum 24(2) pp 183–192 DOI: 10.1016/j.ejpe.2015.05.011

[21] Un U T, Onpker S E and Ozcel E 2017 The treatment of chromium containing wastewater using electrocoagulation and the production of ceramic pigments from the resulting sludge Journal of Environmental Management 200(11) pp 196–203 DOI: 10.1016/j.jenvman.2017.05.075

[22] Zahvatov G I 2017 The force of electrical factors on efficiency of electroneutralization process for water emulsions Izvestiya KGASU 2(40) pp 213–218

[23] Zahvatov G I 2017 The role of some addition factors in electro neutralization process of water emulsions Izvestiya KGASU 3(41) pp 167-172