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ADSORPTION OF 4-CHLOROPHENOL FROM AQUEOUS SOLUTION ON ACTIVATED CARBONS DERIVED FROM HORNBEAM WOOD

Beata Doczekalska, Agata Pawlicka
Poznań University of Life Sciences, Institute of Chemical Wood Technology
Poznan, Poland

Krzysztof Kuśmierek, Andrzej Świątkowski
Military University of Technology, Faculty of Advanced Technologies and Chemistry
Warsaw, Poland

Monika Bartkowiak
Poznań University of Life Sciences, Institute of Chemical Wood Technology
Poznan, Poland

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ABSTRACT

The adsorption of 4-chlorophenol (4-CP) from aqueous solution on activated carbons prepared from hornbeam wood was studied. The adsorption kinetic data were analyzed using pseudo-first order and pseudo-second order models. The adsorption kinetics of 4-CP was better represented by the pseudo-second order equation. The equilibrium adsorption data were described by Langmuir and Freundlich isotherms and the results showed that both models fitted well the 4-CP adsorption; nevertheless, a slightly higher R^2 values were observed for the Langmuir model. The effects of solution pH and ionic strength on the adsorption were so investigated. The high 4-CP adsorption capacity (2.71–4.37 mmol·g^{-1}) shows that hornbeam wood is a good precursor for the preparation of activated carbons for the adsorptive removal of organic contaminants.

KEYWORDS: Hornbeam wood, activated carbon, adsorption, 4-chlorophenol.

INTRODUCTION

The organic pollutants in water and many industrial wastewaters are toxic for humans and aquatic life, therefore their removal via the most efficient way is very important for environmental remediation treatment. The methods used for the removal of organic contaminants from water include physicochemical treatment processes, chemical oxidation, and biological degradation. The adsorption process by solid adsorbents is one of the most efficient methods for the removal of organic compounds from water (Dąbrowski et al.2005, Foo and Hameed 2010, Soto et al. 2011). Adsorption has advantages over the other methods because of simple design and can involve low investment in term of both initial cost and land required. Activated carbons (AC), due to their high specific surface area and well-developed porous structure, are now the most commonly used adsorbents for the removal of organic compounds from wastewater.

Raw materials applied in the preparation of activated carbons used on an industrial scale are now primarily coals with varying degrees of metamorphism as well as wood, peat or coconut shells. Valuable activated carbon precursors may also be other lignocellulosic materials with high density and hardness, and denoting a high content of lignin. The chemical and supramolecular structure of natural cellulose-lignin composite makes it a very good raw material for the production of activated carbons (Bansal and Goyal 2005). Although the cellulose and lignin are included in polymers having the lowest of carbon content and the highest of oxygen, they satisfy the requirements of raw materials for the production of activated carbons. The potential possibility to obtain of high quality carbon with a very low content of mineral substances that are additionally natural catalyst for oxidation processes during activation, the ability to achieve a high mass of raw material and its low price, biocompatibility with the natural environment, the possibility of recovery of the raw materials and favorable technological properties, make the World production of activated carbons from lignocellulosic raw materials are of great importance (Bansal and Goyal 2005).

Due to their particular porous characteristics, woody materials are very relevant and challenging raw materials to prepare activated carbons, namely for the adsorption of solutes in the liquid phase (Wu and Tseng 2006). The wood industry is responsible to produce great amounts of woody waste materials that might be recycled to produce AC. Also, several forest residues can be used, additionally contributing to a better forest management and conservation. Many studies were made concerning the recycling of these materials for the production of AC. Woody materials of different types such as fir, oak, acacia, as well as from tropical trees have already been used (Wu and Tseng 2006, Zhang et al. 2012; Danish et al. 2013, Dias et al. 2007). In this study as precursor wood hornbeam was used. The choice of material for the research was dictated by the desired physical characteristics of the wood i.e. its high density, high hardness and homogeneity.

The purpose of this work was to evaluate the adsorption potential of activated carbons derived from hornbeam wood for 4-chlorophenol (4-CP). The 4-chlorophenol was chosen as the target contaminant because is commonly found in drinking water (Michałowicz 2005) and it is poisonous to aquatic life, plants and humans at low level (Igbinosa et al. 2013). Kinetic studies and adsorption isotherms of 4-CP were carried out and the results were analyzed by applying conventional theoretical models. The influences of solution pH and ionic strength on the adsorption capacities of activated carbons for the 4-CP were also investigated. To our knowledge, the adsorption of 4-chlorophenol using hornbeam wood based activated carbon was not studied.

MATERIAL AND METHODS

Reagents

The 4-chlorophenol (4-CP) used for adsorption tests was purchased from Sigma (St Louis, MO, USA). The hydrochloric acid, sodium sulfate, potassium hydroxide, sodium hydroxide and sodium chloride were obtained from Avantor Performance Materials (Gliwice, Poland).

Preparation and characterization of activated carbon

Activated carbons were obtained from hornbeam wood. Crushed hornbeam wood was subjected to pyrolysis and carbonization in oxygen free atmosphere by heating to 800°C at the temperature rate of 3°C·min^{-1} and then, holding in stable conditions for 1 h. The carbonizates after grinding were activated with KOH or NaOH at mass ratio 1:4 in argon atmosphere at a temperature of 950°C for 15 or 30 minutes in nonporous ceramic reactor. ACs were extracted with 2% hydrochloric acid and deionized water to the neutral pH. Prior to use, the activated carbons were dried in an oven at 120°C to a constant weight and kept in a desiccator for further study.

Chemical composition of hornbeam wood was determined according to the analytical methods used in wood chemistry as follows (Fengel and Wegner 1989): cellulose by Seifert method, lignin by Tappi method, holocellulose by Haas method, pentosans by Tollens method, extraction substances by Soxhlet method (TAPPI T 204 om-88) and mineral substances. The contents of carbon, hydrogen and nitrogen in the hornbeam wood and charcoal were determined at Flash EA 1112 Thermo Electron company.

The point of zero charge (pH_{PZC}) of the activated carbons was measured using the pH drift method. The 0.1 g of the activated carbon was added to an Erlenmeyer flasks containing 20 mL of 0.01 mol·L^{-1} sodium chloride. The pH within each flask was adjusted to values ranging from 2 to 10 by 0.1 mol·L^{-1} NaOH and/or 0.1 mol·L^{-1} HCl. The flasks were shaken for 24 hours, and the final pH of the solution was measured. The pH_{PZC} was measured as the point where the curve of final pH vs. initial pH crosses the line $pH_{Final} = pH_{Initial}$.

Thermogravimetric analyses were carried out on a LabsysTM thermobalance of the Setaram Company in the following conditions: final temperature 900°C, rate of temperature increase - 5°C·min^{-1}, atmosphere – helium flowing at the rate of about 2 dm^3·h^{-1}.

Parameters of the porous structure were determined from nitrogen sorption isotherms at -196°C (Micromeritics ASAP 2010). Samples before measurement were degassed at 300°C for 10 hours at pressure $1 \cdot 10^{-6}$ Pa. Collected sorption data allowed to calculate the following structural parameters in the area of micro- and mesopores:

S_{BET} – specific surface area by BET method – to the relative pressure $p/p_0 \approx 0.2$,
V_{total} – a total pore volume determined from the isotherm at a relative pressure $p/p_0 \approx 0.975$,
V_{meso} – mesopores volume by BJH method,
V_{micro} – micropores volume from differences $V_{total} - V_{meso}$,
$d_{average}$ – average pore diameter calculated from formula $d_{average}=4V_{total}/S_{BET}$,
contribution of micropores to mesopores from a volume ratio of V_{micro}/ V_{meso}.

Adsorption studies

Batch adsorption studies were carried out as follows: 0.01 g of each activated carbon was first added to a 100 mL Erlenmeyer flasks containing 0.04 L of aqueous 4-chlorophenol solution of known concentration (0.5-2.0 mol·L^{-1}). The flasks were then agitated at ambient temperature (25°C) at constant speed (200 rpm). The 4-CP concentration in the aqueous phase

was determined using UV-Vis spectrophotometer (Carry 3E, Varian, USA) at the wavelength of 278 nm and the amount of adsorbed compound q_e (mmol·g^{-1}) was calculated by the Eq. 1:

$$q_e = \frac{(C_0 - C_e)V}{m} \tag{1}$$

where: C_0 and C_e - initial and equilibrium concentration of 4-CP (mol·L^{-1}),
V - volume of the solution (L)
m - mass of the adsorbent (g).

The kinetic studies were conducted for an initial 4-CP concentration of 1.0 mmol·L^{-1} and the mass of the adsorbents of 0.01 g. The amount of 4-CP adsorbed onto the activated carbon at time t, q_t (mmol·g^{-1}), was calculated by the following Eq. 2:

$$q_t = \frac{(C_0 - C_t)V}{m} \tag{2}$$

where: C_t is the concentration of 4-CP at the time t (mmol·L^{-1}).

The effect of pH on the 4-CP adsorption was studied by varying the initial pH of the solutions from pH 2 to 11. The pH was adjusted (prior to the addition of the adsorbent) using 0.1 mol·L^{-1} HCl or 0.1 mol·L^{-1} NaOH and was measured using pH meter. The initial concentration of 4-CP was fixed at 1.0 mmol·L^{-1}.

The effect of salt presence (ionic strength) on 4-CP removal was investigated similarly as described above with the difference that the adsorbate was adsorbed from the 0.01, 0.02, 0.05 and 0.1 mmol·L^{-1}solutions of Na_2SO_4.

All the experiments were carried out in duplicate, and average values were used for further calculations. The maximum deviation was found to be below 5%.

RESULTS AND DISCUSSION

Characterization of activated carbons

The raw hornbeam wood used as precursor for preparation of activated carbons contained 40.4±0.3% cellulose, 20.2±0.2% lignin, 24.0±0.3% pentosans, 1.6±0.4% substances soluble in ethanol and 0.35±0.02% mineral substances. The elemental analysis results showed that the hornbeam wood contained 49.77% carbon, 6.07% hydrogen and 0.16% nitrogen. The oxygen content was calculated from the difference and was found to be 44.00%. Carbonizate was consisted of 95.83% C, 1.45% H, 0.13% N and 2.59% O. The molar ratios of H/C, O/C and N/C were 1.46, 0.66 and 0.003, for hornbeam wood and 0.18, 0.02 and 0.001, for carbonizate, respectively.

Thermogravimetric characteristics of hornbeam wood was as follows: temperature corresponding to the beginning of the decomposition – T_i = 209°C; temperature corresponding to the ending of the decomposition – T_f = 359°C; temperature corresponding to the maximum rate of weight loss – T_{max} = 344°C; weight loss at T_i, W_{Ti} = 59.25 %, weight loss at T_{max}, W_{Tmax} = 55.2 %, weight loss at 600, 700, 800°C, W_{600} = 72.62 %, W_{700} = 73.37 %, W_{800}= 74.18 %; total weight loss (temperature 900°C) – W_T =74.97 %.

Results of the thermogravimetric analysis of activated carbons obtained from hornbeam wood are presented in Fig. 1 and in Tab. 1. The temperature ranges 200-500°C and 500-700°C

are connected with thermal decomposition of acidic and weak acidic oxygen surface functional groups, respectively (Figueiredo et al. 1999, Boehm 2002). In higher temperature ranges decompose basic functional groups.

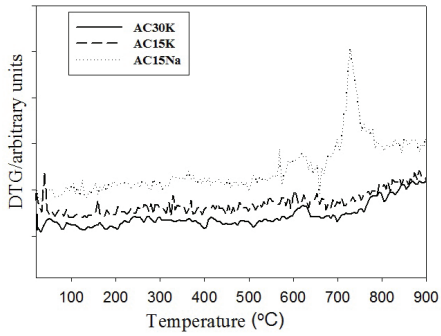

Fig. 1: DTG curves of activated carbons obtained from hornbeam wood.

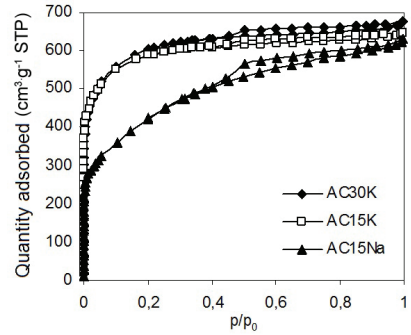

Fig. 2: Nitrogen adsorption-desorption isotherms of the activated carbons at -196 °C.

Tab. 1: Weight loss of activated carbons obtained from hornbeam wood.

Activated carbon	Weight loss (% wt.)				
	20-200°C	200-500°C	500-700°C	700-900°C	Total 20-900°C
AC15Na	0.61	2.26	2.59	6.05	11.51
AC15K	0.21	1.14	1.26	2.51	4.81
AC30K	0.67	1.93	1.66	3.35	7.62

The point of zero charge (pH_{PZC}) of the activated carbons measured using the pH drift method was as follows: 7.90 for AC15Na, 6.85 for AC15K and 7.05 for AC30K. The order of this value is in accordance with the order of shares of mass losses related to the acidic groups in the total mass losses.

Nitrogen adsorption/desorption isotherms for all of the activated carbons were determined at -196 °C (Fig. 2). Porous structure parameters obtained from the N_2 isotherms are listed in Tab. 2. The specific surface areas for KOH as activating agent are much greater than for NaOH. On the other hand the increasing the activation time also increases the BET surface area. The use of KOH gives a much greater share of micropores than in the case of NaOH. This is accompanied by a greater total pore volume and less weight loss after activation process. Effect of activation time plays in this case a smaller role than the type of activating agent.

Tab. 2: Porous structure characteristics of obtained activated carbons.

AC	S_{BET} ($m^2 \cdot g^{-1}$)	V_{mi} ($cm^3 \cdot g^{-1}$)	V_{me} ($cm^3 \cdot g^{-1}$)	V_s ($cm^3 \cdot g^{-1}$)	d_p (nm)	Weight loss, W_{wa}
AC15Na	1492	0.247	0.726	0.973	2.61	0.62
AC15K	1862	0.786	0.213	0.999	2.15	0.40
AC30K	1934	0.783	0.263	1.046	2.16	0.38

W_{wa} – weight loss after activation process, $W_{wa} = 1 - m_p/m_o$; m_p – mass of the carbon after activation; m_o – mass of the carbon before activation

Adsorption of 4-chlorophenol

Adsorption kinetics

Fig. 3 shows the adsorption kinetics of the 4-CP on all of the activated carbons. It was observed, that the adsorption equilibrium was achieved approximately after 4-5 hours. The experimental results were described by the pseudo-first (Lagergren 1898) and pseudo-second order (Ho and McKay 1999) equations. The pseudo-first order kinetic model is expressed in linear form as:

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303}t \tag{3}$$

where: k_1 is the rate constant of pseudo-first order adsorption (L·min^{-1}).

The pseudo-second order equation has the linear form:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^{\,2}} + \frac{1}{q_e}t \tag{4}$$

where: k_2 is the rate constant of pseudo-second order adsorption (g/mmol•min).

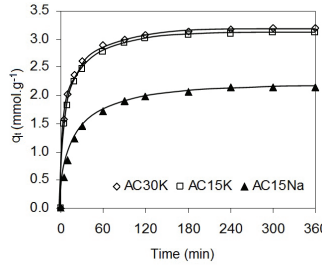

Fig. 3: Adsorption kinetics of 4-chlorophenol on activated carbons from hornbeam wood.

The rate constants of the pseudo-first and pseudo-second order adsorption were calculated from the straight line plots of log (q_e - q_t) vs. t and t/q_t vs. t, respectively. The values of the k_1 and k_2 as well as the correlation coefficients are presented in Tab. 3. The results obtained suggest that the pseudo-second order model fitted well to the kinetic data of 4-CP. The values of the qe(CAL) obtained from the pseudo-second order kinetic model were in close agreement with that of experimental values ($q_{e(EXP)}$). Moreover, the correlation coefficients for the pseudo-first order kinetic model were relatively low, whereas the pseudo-second order model gives a better fitting with the high R^2 values (>0.99). The k_2 values obtained for the AC30K, AC15K and AC15Na activated carbons were 0.046, 0.043 and 0.028 g/mmol•min, respectively. Also the pseudo-first order rate constants k_1 decreased in the same order. The rate of the 4-CP adsorption increases in the direction: AC15Na < AC15K < AC30K.

Tab. 3: Kinetic parameters for the adsorption of 4-CP on activated carbons derived from hornbeam wood.

Adsorbent		Pseudo-first order model			Pseudo-second order model		
	$q_{e\ (EXP)}$	k_1	R^2	$q_{e\ (CAL)}$	k_2	R^2	$q_{e\ (CAL)}$
	(mmol·g^{-1})	(1·min^{-1})		(mmol·g^{-1})	(g·mmol^{-1}·min^{-1})		(mmol·g^{-1})
AC15Na	2.214	0.010	0.898	1.173	0.028	0.999	2.258
AC15K	3.121	0.022	0.942	1.744	0.043	0.999	3.183
AC30K	3.197	0.023	0.974	1.747	0.046	0.999	3.254

In order to investigate the mechanism of the adsorption of 4-CP on the activated carbons, the Weber-Morris model (the intra-particle diffusion model) (Weber and Morris 1963) was also used:

$$q_t = k_i t^{0.5} + C_i \quad (5)$$

where: k_i - intra-particle diffusion rate constant (mmol·g^{-1}·min$^{-1.5}$),
C_i - thickness of the boundary layer (mm).

The Weber-Morris plots (q_t vs. $t^{0.5}$) for 4-CP on all of the adsorbents was presented in Fig. 4. If the plot of q_t vs. $t^{0.5}$ passes through the origin, then the rate limiting process is only due to the intra-particle diffusion. If the plot is linear, then the diffusion is involved in the entire adsorption process. As shown in Fig. 4, the plots were not linear over the whole time range. The first, sharper region is the instantaneous adsorption or external surface adsorption, while the second step corresponds to the gradual adsorption stage, where the intra-particle diffusion is the rate-limiting step (Lorenc-Grabowska et al. 2013). Moreover, none of the lines passed through the zero point. This indicates that more than one process affected adsorption and that the intra-particle diffusion was not the only rate-controlling step (Lorenc-Grabowska et al. 2013).

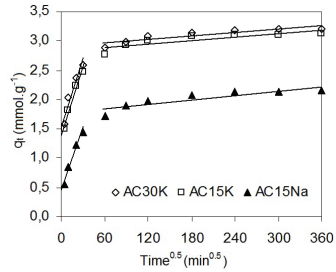

Fig. 4: Intra-particle diffusion kinetics for adsorption of 4-chlorophenol from aqueous solutions.

Adsorption isotherms

The adsorption isotherms of 4-CP on the AC30K, AC15K and AC15Na activated carbons are shown in Fig. 5. To test the fitting of the experimental data, the Langmuir (1916) and Freundlich (1906) isotherm equations were used. The Freundlich isotherm model proposes a multilayer adsorption with a heterogeneous energetic distribution of active sites, accompanied by interactions between adsorbed molecules. The linear form of the Freundlich equation is described by the formula:

$$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e \quad (6)$$

where: K_F - ((mmol·g^{-1}) (L·mmol^{-1})$^{1/n}$),
n - the Freundlich equation constants calculated from the intercept and slope of lnqe vs. lnC_e plot.

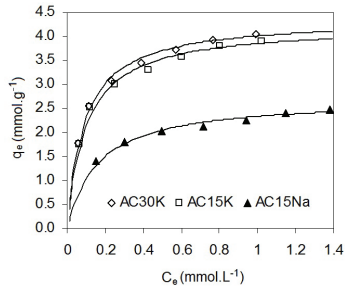

Fig. 5: Adsorption isotherms of 4-chlorophenol on hornbeam wood activated carbons.

The Langmuir isotherm is based on the assumptions that the adsorption is monolayer and takes place at specific homogeneous sites on the adsorbent surface, where no further adsorption can occur when a site is occupied with adsorbate. The linear form of the Langmuir isotherm is as follows:

$$\frac{C_e}{q_e} = \frac{1}{q_m b} + \frac{C_e}{q_m} \tag{7}$$

where: q_m (mmol·g^{-1}) - the maximum adsorption capacity,
b (L·mmol^{-1}) - the constant related to the free energy of adsorption. These constants were calculated from the intercept and slope of C_e/q_e vs. C_e plot.

The Freundlich and Langmuir adsorption isotherm model parameters and the correlation coefficients R^2 for the adsorption of the 4-chlorophenol on the activated carbons are listed in Tab. 4. The linear regression correlation coefficient values show that the equilibrium data obtained for all of the adsorbents were well represented by both models, nevertheless, a slightly higher R^2 values were observed for the Langmuir equation. The values of the Langmuir maximum adsorption capacity (q_m) were 4.369, 4.226 and 2.711 mmol·g^{-1} for the AC30K, AC15K and AC15Na activated carbons, respectively. Also the Freundlich constants K_F decrease in the order: AC30K > AC15K > AC15Na. The values of the Freundlich constant n were greater than one, indicating a favorable adsorption of 4-CP by all of the adsorbents. The q_m and K_F values obtained for the AC30K and AC15K activated carbons are similar, whereas the adsorption capacity of the AC15Na activated carbon is much smaller. This fact is closely related to the specific surface area of the carbon materials tested. For comparison, the values of the Langmuir constants q_m and b for the carbonizate (S_{BET} = 45 m^2.g^{-1}) were 0.083 mmol·g^{-1}and 0.442 L·mmol^{-1}, while the values of the Freundlich constants K_F and n were 0.025 (mmol·g^{-1})(L·mmol^{-1})$^{1/n}$ and 1.401, respectively (data not shown).

Tab. 4: The Langmuir and Freundlich isotherm equation parameters and correlation coefficients for adsorption of 4-chlorophenol on activated carbons from hornbeam wood.

Adsorbent	Langmuir model			Freundlich model		
	q_m	b	R^2	K_F	n	R^2
	(mmol·g^{-1})	(L·mmol^{-1})		(mmol·g^{-1}) (L·mmol^{-1})$^{1/n}$		
AC15Na	2.711	6.148	0.997	2.318	4.082	0.978
AC15K	4.226	10.24	0.998	4.081	3.712	0.946
AC30K	4.369	11.17	0.999	4.298	3.699	0.961

From literature review, several studies have been done on the adsorption of 4-CP using various activated carbons. Table 5 compares the maximum adsorption capacity (q_m) of different types of activated carbons used for the removal of 4-CP from aqueous solutions. The values of q_m obtained for the AC30K, AC15K and AC15Na activated carbons are comparable or larger than those in most of previous works which suggests that the 4-CP could be easily adsorbed by activated carbons derived from hornbeam wood.

Tab. 5: Comparison of 4-CP adsorption on various activated carbons.

Activated carbon	Adsorption capacity, q_m (mmol·g^{-1})	S_{BET} (m^2·g^{-1})	Reference
AC from cane pith CPKC5	5.040	2207	Tseng and Tseng (2006)
AC30K	4.369	1934	this study
AC15K	4.226	1862	this study
AC from cane pith CPKC4	4.100	1806	Tseng and Tseng (2006)
AC from cane pith CPKC3	3.640	1518	Tseng and Tseng (2006)
AC from cane pith CPKC2	3.500	912	Tseng and Tseng (2006)
modified Norit R3ex AC	3.004	1530	Kuśmierek et al. (2015)
AC from sewage sludge (1:3)	2.820	1832	Monsalvo et al.(2011)
AC15Na	2.711	1492	this study
Commercial CXZ 2 (Gryfskand)	2.505*	977	Lorenc-Grabowska et al. (2010)
Commercial AC (Prolabo)	1.981*	929	Hamdaoui and Naffrechoux (2007)
Commercial L2S Ceca	1.981	925	Kuśmierek et al. (2015)
AC from sewage sludge (1:1)	1.809	950	Monsalvo et al.(2011)
Commercial F-400	1.537	997	Kuśmierek and Świątkowski (2015 a)
AC from rattan sawdust	1.468*	1083	Hameed et al. (2008)

* converted from mg·g^{-1} to mmol·g^{-1}

Effect of solution pH

The pH of the solution is a critical parameter as it strongly affects the surface charge of the adsorbent as well as the degree of ionization and speciation of adsorbate. The effect of the initial solution pH on the adsorption equilibrium of the 4-CP was studied in the range of 2 to 11 and the results are presented in Fig. 6. The q_e value decreased with an increase in the pH from 2 to 11 from 0.155 to 0.075 mmol·g^{-1} for the AC30K, from 0.153 to 0.062 mmol·g^{-1} for the AC15K and from 0.111 to 0.035 mmol·g^{-1} for the AC15Na activated carbon, respectively. The adsorption of the 4-CP was almost constant from the pH 2 to 7 on the AC30K and AC15K activated carbons and from pH 2 to 9 on the AC15Na, and decreased significantly with further increase in the pH. These differences are due to different pH_{PZC} values of the individual materials. The pH_{PZC} of the AC30K, AC15K and AC15Na was 6.85, 7.05 and 7.90, respectively. At a pH greater than the pK_a value (9.3), the 4-CP existed predominantly in anionic forms as a negatively charged phenolate anions. In the pH below the pH_{PZC}, the surface of adsorbents was positively charged, while at a pH greater than pH_{PZC}, the surface had a net negative charge. The results showed that the non-dissociated form of 4-CP was preferred by the positively charged surface of the activated carbons. The large reduction in 4-CP adsorption at highly basic conditions can be attributed

to electrostatic repulsion between the negatively charged activated carbons and the dissociated adsorbate molecules. Similar results were reported for the adsorption of 4-CP onto activated carbon prepared from rattan sawdust (Hameed et al. 2008) and Norit R3-ex granular activated carbon (Kuśmierek and Świątkowski 2015).

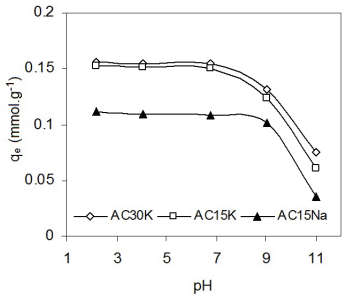

Fig. 6: Effect of initial pH on the adsorption of 4-CP onto activated carbons

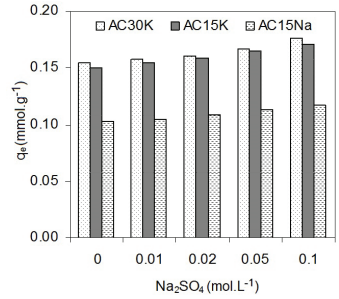

Fig. 7: Effect of initial concentration of sodium sulfate on the adsorption of 4-CP.

Effect of salt presence

The effect of salt presence is an important parameter in adsorption studies because water and wastewater effluent are usually high in salinity and contains a certain amount of salt. The presence of salts in the solution can modify the strength of the adsorbent-adsorbate electrostatic interactions. When the electrostatic interaction between the adsorbent surface and the adsorbate is repulsive, or the surface concentration is sufficiently high, the adsorption will increase with the increased ionic strength. On the other hand, when the electrostatic interaction is attractive, and the surface concentration is sufficiently low, an increase in the ionic strength will decrease the adsorption (Moreno-Castilla 2004). The effect of the sodium sulfate concentration on the adsorption of 4-CP on the hornbeam wood activated carbons is presented in Fig. 7.

In comparison to the adsorption from distilled water the adsorption of the 4-CP from 0.1 mol·L^{-1} Na_2SO_4 solution on the AC30K, AC15K and AC15Na activated carbons increased by 14.0, 13.6 and 14.6%, respectively. The experimental data indicate that the presence of salt in the solution improves the adsorption capacity of the activated carbons. The removal of the 4-CP increased with the increase in the ionic strength of the solution. A similar dependency, enhanced adsorption of the 4-CP in salt presence, was observed for adsorption on F-400 activated carbon (Kuśmierek and Świątkowski 2015).

CONCLUSIONS

The present study revealed that hornbeam wood can be used as a precursor for preparation of activated carbons. The activation conditions (time and activator used) affect the physico-chemical properties of the activated carbons and, in consequence, affect their adsorption abilities towards the 4-chlorophenol. The best adsorbent was found to be the AC30K activated carbon. The adsorption kinetics was found to follow the pseudo-second order kinetic model. Both the Freundlich and Langmuir isotherm models described the 4-CP adsorption on the activated carbons well; nevertheless, a slightly higher R^2 values were observed for the Langmuir model. The adsorption of the 4-CP decreased with an increase in the initial solution pH and increased

with the increase in the ionic strength of the solution. The results showed that the activated carbons derived from hornbeam wood can effectively be used as adsorbents for the removal of 4-chlorophenol from aqueous solutions.

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Beata Doczekalska*, Agata Pawlicka
Institute of Chemical Wood Technology
Poznań University of Life Sciences
Wojska Polskiego 28
60-637 Poznan
Poland
Corresponding author: beatadoc@up.poznan.pl

Krzysztof Kuśmierek, Andrzej Świątkowski
Military University of Technology,
Faculty of Advanced Technologies and Chemistry
Warsaw, Poland

Monika Bartkowiak
Poznań University of Life Sciences,
Institute of Chemical Wood Technology
Poznan, Poland