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ORIGINAL ARTICLE

Waste dolomite powder as an adsorbent of Cd, Pb(II), and Zn from aqueous solutions

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Abstract Sorption experiments of the Cd, Zn, and Pb(II) ions from aqueous solutions on waste dolomite powder were investigated. Waste dolomite powder is inconvenient during storage due to fine particle size; therefore, its practical application is needed. The sorption experiments were conducted with variables: initial metal concentration (500, 1000, and 2000 mg/dm^3) in single- and multi-element solutions, adsorbent dose (0.5, 1, and 2 g), and contact time (45, 90, and 180 min). Results showed that dolomite powder removed all ions from experimental solutions. For multi-element solution, Pb(II) was adsorbed almost in 100% at the initial concentration equal to 2000 mg/dm^3. For Cd and Zn, sorption properties decreased with the increase in the initial metal concentration and the maximum values at the initial metal concentration of 500 mg/dm^3 were 42 and 47%, respectively. The results suggest that waste dolomite powder can be considered for application as sorbent in wastewater purification.

Keywords Dolomite powder · Adsorption · Cadmium · Lead · Zinc · Sorption isotherms

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Introduction

Water and wastewater pollution with heavy metals causes the necessity of water treatment in order to lower heavy metal concentrations to the permissible levels, specified in the national legal regulations. Adsorption is a very important process here, and the type of adsorbent material is crucial in that process. Adsorbent should represent proper technical parameters, mainly such as ion selectivity and cation exchange capacity, as well as the capacity of parameter recovery. Moreover, the material should be inexpensive. For that reason, many different materials have been studied as possible sorbents, i.e., kaolin (Arias et al. 2002), perlite (Mathialagan and Viraraghavan 2002), bentonite (Naseem and Ve Tahir 2001), fly ash (Panday et al. 1984; Bayat 2002), zeolites (Franus et al. 2015), and even steel converter and blast furnace slag (Ortiz et al. 2001; Johansson 1999). More and more often, low-cost materials are investigated as adsorbents (Salam et al. 2011; Hegazi 2013; Mikoda et al. 2017). Experimental usage of calcite for heavy metal sorption, carried out by Zachara et al. (1991), showed a good sorption capacity of that mineral. Research concerning the sorption of metals from wastewater (Brady et al. 1999; Ayoub and Mehaweh 2007; Merrikhpour and Jalali 2012) showed that carbonate minerals

had very good sorption properties. Besides, carbonates increased pH, with the reduction of the mobility of metals at the same time; therefore, carbonates were recognized as good materials to remove heavy metals from industrial wastewaters and to immobilize metals (Merrikhpour and Jalali 2012; Tozsin 2016). Other authors in their latest research revealed that dolomite is also an effective sorbent of metals (Ghaemi et al. 2011, 2013; Mohammadi et al. 2015; Yamkate et al. 2017).

Very fine grain size waste minerals are difficult to dispose of. That is resolved by addition of such waste to cement production (Nocuń-Wczelik and Małolepszy 1995; Jarosz-Krzemińska et al. 2015) or mixing it with concrete (Gougar et al. 1996; Batchelor 2006; Giergiczny and Król 2008). Those methods are generally used in the disposal of such types of waste minerals. However, the finest grain size material is added to construction aggregates rather in small quantities. Consequently, large amounts of fine grain size waste minerals have to be dumped anyway. On the other hand, small particle size corresponds to large outer surface area of the material, as well as large adsorption surface (Ahmaruzzaman 2011).

The aim of the present study was to define the waste dolomite powder's sorption properties, in respect of Cd, Pb(II), and Zn, occurring in aqueous solutions to determine the powder's usefulness in the commercial use in water and wastewater treatment for heavy metals removal. Innovative approach should be stressed in the present experiments because dolomite powder was not considered as adsorbent in any earlier experiments. Moreover, the tested dolomite powder has hardly any practical application and almost the whole quantity of this material is currently disposed of.

Materials and methods

Material

Dolomite powder was chosen for experiments due to the fact that it is a type of waste, and therefore, it is inexpensive and available. The material used in the present work was waste dolomite powder generated in large quantities in the process of mechanical dedusting of dolomite aggregates, used for building and road construction purposes in southern Poland. Our chemical composition analyses (Gruszecka-Kosowska et al. 2015) showed that CaO, MgO, and SiO_2 were dominant in the chemical composition of raw dolomite. The chemical composition in question was as follows: SiO_2: 15.38%, Al_2O_3: 4.12%, Fe_2O_3: 4.12%, CaO: 48.36%, MgO: 19.38%, Na_2O: 0.50%, K_2O: 0.60%, SO_3: 4.64%, TiO_2: 0.18%, and P_2O_5: 0.27%. Additionally, our water leaching tests of metals (Gruszecka-Kosowska et al. 2015) showed that the released metal concentrations

did not exceed permissible levels defined in the Polish Regulation of the Minister of the Environment of December 16, 2014, amending the Regulation on the conditions to be met when introducing sewage into water or soil, and on the substances particularly harmful to the aquatic environment (published in Dz.U. 2014, Item 1800). Besides, waste dolomite powder is not identified as hazardous under the US EPA Toxicity Characteristic Leaching Procedure (the TCLP test). Since it was concluded in previous research that heavy metals had not been released in hazardous concentrations (Gruszecka-Kosowska et al. 2015), our new experiments designed to determine sorption properties were justified.

Sample preparation

Due to the fine grain size of the dolomite powder (Gruszecka-Kosowska et al. 2015), experiments with the grain size ranging from 0.3 to 110 μm and the predominant grain size of 20 μm were conducted. The material was not milled; pH was measured with the use of distilled water (L/S ratio 10:1), and it amounted to 13.8.

Sorption experiments

Adsorption experiments were carried out to determine the sorption values of the Cd, Pb(II), and Zn in aqueous solutions. Stock solutions of Cd, Pb(II), and Zn were achieved by separate dilution of the proper amounts of $CdCl_2 \bullet 2.5H_2O$, $PbCl_2$, and $ZnCl_2$ in Millipore deionized water to obtain the different concentrations of 500, 1000, and 2000 mg/dm^3 for each of the three investigated metals. Multi-element solutions containing 500, 1000, and 2000 mg/dm^3 of Cd, Pb(II), and Zn each were also carried out. The concentration of obtained solution was determined via AAS method. In our experiments, we used the pH 3 solution, which was the boundary value for the optimum pH value of the adsorbent to remove Zn, Pb(II), and Cd ions from solutions, as reported by Merrikhpour and Jalali (2012) and Kocaoba (2007). The variable parameters of sorption experiments were the following: adsorbent doses equal to 0.5, 1, and 2 g and the contact time equal to 45, 90, and 180 min for each adsorbent dose. Samples were shaken on a mechanical shaker, with the speed of 450 rpm. Additionally, blank samples (sorbents with only Millipore deionized water) were prepared and run in similar conditions as those of the tested samples to identify any impact of the laboratory equipment.

The amounts of adsorbed heavy metal doses are calculated from Eq. (1):

$$q_e = (C_o - C_e) \cdot V/M \tag{1}$$

where q_e—total amount of adsorbed metal ions (mg/g), C_o—initial concentration of metal in the solution (mg/

dm^3), C_e—equilibrium concentration of metal in the solution (mg/dm^3), V—volume of the analyzed solution (dm^3), M—adsorbent mass (g).

The percent metal ion removal (R, %) was calculated based on Eq. (2):

$$R\% = [(C_o - C_e)/C_o] \cdot 100\%. \tag{2}$$

Freundlich model of sorption

Freundlich sorption isotherms were designated for the sorption of Cd, Pb(II), and Zn ions, because that model of sorption provided a better adjustment in case of sorption from solutions. For the linear form of the Freundlich equation, Eq. (3) was used:

$$\ln q_e = \ln K_F + (1/n) \ln C_e \tag{3}$$

where K_F—Freundlich constant (dm^3/g) and $1/n$—heterogeneity factor.

Langmuir model of sorption

For linear form of Langmuir equation, Eq. (4) was used (Franus and Wdowin 2010):

$$C_e/q_e = 1/(q_{max} K_L) + C_e/q_{max} \tag{4}$$

where q_e—equilibrium amount of NH_4^+ exchanged by tested materials (mg/g), C_e—equilibrium NH_4^+ concentration in the solution (mg/dm^3), q_{max}—maximum uptake of ammonia exchanged (mg/g), K_L—Langmuir constant (dm^3/mg).

Temkin model of sorption

Temkin isotherms contain a factor that explicitly taking into the account of adsorbent–adsorbate interactions. As implied in the equation, its derivation is characterized by a uniform distribution of binding energies was carried out by plotting the quantity sorbed q_e against lnC_e and the constants were determined from the slope of trend line. The model is described by the following (5–8) equations (Tempkin and Pyzhev 1940):

$$q_e = (RT/b) \cdot \ln(A_t C_e) \tag{5}$$

$$q_e = (Rt/b) \cdot \ln A_t + (RT/b) \cdot \ln C_e \tag{6}$$

$$B_t = RT/b \tag{7}$$

$$q_e = B_t \ln A_t + B_t \ln C_e \tag{8}$$

where A_t—Temkin isotherm equilibrium binding constant (L/g), b—Temkin isotherm constant, R—universal gas constant (8.314 J/mol/K), T—temperature 298 K, B_t—constant related to heat of sorption (J/mol).

Dubinin–Radushkevich model of sorption

The Dubinin–Radushkevich (DR) isotherm model is used to estimate the characteristic porosity of the biomass and the apparent energy of adsorption (Itodo and Itodo 2010). The model is represented by the following (9–11) equations:

$$q_e = q_s \exp(-B_D RT \ln(1 + 1/C_e) \tag{9}$$

where B_D—related to the free energy of sorption per mole of the sorbate as it migrates to the surface of the biomass from infinite distance in the solution, q_s—Dubinin–Radushkevich isotherm constant related to the degree of sorbate sorption by the sorbent surface (Horsfall et al. 2004; Itodo et al. 2009).

The linear form of Eq. (10) is as follows:

$$\ln q_e = \ln q_s - 2B_D RT \ln(1 + 1/C_e). \tag{10}$$

A plotting of lnq_e against $RT \ln (1 + 1/C_e)$ for modified sorbents gives straight lines and indicates a good fit of the isotherm to the experimental data.

The apparent energy (E_D) of adsorption from Dubinin–Radushkevich isotherm model can be calculated using relation (11) given as below (Horsfall et al. 2004).

$$E_D = \sqrt{1/2B_D}. \tag{11}$$

Apparatuses

The concentrations of Cd, Pb(II), and Zn were determined in the solution after our sorption experiments, using inductively coupled plasma mass spectrometry (ICP-MS, PerkinElmer Sciex ELAN 6000). Mineralogical characteristics were performed, using a scanning electron microscope (SEM–EDS (SEM) FEI Quanta 250 FEG), equipped with a system of chemical composition analysis, based on energy-dispersive X-ray-EDS of EDAX Company, where the morphological forms and the chemical composition of the main mineral components were determined.

Results and discussion

Mineralogical characteristics of tested material

XRD mineralogical analyses carried out by Gruszecka-Kosowska et al. (2015) showed that the raw waste consisted mainly of carbonate minerals (dolomite, calcite, and ankerite), while quartz, feldspars, and galena were observed in much smaller concentrations. The SEM–EDS analysis (Fig. 1) confirmed that the carbonate minerals mentioned above were dominant in the mineral composition. The analysis also showed that the material was

characterized by medium-sized grains. Generally, two fractions were observed in the tested materials: fine, in the form of aggregates with the particle size of 1–2 microns (Fig. 1A), and large of 5–20 μm (Fig. 1B). Observation of grain morphologies identified visible and well-formed carbonate mineral crystals (of calcite and dolomite).

The SEM–EDS analysis of the sorption experiment showed that the adsorbed heavy metals (Cd, Pb(II), and Zn) penetrated the waste dolomite structure as a result of ionic substitution since the observation of grain surface did not reveal precipitation of pure metals. However, the EDS analysis showed the presence of those metals in the sample after sorption (Fig. 2).

Sorption experiments

Blank experiment

When analyzing only Millipore deionized water (25 cm^3) in contact with adsorbent (2 g), it was observed that mainly Ca, K, and Mg ions were released from the material being analyzed during the contact time of 180 min (Table 1). In low quantities (below 0.3 mg/dm^3), Pb, Ba, Cu, and Al ions were released. Upon the comparison of the released concentrations of elements to the permissible daily levels defined in the above-mentioned Polish Regulation (Dz.U. 2014, Item 1800), it can be stated that the elements released during water leaching did not exceed permissible standards. That is important because leachate from waste under discussion can get into the environment (i.e., into water or soil).

Contact time effect

The results of our experiments carried out with the initial concentration of 500 mg/dm^3 each, in respect of the three analyzed metals, and with the adsorbent doses equal to 0.5 g (Fig. 3A), 1 g (Fig. 3B), and 2 g (Fig. 3C) showed that the sorption values of Cd and Zn were equal to 100%, regardless of contact time. The highest sorption value of Pb(II) 98.6% was achieved in the shortest contact time of 45 min. However, after a longer contact time, the sorption value slightly decreased: Pb(II) removal amounted to 96.9% in the contact time of 180 min.

It was also observed that already at the lowest adsorbent dose (0.5 g) and the shortest contact time (45 min), the sorption value was equal to 100% of Cd, 99.9% of Zn, and 98.6% of Pb(II). We concluded that the established initial concentrations, which soon became very high, were still too low to define maximum sorption. However, higher values were not necessary due to the fact that the concentrations of metals in water and wastewater are much lower than those appearing in our experiments. On the other hand, our experiments showed that dolomite powder offered a chance for a very good metal adsorption from wastewater with high metal content.

Adsorbent dose effect

The metal sorption rate depended on the waste dose applied as adsorbent, as shown in Fig. 3. It was observed that the sorption value was equal to 100% of Cd and Zn each, regardless of the contact time, while in the case of Pb(II), an increased adsorbent dose caused increase in the sorption value, which was not lower than 97%.

Initial metal concentration effect

An experiment relating to initial concentration effects was carried out with the adsorbent dose equal to 0.5 g and the contact time of 45 min. The solutions with the initial
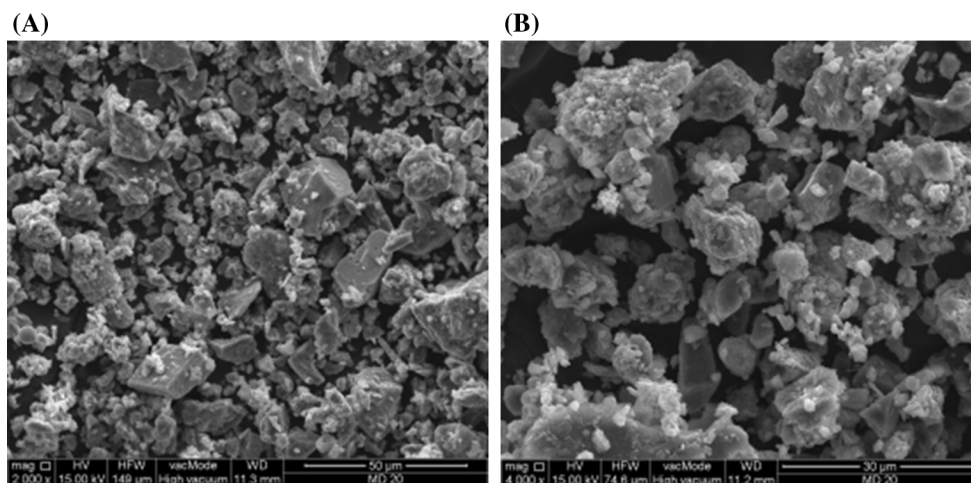

Fig. 1 SEM microphotographs of the tested dolomite powder: **a** magnification ×2000 **b** magnification ×4000

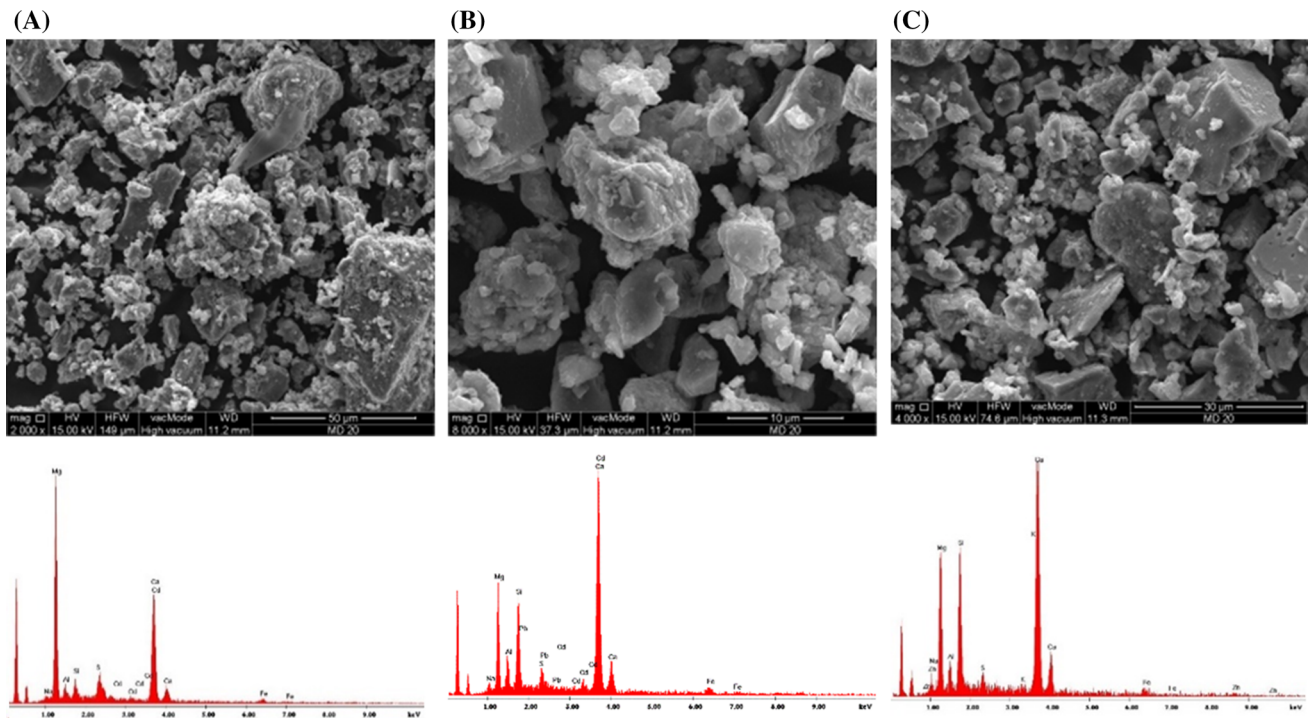**(A)**　　　　　　　　　**(B)**　　　　　　　　　**(C)**

Fig. 2 SEM–EDS analysis of dolomite powder after sorption experiments: **a** after Cd sorption, **b** after Pb(II) sorption, **c** after Zn sorption

Table 1 Element concentrations in eluates from water leaching of a dolomite powder sample (L/S 12.5:1) and the maximum permissible levels of concentrations

Element	Concentration in eluates after 180 min. of shaking (mg/dm^3)	Maximum permissible levels[a] (mg/dm^3)
Cd	0.00	0.007
Mn	0.00	–
Fe	0.00	10
Co	0.00	0.1
Zn	0.00	2
Ni	0.00	0.1
Cr	0.00	0.5[b]
Al	0.09	3
Cu	0.10	0.5
Ba	0.14	2
Pb	0.29	0.5
Mg	0.71	–
K	4.88	80
Na	11.50	800
Ca	212.50	–

[a] Regulation of the Minister of the Environment of December 16, 2014, amending the Regulation on the conditions to be met when introducing sewage into water or soil, and on the substances particularly harmful to the aquatic environment (Dz.U. 2014, Item 1800)

[b] Total chromium

– Not defined in Dz.U. (2014), Item 1800

concentrations of 500, 1000, and 2000 mg/dm^3 of Cd, 500, 1000, and 2000 mg/dm^3 of Pb(II) and 500, 1000, and 2000 mg/dm^3 of Zn were prepared. The results concerning Cd and Zn (Fig. 4) showed that the sorption values decreased, with the increase in the metal concentration in the solution. At the initial concentration of 500 mg/dm^3, the sorption values of Cd and Zn were equal to 100 and 99.8%, respectively. Comparing to the initial concentration of 500 mg/dm^3 at the initial concentration of 1000 mg/dm^3, sorption decreased by ca. 2% of Cd and ca. 6% of Zn. At the initial concentration of 2000 mg/dm^3, a significant decrease in the sorption value by ca. 37% of Cd and 54% of Zn was observed. In the case of Pb(II), it was observed that, regardless of the initial solution concentration, the sorption value of Pb(II) was at the level which was not lower than 98.6%.

Multi-element solution effect

It is important to remove as many pollutants in the highest possible concentrations as possible during the treatment process before wastewater is dumped into the environment. Therefore, regarding the optimum sorption conditions of Cd, Pb, and Zn, defined above, a competitive sorption experiment was carried out to determine whether the sorption values would also be that high when a multi-element solution is applied. A sorption experiment was carried out with the adsorbent dose of 0.5 g and the contact time of 45 min, as well as the use of multi-element solutions

Fig. 3 Influence of contact time on the removal of Cd, Pb(II), and Zn, with the adsorbent dose of 0.5 g (**a**), 1 g (**b**), and 2 g (**c**)
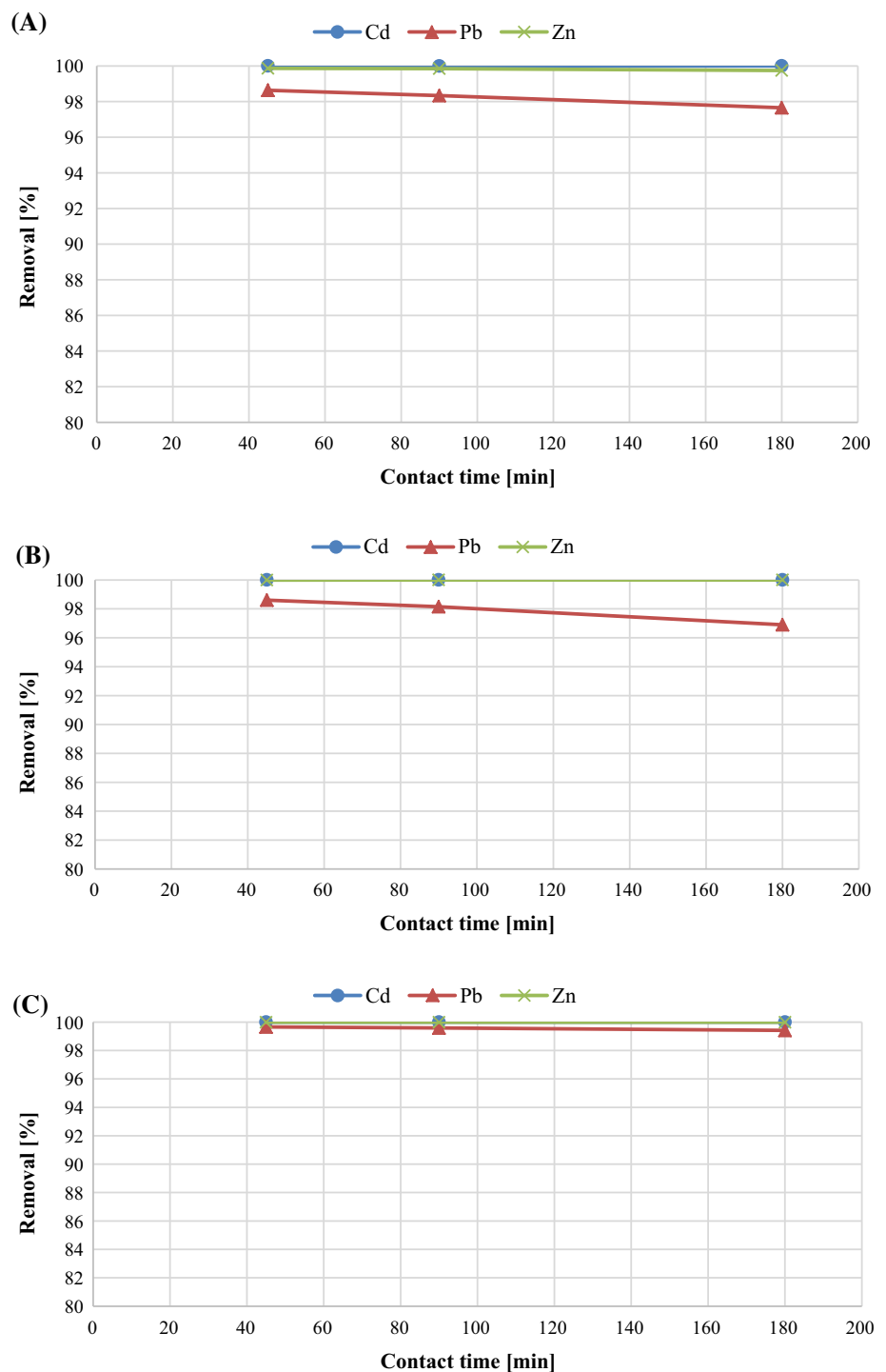
representing the initial metal concentrations of 500, 1000, and 2000 mg/dm^3 of Cd, Pb(II), and Zn, respectively. The experimental results (Fig. 5) showed that the sorption values were the highest in the case of Pb(II) (>99.3%), regardless of the initial metal concentration in the solutions. A significant decrease in Zn and Cd sorption values was observed, with the increase in metal concentrations in

the initial solutions. The maximum sorption value of Zn was 47% and that of Cd was 42% at the initial concentration of 500 mg/dm^3 of the multi-element solutions. The sorption values were equal to 28% of Zn and 23% of Cd at the initial concentration of 1000 mg/dm^3, while the values of Zn and Cd were equal to 19 and 17%, respectively, at the concentration of 2000 mg/dm^3.
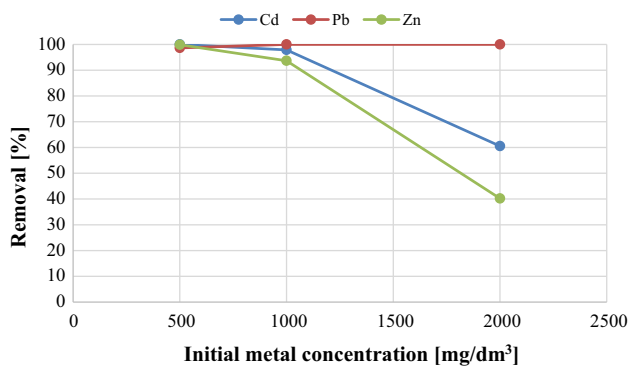
Fig. 4 Influence of the initial metal concentration on the removal of Cd, Pb(II), and Zn (adsorbent dose 0.5 g, contact time 45 min)

The sorption results with the adsorbent dose of 0.5 g were used to define the maximum sorption value (Table 2). The results showed that the maximum sorption value could be defined for Cd and Zn as equal to 93.5 mg/g and 51.4 mg/g, respectively, at the initial concentration of 1000 mg/dm^3 of the analyzed element. The maximum sorption value of Pb(II) was equal to 59.7 mg/g at the initial concentration of 1000 mg/dm^3; and the value kept increasing up to of 212 mg/g at the concentration of 2000 mg/dm^3.

In the case of a multi-element solution, it was observed that the sorption values were significantly lower for Cd and Zn in comparison with one-element solutions and they kept rising constantly, achieving the values of 29.3 mg/g of Cd and 19.6 mg/g of Zn at the initial concentration of 2000 mg/dm^3. The Pb(II) sorption value was close to or a little bit higher than the results obtained in one-element experiments. Consequently, the maximum sorption value could not be defined either.

A general rule says that the sorption value increases with the increase in the initial concentration in the solution (Ahmaruzzaman 2011). It was found in our experiments that the maximum sorption values of Cd and Zn existed at
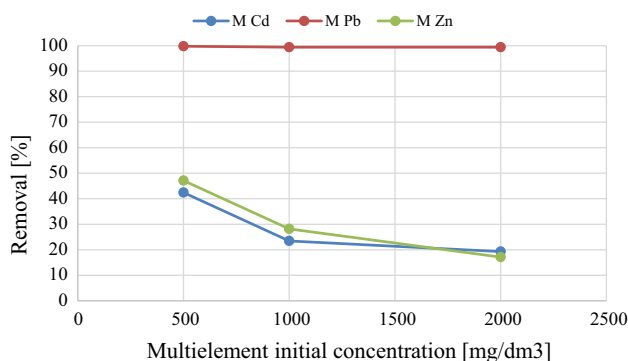

Fig. 5 Influence of initial multi-element metal concentration on the removal of Cd, Pb(II), and Zn (adsorbent dose 0.5 g, contact time 45 min)

the initial concentration of 1000 mg/dm^3, while the highest value of Pb(II) was found at the initial concentration of 2000 mg/dm^3 (the maximum Pb(II) sorption was not defined for the selected initial concentrations).

Freundlich, Langmuir, Temkin, and Dubinin–Radushkevich model of sorption

Sorption isotherms for single-element and multi-element solutions differed significantly from each other. In presented paper, the attempts were taken to formalize the experimental data using the adsorption equations described above. Our analysis has shown that Freundlich sorption isotherms (Figs. 6, 7, 8) were the best fit of the model for the all ions sorption at R^2 equal to 0.89 for Cd and 0.7 for Zn and Pb (Table 3), and the better fit was for multicomponent solution for Zn and Pb(II) in almost all R^2 of each sorption models. The calculated constant K_F was an approximate indicator of adsorption capacity, while 1/n was a function of the strength of adsorption in the adsorption process (Voudrias et al. 2002). The values of 1/n were lower than 1 in all the tested cases, which indicated positive removal of heavy metals (Karadag et al. 2006; Ivanova et al. 2010; Franus and Wdowin 2010; Dada et al. 2012). The smaller the 1/n, the greater the expected heterogeneity as in case of Zn multicomponent solution (Dada et al. 2012). In the case of fitting to the equilibrium of a simple Temkin isotherm, the resulting data have negative values, what do not have the physical sense. Therefore, this isotherm was not shown in the graphs.

The graphs show Langmuir, Freundlich, and DR adsorption isotherms, based on determined constants. Points indicate experimental values (Figs. 6, 7, 8). A weak match of isotherms only for single-ion was observed. This is due to the complete removal of the ions for all the output concentrations.

In the case of adsorption from the mixture, a better fit for all the adsorption equations was observed. Considering the mechanism of removing the analyzed ions, the applied formalism did not give unambiguous answer whether we were dealing with the phenomenon of physical nature or chemisorption. When using DR equals, the calculated energy value could suggest what mechanism we were dealing with. Based on the obtained results, it appeared that the attempt to formalize experimental data with the DR equation did not give evident proofs for such conclusions.

Matching experimental points was unsatisfactory. Perhaps more points on the isotherm would give more opportunities. But here it is worth considering whether the calculated energy from the DR equation would be decisive. It should be remembered that DR equation was derived for pure microporous adsorbents with homogeneous pore diameters. What is more, the linear form of the DR

Table 2 Sorption of Cd, Pb(II), and Zn (mg/g) on 0.5 g of dolomite powder

Initial concentration of metals in solutions (mg/dm^3)	Sorption (mg/g)			Sorption from multiple solution: Cd–Pb–Zn (mg/g)		
	Cd	Pb	Zn	Cd	Pb	Zn
500	27.0	24.8	24.0	17.8	35.1	14.7
1000	93.5	59.7	51.4	15.3	62.1	17.6
2000	89.9	212	39.8	29.3	211	19.6

(A)

(B)

Fig. 7 The sorption isotherms of Zn (**a**) and Zn-M (**b**)
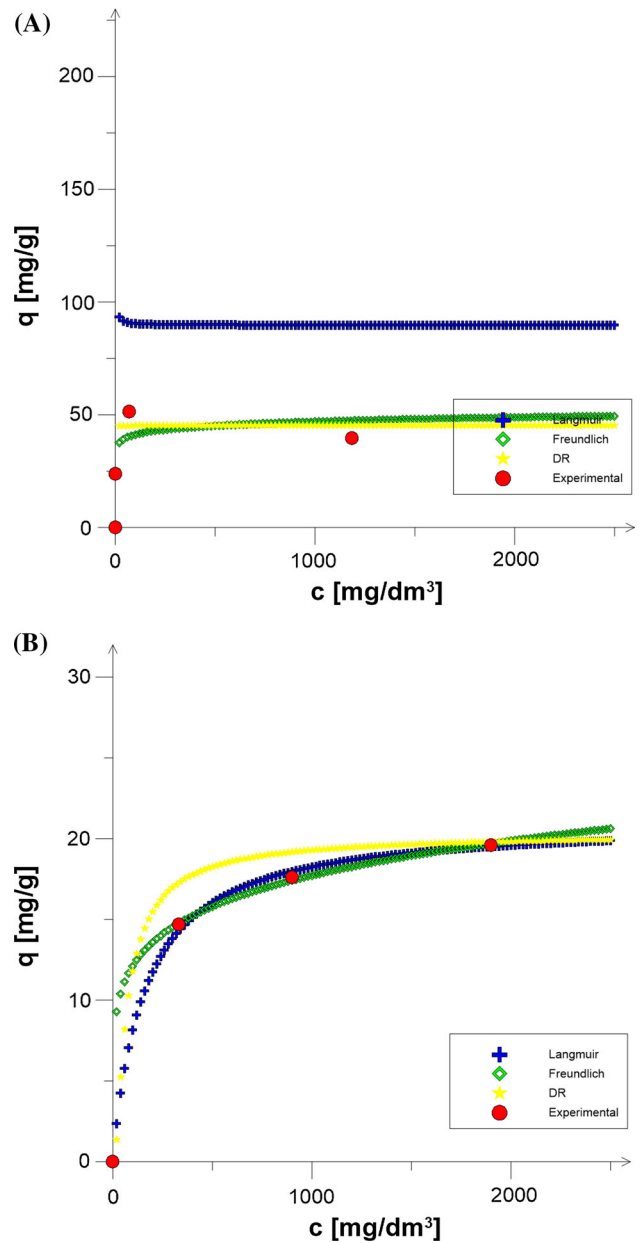

(A)

(B)

Fig. 6 The sorption isotherms of Cd (**a**) and Cd-M (**b**)

equation was not consistent with the full range, and for the initial points the isotherm deviated from the linearity. And in the case of the investigated adsorption systems we found very low concentrations. In addition, dolomite powder was not microporous adsorbent.

The calculated surface area was not the result of the presence of pores (micro, meso or macro) but only the size of the adsorbent fragmentation (the finer the particle size of this adsorbent the greater the surface area of 1 g adsorbent). However, it seems that the evaluation of the nature of the ion-adsorbent interaction may be based on the results of the experiment of the ion mixture. In the case of
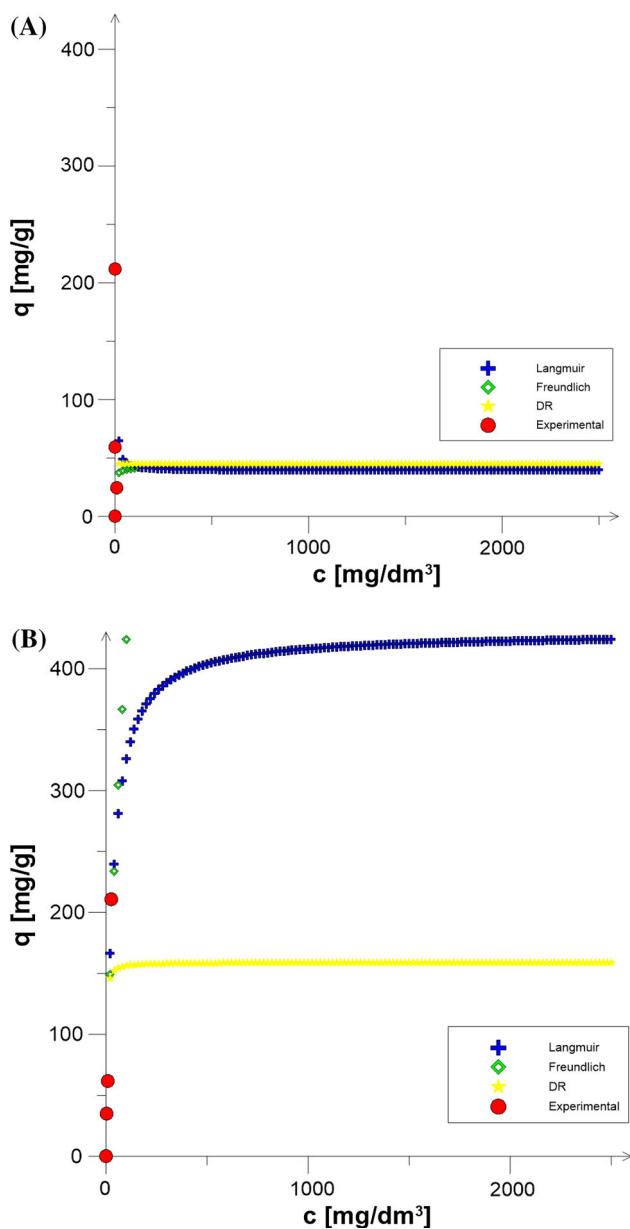
Fig. 8 The sorption isotherms of Pb(II) (**a**) and Pb-M (**b**)

Table 3 Isotherm constants for different models of sorption for Cd, Pb(II), and Zn

Element	Freundlich			Langmuir			Temkin				Dubinin–Radushkevich			
	$1/n$	K_F (mg/g)	R^2	q_{max} (mg/g)	K_L (L/mg)	R^2	A_t (L/g)	B_t (J/mol)	b	R^2	K_{ad} (mol^2/kJ^2)	q_s (mg/g)	E (kJ/mol)	R^2
Cd	0.1	46.5	0.89	89.84	−1.32	0.99	0.00013	−6.24	−396.91	0.88	6.29382E−05	92.03	0.006	0.998
Cd-M	0.3	2.11	0.59	39.65	0.001	0.79	64.025	−7.41	−334.305	0.65	0.05	26.62	0.158	0.375
Zn	0.007	31.85	0.69	39.555	−0.13	0.99	1.34E−08	−1.86	−1328.80	0.60	3.26E−05	45.27	0.004	0.889
Zn-M	0.2	5.65	0.99	21.16	0.006	1.00	1.748	−2.808	−882.04	1.00	0.022	20.39	0.105	0.977
Pb	−0.3	46.12	0.69	24.71	−30.93	1.00	25.000	21.72	114.07	0.45	−0.0001	22.579	–	0.711
Pb-M	0.7	21.38	0.92	462.49	0.03	0.46	1.41	−62.85	−39.42	0.82	0.0007	159.13	0.019	0.73

Cd-M—Cd from multi-element solution

Zn-M—Zn from multi-element solution

Pb-M—Pb from multi-element solution

adsorption of single ions, we have to deal with practically the entire removal of a given ion, which may occur in the case of both chemical and physical sorption. However, in the case of the mixture we can see a certain regularity associated with the position of the metals in the galvanic series.

For example, the zinc has the most negative potential, and the lead is the highest of the tested metals in the galvanic series. As it is known, metals with a higher standard potential are easier to reduce. Observing the results of the adsorption in the mixture, lead was removed in the first place, followed by cadmium and then zinc. Interpretation of the position in the galvanic series, taking into account

Table 4 Comparison of the adsorption capacity of various materials

Adsorbent	Adsorption capacity (mg/g)			References
	Cd	Pb	Zn	
Bentonite	11.4	20.0	4.54–52.9	Babel and Kurniawan (2003)
Blast furnace slug	38.0	40.0	103.3	Ahmaruzzaman (2011)
Blast furnace slug	38.0	40.0	17.6	Ahmaruzzaman (2011)
Chabazite	6.70–137	6.00	5.50	Babel and Kurniawan (2003)
Chitosan	5.93–250	16.4	75	Babel and Kurniawan (2003)
Clinoptilolite	1.20–70.0	1.40–62.0	0.50–2.70	Babel and Kurniawan (2003)
Coffee husk	6.85	–	5.57	Ahmaruzzaman (2011)
Dolomite powder	27.0–93.5	24.8–212	24.0–51.4	This study
Fly ash	0.05–198.2	12.61–566	0.068–30.8	Ahmaruzzaman (2011)
Illite	–	4.29	–	Babel and Kurniawan (2003)
Kaolinite	0.32	0.12–0.41	–	Babel and Kurniawan (2003)
Lignin	6.7–7.5	1865	11.24–73	Ahmaruzzaman (2011)
Montmorillonite	0.72–4.78	0.68	4.98	Babel and Kurniawan (2003)
Red mud	66.7	–	12.6	Ahmaruzzaman (2011)
Sugar beet pulp	38.0–46.1	43.5	35.6	Ahmaruzzaman (2011)
Tea industry waste	8.64	2–65	11	Ahmaruzzaman (2011)
Waste slurry	45.7	1030	–	Ahmaruzzaman (2011)

– Data not available

the conclusions of the position in this series, allows us to claim that the chemical character of adsorption on the surface of dolomite dust was observed.

Comparison of the adsorption capacity and metal ion removal efficiency depending on the use of various adsorbents reported in the literature

The sorption properties of various materials reported in the literature were compared to the results achieved in respect of waste dolomite powder. Considering data presented by other authors (Table 4), it is seen that such type of waste can be a promising material in removal of heavy metals. We can conclude that the sorption properties of dolomite powder were very good. Furthermore, the sorption properties were also very good in the case of treating multi-element solutions. The main reason of investigation that was carried out was a problem with dolomite powder waste in some Polish mining sector. The novelty of the problem is that so far in Poland such type of waste was not considered as a potential sorbents of heavy metals. Especially that, this waste cannot be applied in production of concrete, etc., due to not suitable chemical composition. Considering data presented by others authors (Table 4), it can be seen that such type of waste can be a promising material in removal of heavy metals. That led us to the conclusion that waste dolomite powder could be efficient in the removal of heavy metals found in high concentrations in multi-element solutions. As it was stated before, dolomite powder is a

waste material that is inexpensive and easily available, thus worth to use in industrial application.

Conclusions

The analysis of the heavy metal sorption on waste dolomite powder presented in this paper showed very good sorption properties of the material. Dolomite powder adsorbed almost 100% of the Cd, Pb(II) , and Zn ions being present in the solution at the selected initial metal concentrations of 500, 1000, and 2000 mg/dm^3. Application of various contact times (45, 90, and 180 min) proved that the entire sorption process was completed as early as after 45 min of contact time. Our experiments with various adsorbent doses (0.5, 1, and 2 g) showed that, regardless of the adsorbent dose applied, the sorption values of Cd, Pb(II), and Zn were not lower than 97%. The best sorption results of multi-element experiments were reached in the removal of Pb(II) from aqueous solutions, where sorption of each metal was at the level of 99% from 2000 mg/dm^3 of the initial concentration. However, Cd and Zn sorption decreased with higher initial multi-element concentrations: from 42 to 47%, respectively, in the multi-element concentration of 500 mg/dm^3 to 19 and 17%, respectively, in the multi-element concentration of 2000 mg/dm^3. Considering the choosing of isotherm models, the best fitting is observed in case of Freundlich equations. Thus, it is desirable to continue experiments with sorption on waste

dolomite powder, with the use of actual wastewater in multi-element solutions, as well as with enriched concentrations of metals in wastewater. Besides, experiments in the dynamic condition are needed.

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