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Adsorption of Organic Compounds on to Bentonites Modified with Single or Dual Quaternary Ammonium Cations

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ABSTRACT: The adsorption of benzoic acid, hydroquinone and toluene on to bentonites modified with single or dual quaternary ammonium cations was studied. Thus, the mineral surface of the bentonite was modified by replacing the inorganic ions with four quaternary ammonium cations, i.e. tetramethylammonium (TMA), benzyltriethylammonium (BTEA), hexadecyltrimethylammonium (HDTMA) and octadecyltrimethylammonium (ODTMA). The inorganic cations on the bentonite were exchanged with the quaternary ammonium cations to the respective extent of ca. 35% TMA, 75% BTEA, 83% HDTMA, 90% ODTMA, 35% TMA/54% HDTMA, 35% TMA/58% ODTMA and 75% BTEA/12% HDTMA of the cation-exchange capacity (CEC) of the bentonite, resulting in a change in the surface properties from hydrophilic to organophilic.

The experimental results obtained indicated that the adsorption affinity on dual-modified bentonites was generally lower than that on single-modified bentonites. It was concluded that this resulted from two different adsorption mechanisms and the competitive adsorption of binary solutes.

INTRODUCTION

Various organic chemicals potentially toxic to biota are produced for agricultural, industrial and domestic uses. There is growing public concern regarding the widespread contamination of surface water and groundwater by organic compounds. The use of a containment system provides one of the most economical ways to prevent and control contaminant migration from the soil to surrounding areas (Li and Denham 2000). Nowadays, several options such as chemical degradation, thermal treatment, soil vapour extraction and biodegradation are available for the treatment of aromatic wastes and the matrices they contaminate, particularly soils. However, the application of these techniques entails high costs. In addition, present methods for disposing of these wastes (i.e. placement in drums for burial, pooling for evaporation) are not reliable and do not provide a permanent solution for containment.

It is essential that safe and cost-effective clean-up processes be developed as an alternative to the current treatment and disposal practices. One such treatment process could be the use of modified (organophilic) clays to adsorb aromatic compounds from contaminated soils and prevent

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them from polluting groundwater (Gitipour *et al.* 1997). Of various modified (organophilic) clays, organobentonites have been the most widely investigated by many researchers (Wolfe *et al.* 1981; Boyd *et al.* 1988; Smith *et al.* 1990, 1991; Jaynes and Boyd 1991; Dentel *et al.* 1995; Jaynes and Vance 1996; Sheng *et al.* 1997; Zhu *et al.* 1997, 1998; Deitsch *et al.* 1998; Yıldız *et al.* 2000; Shen 2002).

Organobentonites are produced by the exchange of organic cations (typically possessing a quaternary ammonium structure) for inorganic ions (e.g. H^+, Na^+, Ca^{2+}) on the internal and external mineral surfaces of the bentonite (Smith *et al.* 1991). The sorption properties of the modified bentonite surfaces may be significantly altered by this exchange reaction. Thus, the resulting organobentonite may become organophilic because the organic functional groups of the quaternary ammonium cations are not strongly hydrated by water. Hence, organobentonites are powerful sorbents for non-ionic organic pollutants relative to natural bentonite and other clays (Boyd *et al.* 1988; Smith *et al.* 1990, Zhu *et al.* 1998). The sorption properties of organobentonites depend greatly on the characteristics of the exchanged organic cations. Smith and co-workers (Smith *et al.* 1990; Smith and Galan 1995) demonstrated that the sorption of tetrachloromethane on to bentonite modified via the exchange of small organic cations was characterized by non-linear isotherms, strong solute uptake and competitive sorption. In contrast, tetrachloromethane sorption on to bentonites modified by relatively large organic cations ($C > 10$) was characterized by essentially linear isotherms, lower solute uptake and non-competitive sorption. The authors concluded that the differences between the two groups of organoclay sorbents were attributable to different sorption mechanisms: adsorption for bentonite modified with organic cations with small functional groups and partition for bentonite modified with organic cations with relatively large functional groups. The small organic cations (e.g. tetramethylammonium) create relatively rigid, non-polar surfaces amenable to non-ionic solute uptake via adsorption. The larger organic cations (e.g. hexadecyltrimethylammonium bromide) create an organic partition medium through conglomeration of their flexible alkyl chains.

Whereas many researcher have studied the sorption of organic compounds by organoclays modified by single organic cations (Mortland *et al.* 1986; Boyd *et al.* 1988; Lee *et al.* 1990; Jaynes and Boyd 1990; Smith and Jaffe 1991; Lo *et al.* 1994; Xu and Boyd 1995; Li and Denham 2000; Koh and Dixon 2001), a small number of studies have been reported on the sorption of binary mixtures of organic compounds by organoclays containing single or dual organic cations. Thus, Smith and Galan (1995) modified Wyoming bentonite by exchanging two classes of quaternary amine cations (both short-chain alkyl or aryl functional groups and long-chain alkyl groups) for the metal cations on the bentonite. Sorption isotherms for tetrachloromethane, trichloroethene and benzene from aqueous solution on to dual organic cation bentonite were studied.

Removal by an adsorption mechanism is appropriate for environmental applications involving a small number of contaminants at low concentrations compared with their solubility in water, while removal by a partition mechanism is suitable for application when multiple contaminants are present at higher concentrations. The objective of the dual organic cation bentonite was to share the advantages of both adsorption and partition mechanisms associated with short- and long-chain hydrocarbon cations, respectively (Smith and Galan 1995).

Lee *et al.* (1997) carried out single and multi-component competitive adsorptions in a batch reactor to investigate the removal of three toxic organic phenols, i.e. 2-chlorophenol, 3-cyanophenol and 4-nitrophenol, using organically modified montmorillonite. To study the removal capacity of phenolic contaminants dissolved in aqueous solution, two organic cations, tetramethylammonium (TMA) and hexadecyltrimethylammonium(HDTMA), were exchanged for the metal cations on the

montmorillonite to the extent of ca. 40% and 45%, respectively, of the cation-exchange capacity (CEC) of the montmorillonite, resulting in a change in the surface properties from hydrophilic to organophilic. As a consequence, they found that the adsorption affinity on the TMA/HDTMA-montmorillonite was in the order 2-chlorophenol > 4-nitrophenol > 3-cyanophenol.

Experimental isotherms quantifying single- and binary-component competitive adsorption of organic chemicals widely used and posing environmental dangers, such as benzoic acid, hydroquinone and toluene, from water to single (35% TMA, 75% BTEA, 83% HDTMA, 90% ODTMA) or dual organic cation (35% TMA/54% HDTMA, 35% TMA/58% ODTMA and 75% BTEA/12% HDTMA) bentonites are presented in this study.

MATERIALS AND METHODS

Fractions smaller than 75 μm of white colour Çankırı (Turkey) sodium bentonite were used in these studies. The natural organic carbon content of the bentonite was 0.7% and its cation-exchange capacity was 79 mequiv/100 g clay. The CEC of the bentonite was determined via the Methylene Blue test (ANSI/ASTM C837-76).

Preparation of organobentonites

The single- and dual-modified organobentonites were prepared as described in detail by Lee *et al.* (1997). Thus, the organobentonites were synthesized by combining bentonite with an aqueous solution containing one and/or two quaternary ammonium cations. The total mass of each cation in the aqueous solution was determined based on the desired organic carbon content of the final organobentonite. In some cases, only a single type of organic cation (TMA, BTEA, HDTMA, ODTMA) was exchanged on to the bentonite.

The resulting material is identified below by a prefix stating the percentage cation-exchange capacity of the bentonite satisfied by the organic cation, followed by the abbreviation for the specific type of organic cation employed. Thus, 35TMA-B, for example, identifies an organobentonite in which only 35% of its CEC was satisfied by TMA cations. In order to prepare single organic cation bentonite, the inorganic cations in the bentonite were exchanged by quaternary organic cations. Adsorption of the quaternary organic cations (TMA, BTEA, HDTMA or ODTMA) was carried out in a 2-l batch reactor using 1 l of a TMA solution whose concentration was twice the CEC value of the bentonite. In this case, 30 g washed bentonite were added to the reactor and agitated with a mechanical stirrer at 500 rpm for 8 h. The single organic cation bentonites were then allowed to settle by gravity for 2 h. The resulting organobentonites were separated from the supernatant liquid and washed two to three times separately with 1 l distilled water under mechanical stirring until a negligible amount of TMA, BTEA, HDTMA or ODTMA was found in the washed solution. Supernatant solutions were analyzed for their organic cation concentrations using a total organic carbon analyzer, TOC C-MAT 5500 (Strohlein, Germany). The synthesized organobentonites were subsequently collected and dried in a freezer dryer for 48 h at −55°C and 10^{-1} mbar pressure.

Dual organic cation bentonites were prepared by adsorption of HDTMA or ODTMA on to 35TMA-B or 75BTEA-B prepared as above. This operation was again performed in a 2-l batch reactor using 1 l of a HDTMA or ODTMA solution whose concentration corresponded to the remaining CEC of the TMA-B or BTEA-B. Thus, 25 g dried TMA-B or BTEA-B was added to the reactor that was agitated mechanically for 8 h at 500–600 rpm. After such agitation, the

TMA/HDTMA-B, TMA/ODTMA-B or BTEA/HDTMA-B samples prepared were collected by settling for 1 h. The collected bentonites were washed twice using 1 l distilled water each time with mechanical stirring until the amounts of free HDTMA or ODTMA found in the washed solution were quite small. All the supernatant solutions were analyzed for non-adsorbed HDTMA or ODTMA using the TOC analyzer. The 35TMA/54HDTMA, 35TMA/58ODTMA or 75BTEA/12HDTMA thus prepared were stored in brown bottles until used.

Analytical methods

The concentrations of organic pollutants in the aqueous phase were determined by ultraviolet spectrophotometry (UV-1601, Shimadzu) at appropriate wavelengths, these being 272.5, 288 and 261 nm for benzoic acid, hydroquinone and toluene, respectively.

Sorption experiments

Solutions of each organic contaminant were prepared at concentrations ranging from 10 mg/l to 600 mg/l. A known amount (50 ml) of the solution was placed in a capped 250-ml flask containing 0.2 g of the single or dual organic cation organobentonites and than vigorously shaken on an orbit shaker (at 150 rpm) for 24 h at 25°C. After such shaking, the solutions (benzoic acid and hydroquinone) were centrifuged for 10 min at 5000 rpm. Toluene solutions were filtered in a filter holder. The loss of toluene due to volatilization was analyzed by contrasting with a blank involving no shaking or centrifugation. The results showed that such loss of toluene amounted to 9.23%.

Binary systems were prepared by incorporating two compounds into the solution. Thus, corresponding binary systems of benzoic acid/toluene and hydroquinone/toluene were prepared. Binary-component adsorption experiments were carried out using the same procedures as described for the single-component adsorption experiments.

RESULTS AND DISCUSSION

Single-component adsorption

Figures 1–3 illustrate the single-solute isotherms obtained on 94ODTMA-B, 83HDTMA-B, 35TMA-B and 75BTEA-B for the adsorption of benzoic acid, hydroquinone and toluene from water at 25°C. Sorption of benzoic acid by the four organobentonites was characterized by relatively strong solute uptake and non-linear isotherms. The isotherms display monolayer characteristics and are of type L (Langmuir) according of the classification of Giles *et al.* (1960). Sorption of hydroquinone by 94ODTMA-B, 83HDTMA-B and 35TMA-B was also characterized by a relatively strong solute uptake and a non-linear isotherm (Figure 2). In contrast, hydroquinone sorption on to 75BTEA-B was much weaker and gave a concave isotherm shape at aqueous concentrations less than 75 mg/l. At aqueous hydroquinone concentrations greater than 75 mg/l, the isotherm was approximately linear but the magnitude of hydroquinone sorption was greater than that of 94ODTMA-B, 83HDTMA-B and 35TMA-B. Unfavourable isotherms of this type may result from weak interactions between the solute and the sorbent at low concentrations relative to solubility (Giles *et al.* 1960; Gregg and Sing 1982). At higher solute concentrations, the sorption of the solute increased because of sorbate–sorbate attraction at the mineral/water interface. A similar isotherm shape was also observed by Lee *et al.* (1989, 1990) for the sorption of *o*-xylene and

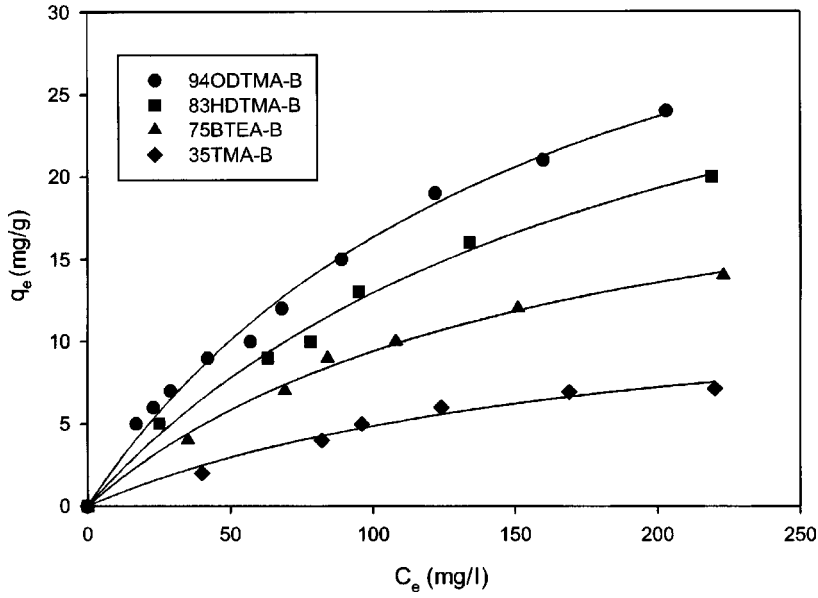


Figure 1. Benzoic acid sorption on to single cation organobentonites.

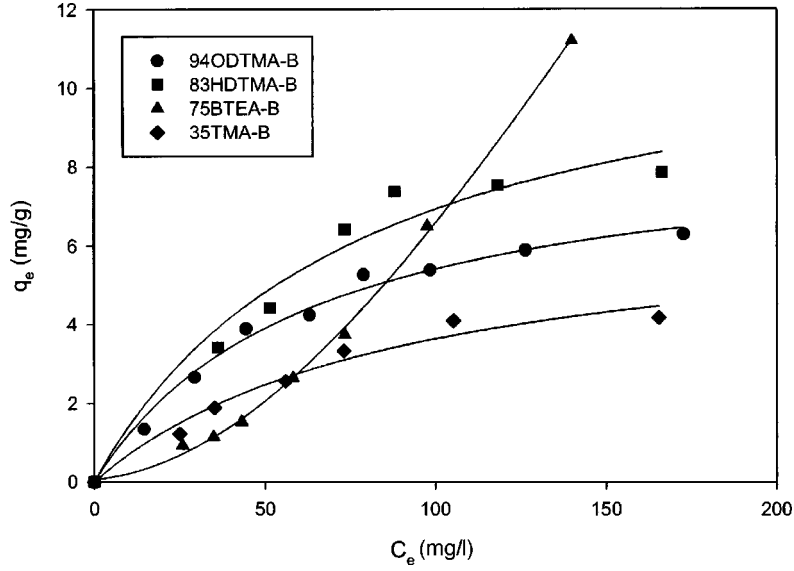


Figure 2. Hydroquinone sorption on to single cation organobentonites.

1,2-dichlorobenzene on to TMA-smectite, by Boyd *et al.* (1988) for the sorption of pentachlorophenol on to various smectite–organic complexes and by Smith and Jaffe (1994) for the sorption of 1,2-dichlorobenzene on to TMA-bentonite.

The adsorption isotherms of toluene on to the four organobentonites are depicted in Figure 3. Sorption of toluene on to 75BTEA-B and 35TMA-B was characterized by relatively strong solute

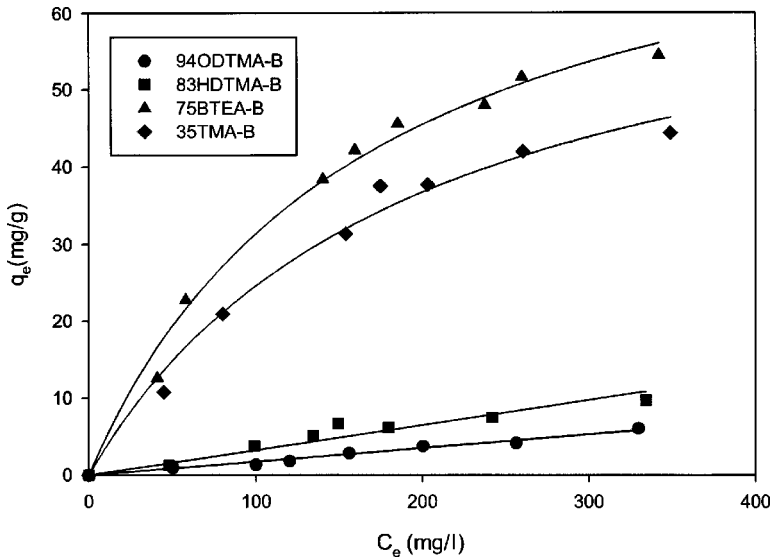


Figure 3. Toluene sorption on to single cation organobentonites.

uptake and isotherm non-linearity. In contrast, toluene sorption on to 94ODTMA-B and 83HDTMA-B was much weaker and the isotherms were linear. Isotherms related to 94ODTMA-B and 83HDTMA-B were of type C (distribution process) (Giles *et al.* 1960). Such curves correspond to the situation where some areas of the adsorbent are very attractive for adsorbate molecules. Being free from adsorbate–adsorbate bonds and provided that the molecule sizes are appropriate, the adsorbate molecule will be capable of penetrating such attractive adsorbent areas and completely fill all those regions which are available on the adsorbent surface.

The experimental results presented in Figure 3 show that toluene was not strongly adsorbed from water by 94ODTMA-B and 83HDTMA-B. On comparing the sorption capacity of each organobentonite for the three solutes, the following orders were followed:

Benzoic acid: 94ODTMA-B > 83HDTMA-B > 75BTEA-B > 35TMA-B;

Hydroquinone: 83HDTMA-B > 94ODTMA-B > 35TMA-B > 75BTEA-B (at low concentration);

Toluene: 75BTEA-B > 35TMA-B > 83HDTMA-B > 94ODTMA-B.

These results show that 94ODTMA-B and 83HDTMA-B are effective adsorbents for benzoic acid and hydroquinone, while 75BTEA-B and 35TMA-B are effective for toluene. This indicates that all four adsorbents could potentially be of use as components of slurry walls at ground-water contamination sites or in earthen landfill liners at hazardous or municipal-waste disposal facilities. Their adsorption capabilities are such that they retard the transport of a variety of non-ionic organic contaminants more effectively than conventional bentonite.

The observed differences between the two groups of sorbents containing small (TMA-B, BTEA-B) and large (ODTMA-B, HDTMA-B) organic cations may be attributed to the involvement of different sorption mechanisms. Thus, adsorption occurred for bentonite modified with quaternary ammonium cations with small functional groups while partition was more prominent for bentonite modified with quaternary ammonium cations with relatively large functional groups (Smith *et al.* 1990). Small organic cations (TMA, BTEA) create a relatively rigid non-polar

TABLE 1. Surface Areas of Organobentonites

Organobentonite sample	Surface area (m^2/g)
original	55.37
TMA35-B	171.30
BTEA75-B	60.31
HDTMA83-B	35.68
ODTMA94-B	28.92

surface amenable to non-ionic solute uptake by adsorption (toluene in this study). Larger organic cations (ODTMA, HDTMA) create an organic partition medium through conglomeration of their flexible alkyl chains.

The reason why the rigid non-polar surface only affects the adsorption of toluene while organic partition contributes to the adsorption of benzoic acid and hydroquinone may be related to the polarities of the solutes and the surface areas of the organobentonites (Table 1). The uptake of a non-polar hydrocarbon (toluene) by organically modified bentonites is essentially due to the adsorption mechanism whereby the non-polar compound trends to adsorb on the non-polar part of the surface of the organic bentonite. Such an adsorption mechanism is supported by the observation of a non-linear isotherm exhibiting a strong solute uptake (Figure 3).

Hydrocarbon sorption by small-cationic organoclays may also be related to the surface areas of the organobentonites. As seen from Table 1, TMA-B and BTEA-B (the two small organic cation bentonites) exhibited surface areas greater than that of untreated bentonite. Such high surface areas suggest that micropores occurred in the interlayer between the organic cations. Small cation organobentonites possess accessible internal surfaces that act as adsorption sites for hydrocarbons. Conversely, HDTMA-B and ODTMA-B exhibited surface areas that were lower than that of untreated bentonite. The increased uptake of polar compounds (benzoic acid and hydroquinone) by large cation organobentonites may be attributed to partition in the organic medium. Hydrocarbon sorption by large-cation organobentonites is unrelated to surface area because sorption by partitioning involves dissolution of the hydrocarbon into a three-dimensional organic phase rather than adsorption on to a non-polar surface (Jaynes and Vance 1996, 1999).

Figures 4–6 depict the isotherms for benzoic acid, hydroquinone and toluene sorption on to organobentonites possessing dual organic cations (35TMA/58ODTMA-B, 35TMA/54HDTMA-B and 75BTEA/12HDTMA-B). The sorption of benzoic acid on to all the organobentonites was characterized by relatively strong solute uptake and a non-linear isotherm similar to sorption on to organobentonites containing single organic cations (Figure 4). The magnitude of benzoic acid sorption on to ODTMA- and HDTMA-bentonites was reduced slightly by the presence of TMA and BTEA cations, being dependent on the decrease in organic carbon content (Table 2). Presumably, TMA and BTEA cations interfere with adsorption sites created by the HDTMA and ODTMA cations and this leads to a reduced solute uptake by partition.

Hydroquinone sorption on to dual organobentonites (35TMA/58ODTMA-B and 35TMA/54HDTMA-B) decreased in the low concentration region and increased slightly in the high concentration region relative to the situation with single organic cation bentonites. Both isotherms exhibited a characteristic S-shape. In contrast, the amount of hydroquinone adsorbed on to 75BTEA/12HDTMA-B changed very little from that on to 75BTEA-B, although it decreased slightly in the high concentration region (Figure 5).

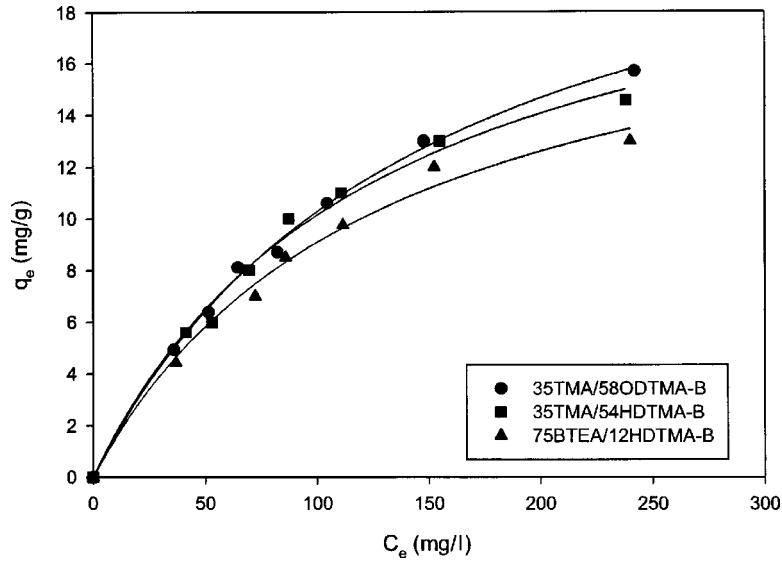


Figure 4. Benzoic acid sorption on to 35TMA/58ODTMA-B, 35TMA/54HDTMA-B and 75BTEA/12HDTMA-B.

The magnitude of toluene sorption on to TMA-B and BTEA-B was also reduced by the addition of ODTMA and HDTMA cations, despite the fact that 35TMA/58ODTMA-B, 35TMA/54ODTMA-B and 75BTEA/12HDTMA-B have a greater organic carbon content than 35TMA-B and 75BTEA-B (Figure 6). This may have resulted from interference between the alkyl chains of the HDTMA and ODTMA cations and the adsorption sites created by the BTEA and TMA cations. Such interference would lead to a reduced solute uptake on adsorption. Although the alkyl chains of the HDTMA and ODTMA cations form a partition medium for solute by adsorption, the magnitude of the increase in solute uptake by partition is less than the magnitude in the decrease in solute uptake by adsorption caused by the HDTMA and ODTMA cations (Smith and Galan 1995). Hence, the magnitude of toluene sorption on to 35TMA/58ODTMA-B, 35TMA/54ODTMA and 75BTEA/12HDTMA-B is less than the magnitude of toluene sorption on to 35TMA-B and 75BTEA-B. Smith and Galan (1995) found similar results for benzene sorption on to 40BTEA and 40BTEA/40HDTMA.

TABLE 2. Organobentonite Sorbents and their Organic Carbon Content

Organobentonite sample	Organic carbon content (%)
original	0.7
35TMA-B	3.49
75BTEA-B	13.78
83HDTMA-B	19.88
94ODTMA-B	24.28
35TMA/58ODTMA-B	17.96
35TMA/54HDTMA-B	15.93
75BTEA/12HDTMA-B	16.55

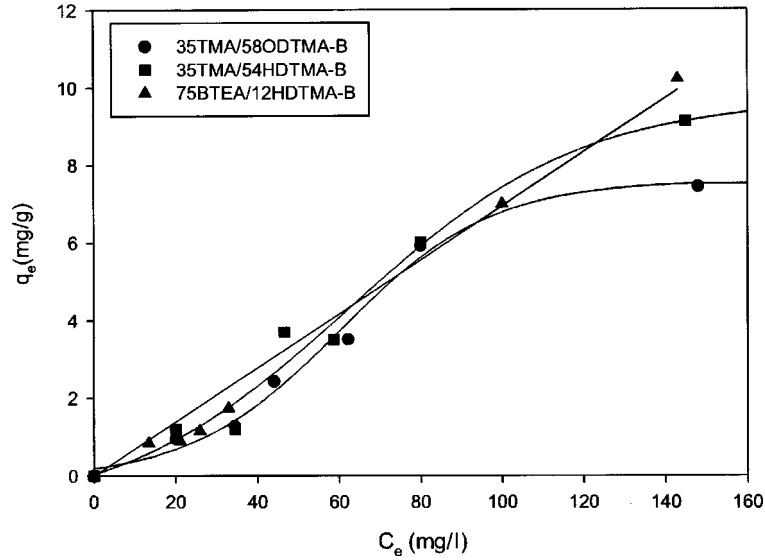


Figure 5. Hydroquinone sorption on to 35TMA/58ODTMA-B, 35TMA/54HDTMA-B and 75BTEA/12HDTMA-B.

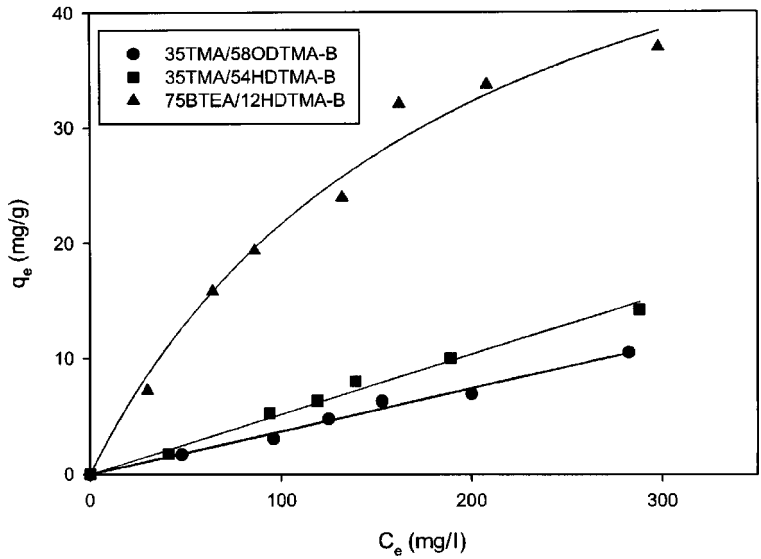


Figure 6. Toluene sorption on to 35TMA/58ODTMA-B, 35TMA/54HDTMA-B and 75BTEA/12HDTMA-B.

The well-known monolayer Langmuir model (Lin and Cheng 2000) was applied to the experimental data for single-solute isotherms. This model may be expressed by the equation:

$$q_e = Q_0 b C_e/(1 + bC_e) \quad (1)$$

where q_e and C_e are the equilibrium adsorption capacity of the organobentonites and the equilibrium solute concentration in the aqueous solution, respectively, and Q_0 and b in the Langmuir

TABLE 3. Langmuir Parameters of Single-solute Systems

Adsorbent	Solute	Q_0	b	r^2
94ODTMA-B	benzoic acid	28.986	0.012	0.986
83HDTMA-B	benzoic acid	26.316	0.009	0.978
75BTEA-B	benzoic acid	23.697	0.007	0.988
35TMA-B	benzoic acid	15.552	0.004	0.989
94ODTMA-B	hydroquinone	12.048	0.009	0.989
83HDTMA-B	hydroquinone	16.639	0.007	0.957
35TMA-B	hydroquinone	11.086	0.005	0.972
75BTEA-B	toluene	125.00	0.030	0.949
35TMA-B	toluene	119.048	0.002	0.982
35TMA/58ODTMA-B	benzoic acid	25.974	0.007	0.994
35TMA/54HDTMA-B	benzoic acid	25.707	0.006	0.971
75BTEA/12HDTMA-B	benzoic acid	22.573	0.007	0.993
75BTEA/12HDTMA-B	toluene	96.154	0.003	0.991

model represent the monolayer adsorption capacity and a constant related to the adsorption equilibrium constant, respectively. Table 3 presents the results of the regression analyses for the different solute–organobentonite combinations considered in this research. The goodness-of-fit of the isotherm model (r^2) was evaluated, the corresponding results close to unity demonstrating the model provided good fits of all the experimental data.

Binary-solute adsorption

Binary competitive adsorptions were performed using two binary systems, i.e. benzoic acid/toluene and hydroquinone/toluene. Two single-solute and two binary-solute isotherms were generated at 25°C and are depicted in Figures 7 and 8, respectively. One of the main features of adsorption was that the adsorption capacity of a given single component was reduced when binary solutes were present, due to the finite adsorption sites available. Figure 7 shows the adsorption isotherms for benzoic acid from single- and binary-component competitive adsorptions. The adsorption capacities of benzoic acid decreased when another solute (toluene) was present due to competitive adsorption for the available sites. Figure 8 shows that the amount of hydroquinone adsorbed on to 94ODTMA-B and 83HDTMA-B was also affected by the competitive adsorption of toluene. Similar results have been reported by Lee *et al.* (1997) for the adsorption of phenolic compounds on to TMA/HDTMA-bentonite.

Binary competitive adsorptions on to dual organic cation bentonites were also studied with the corresponding isotherms being depicted in Figures 9 and 10. The data in Figure 9 quantify the sorption of benzoic acid on to 35TMA/58ODTMA-B, 35TMA/54HDTMA-B and 75BTEA/12HDTMA-B in the presence of a binary solute (toluene). Benzoic acid sorption from water on to dual organic cation bentonites was characterized by the generation of a non-linear isotherm, competitive sorption and relatively strong solute uptake. However, the adsorption capacity of a single component (benzoic acid) was reduced slightly when a binary solute was present.

The curves depicted in Figure 10 quantify hydroquinone sorption on to dual organic cation bentonites in the presence of a binary solute (toluene). In contrast to the sorption of benzoic acid

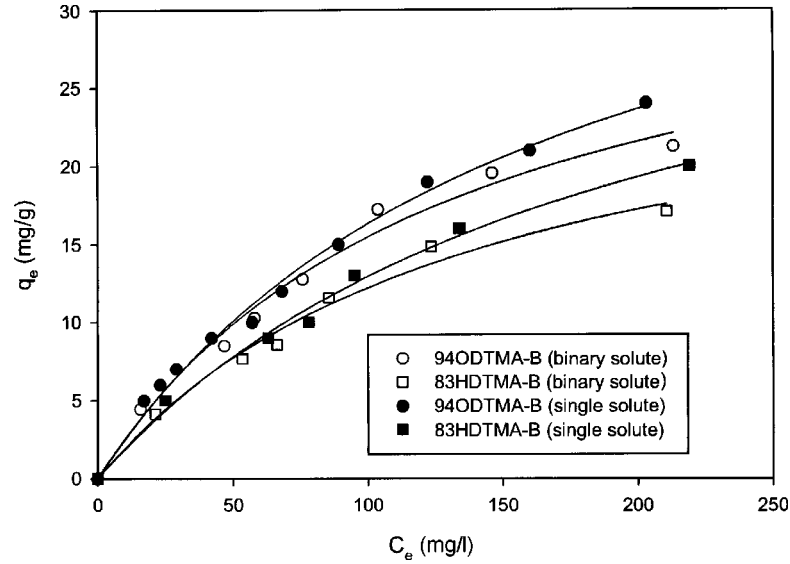


Figure 7. Benzoic acid sorption on to 94ODTMA-B and 83HDTMA-B. The binary solute was toluene.

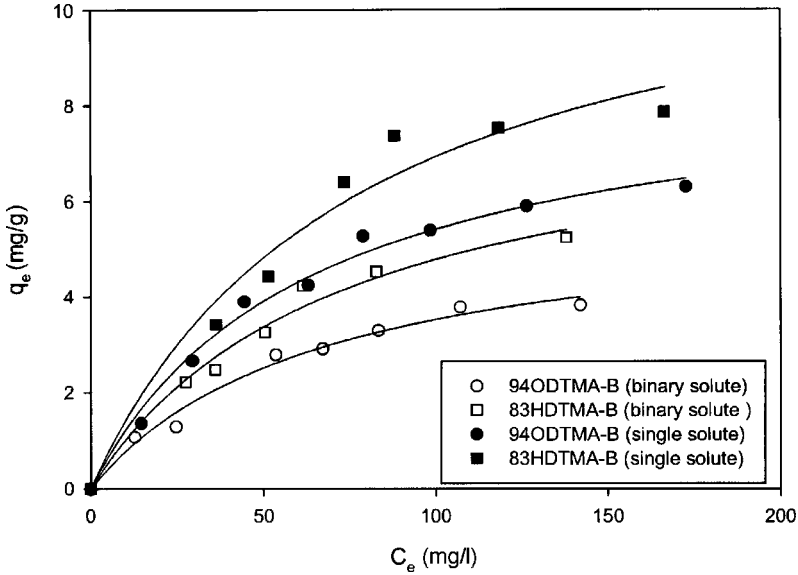


Figure 8. Hydroquinone sorption on to 94ODTMA-B and 83HDTMA-B. The binary solute was toluene.

in the presence of toluene, Figure 10 shows that toluene had only a relatively very small effect on hydroquinone adsorption on to dual organic cation bentonites relative to the situation depicted in Figure 5, with the isotherms again being characterized by an S-shape similar to the isotherms in Figure 5. This result demonstrates that toluene was unable to compete effectively with hydroquinone for adsorption sites.

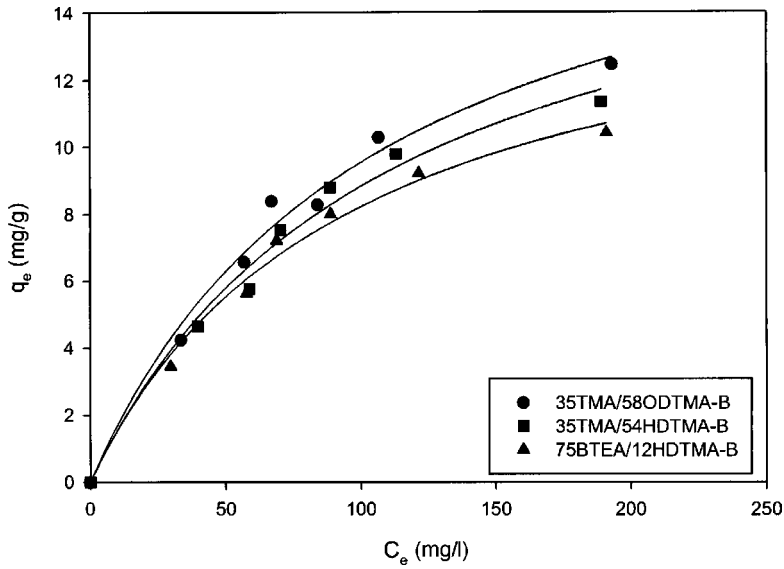


Figure 9. Benzoic acid sorption on to 35TMA/58ODTMA-B, 35TMA/54HDTMA-B and 75BTEA/12HDTMA-B. The binary solute was toluene.

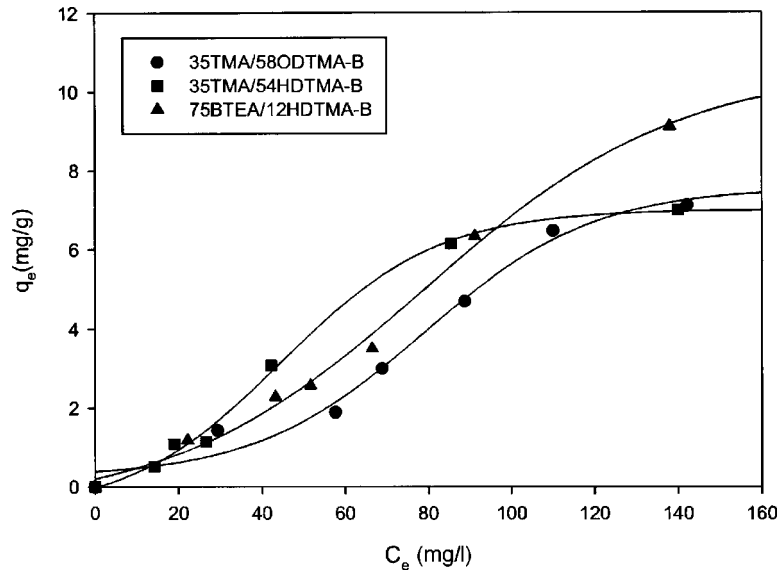


Figure 10. Hydroquinone sorption on to 35TMA/58ODTMA-B, 35TMA/54HDTMA-B and 75BTEA/12HDTMA-B. The binary solute was toluene.

CONCLUSIONS

The adsorption of benzoic acid, hydroquinone and toluene on to single and dual organic cation bentonites has been studied using single and binary systems in aqueous solution at 25°C. Using ion-exchange reactions with organic cations, the surface properties of the original bentonite were

changed from hydrophilic to organophilic. Of the four quaternary amines tested in the present work, BTEA-B and TMA-B performed best towards toluene adsorption, whereas HDTMA-B and ODTMA-B showed inferior behaviour with toluene although they performed well towards the adsorption of hydroquinone and benzoic acid.

The magnitude of benzoic acid, hydroquinone and toluene sorption on to dual organic cation bentonite was somewhat reduced relative to the situation with single organic cation bentonites. It is possible that, over the range of surface coverages in the organic cations studied (expressed as a percentage of CEC), the adsorption and partition components of the dual cation organobentonite sorbents did not function independently. For example, for a given aqueous toluene equilibrium concentration, the concentration of toluene sorbed on to 35TMA/58ODTMA-B, 35TMA/54HDTMA-B and 75BTEA/12HDTMA-B was less than the concentration of toluene sorbed on to 35TMA-B and 75BTEA-B. This indicates that the long-chain functional groups of the ODTMA and HDTMA cations interfered with solute adsorption on to the TMA- and BTEA-modified mineral surfaces of the bentonite.

Single-component adsorption was compared to binary-component adsorption for benzoic acid and hydroquinone (binary solute toluene) on to single and dual organic cation bentonites. It was found that the adsorption capacity of benzoic acid (as measured in single-component systems) was higher than that in binary-component systems for both single and dual organic cation bentonites. This was attributed to competitive adsorption in binary systems. Furthermore, the amount of hydroquinone sorbed on to single organic cation bentonites in single-component systems was higher than that of binary component systems, a situation that showed little change for dual organic cation bentonites.

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