Passive remediation of coalbed natural gas co-produced water using zeolite

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Abstract:

Coalbed natural gas (CBNG) co-produced waters can contain sodium (Na^+) concentrations that may be environmentally detrimental if discharged to receiving bodies of water or applied to land surfaces. A field demonstration and companion laboratory studies were conducted to evaluate the use of a Bear River zeolite (BR-zeolite) for mitigating impacts associated with Na^+ in CBNG waters. Bench-scale kinetic and adsorption isotherm studies were performed to determine both the rate and extent of sodium Na^+ adsorption and assess the effects of bicarbonate (HCO_3^-) and chloride (Cl^-) anions. Results of these studies showed that the adsorption of Na^+ on BR-zeolite followed the Langmuir adsorption model with maximum adsorption equal to 21 and 18 g Na^+ /kg zeolite with 0.0012 and 0.0006 L/mg Langmuir co-efficients (K_L) for sodium bicarbonate and sodium chloride, respectively. The kinetics study indicated that the sorption of Na^+ was inversely related to the size of the zeolite particles with significantly greater adsorption for smaller particles. The field demonstration evaluated the effectiveness of BR-zeolite for mitigating infiltration losses from Na^+ in CBNG waters. The field site utilized 12 open boreholes, each installed to a depth of approximately 1.8 m. Each borehole was lined with a 3.0 m long, 15 cm diameter schedule 40 PVC pipe and fitted with an automatic data logging pressure transducer for measuring water levels over time. The BR-zeolite was found to mitigate much of the deleterious effect that high sodium adsorption ratio ($\text{SAR} = 27 (\text{mol}/\text{m}^3)^{1/2}$) CBNG co-produced water had on soil permeabilities.

Keywords:

Sodium adsorption ratio (SAR), Groundwater infiltration, Hydraulic conductivity, Coalbed methane (CBM), Co-produced water

1. Introduction

The rapid expansion of coalbed natural gas (CBNG) production in the Powder River Basin (PRB) of northeast Wyoming has resulted in concerns related to the environmental impacts of CBNG co-produced water (DOE, 2008). From 1987 through 2011, the amount of water produced in the PRB was 1.2 billion cubic meters as compared to 135 billion cubic meters of natural gas during the same period (WOGCC, 2012). It is estimated that approximately 7 billion cubic meters of CBNG water will be produced by 2025 (BLM, 2002). Much of the CBNG co-produced water is characterized by high sodium adsorption ratios ($\text{SAR} > 12 (\text{mol}/\text{m}^3)^{1/2}$) and specific electrical conductivities (EC) greater than 2 dS/m (Jackson and Reddy, 2007).

High SAR values are a potential concern regarding the management of CBNG co-produced water (Ganjegunte et al., 2005). The presence of Na^+ laden water in soil can cause common ion

exchange by replacing Ca^{2+} with Na^+ which can have a detrimental effect on the soil's structure and permeability as a result of clay particle dispersion (Payne, 2004). High SAR values can also reduce the absorption of water by vegetation (Warrance et al., 2001). Researchers have reported that water from CBNG wells in the PRB is mostly dominated by Na^+ and bicarbonate (HCO_3^-) ions with pH values ranging from 6.8 to 9.2, EC ranging from 0.4 to 5.0 dS/m, and SAR ranging from 5.0 to 70.0 $(\text{mol}/\text{m}^3)^{1/2}$ (Rice et al., 2000; Ganjegunte et al., 2005; Jackson and Reddy, 2007; Johnston et al., 2008; Vance et al., 2008). Generally, SAR values between ~ 10 and 18 $(\text{mol}/\text{m}^3)^{1/2}$ are considered a medium hazard, SAR values between 18 and 26 $(\text{mol}/\text{m}^3)^{1/2}$ are a high hazard, and SAR values above 26 $(\text{mol}/\text{m}^3)^{1/2}$ are deemed a very high hazard (Richards, 1954; Fetter, 2001).

The physical and chemical characteristics of topsoil play a significant role in the infiltration of CBNG co-produced waters. When CBNG co-produced water passes through topsoil the rate of water infiltration can be altered due to the salinity and sodicity of the water (Minhas et al., 1994; Johnston et al., 2008, 2011). Threshold laboratory values for electrolyte content in relation to the exchangeable sodium percentage (ESP) derived from laboratory

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studies have been used to predict the permeability effect of SAR on soils varying in texture, clay mineralogy, ionic exchange capacity, organic matter, and pH (Bresler et al., 1982; Quirk, 1971; Shainberg and Letey, 1984a,b; Pratt & Saurez, 1990).

Due to their distinctive cation exchange capacities (CEC), zeolites have been utilized for ion-exchange, molecular sieve and catalytic processes. Zeolites have also been shown to be effective in removing ionic substances from polluted waters (Colella, 1996; Pansini, 1996; Mumpton, 1999; Wingenfelder et al., 2005). There are approximately 40 natural (Inglezakis, 2005) and 150 synthesized (Eyde and Holmes, 2006) zeolites that have the potential for use as an ion-exchange material. Zeolites have also been shown to effectively remove Na^+ from CBNG co-produced water (Zhao et al., 2009; Ganjgunte et al., 2011).

A field demonstration and companion laboratory studies were performed to evaluate zeolite for passive remediation of CBNG co-produced water. The aim of this research was to assess the effectiveness of Bear River zeolite (BR-zeolite) in passively remediating the harmful effects of CBNG co-produced water when applied to soil. Specific objectives of this study were to evaluate impacts that HCO_3^- and chloride (Cl^-) ions had on the adsorption of Na^+ and to analyse the effect of BR zeolite on the infiltration of CBNG co-produced water through the unsaturated zone. The findings of this study can be used to further assess the feasibility of zeolite lined evaporation ponds for the management and passive remediation of CBNG co-produced waters. To the best of our knowledge, this is the first field demonstration examining the effectiveness of zeolite for this purpose.

2. Materials and methods

Zeolites are hydrated aluminosilicates of alkaline and alkaline-earth metals that are classified as analcime, chabazite, clinoptilolite, erionite, ferrierite, haulandite, laumontite, mordenite, and phillipsite minerals (Zhao et al., 2008). Bear River zeolite has a mineral composition of 85% clinoptilolite, chemical composition of 3.47% potassium (K), 1.6% Ca, and less than 0.5% of Na (U.S. Antimony United States Antimony Corporation, 2009), surface area of $2.5 \text{ km}^2/\text{kg}$, bulk density of $881\text{--}991 \text{ kg/m}^3$, and CEC of $1.5\text{--}1.8 \text{ eq/kg}$. Two important properties of zeolite, as it pertains to water treatment, are surface area and CEC. The zeolite used in this study (Bear River Zeolite Company, Preston, ID) has been shown to reduce SAR from 30 to below $10 (\text{mol/m}^3)^{1/2}$ (Zhao et al., 2008; Ganjgunte et al., 2011). Surrogate CBNG waters were synthesized by dissolving NaHCO_3 , KCl , Na_2SO_4 , NaCl , $\text{CaCl}_2\cdot 2\text{H}_2\text{O}$, $\text{MgCl}_2\cdot 6\text{H}_2\text{O}$ and $(\text{C}_2\text{H}_5\text{O})_4\text{Si}$ in both de-ionized (type I) and city water (type II). The waters used in the field demonstration included CBNG co-produced water and city water from Sheridan, Wyoming. The CBNG co-produced water came from a nearby water discharge outfall. The SAR and major cation concentrations of the various waters used for the different studies are summarized in Table 1.

2.1. Adsorption isotherm study

An adsorption isotherm study was performed using BR zeolite with sodium bicarbonate (NaHCO_3) and sodium chloride (NaCl) solutions. The BR zeolite was crushed and sieved in order to provide a sample with a uniform particle size of $1.5\text{--}2.0 \text{ mm}$. Forty (40) ml solutions of NaHCO_3 and NaCl with Na^+ concentrations of 625, 1,250, 1,875, 2,500, 3,750 and 5000 mg/L as Na^+ were added to 50 ml vials containing 5 g of BR-zeolite. Each bottle was then tightly capped, placed on a mechanical horizontal rotator (Barnsted Thermolyne, Model 4152110), and rotated at 60 rpm for a period of two days (48 h) at ambient temperature ($\sim 22^\circ \text{C}$) until chemical equilibrium was reached. The supernatant solutions were then

Table 1

SAR and Na^+ , Ca^{2+} , and Mg^{2+} concentrations for the different waters used in the study.

Water type	Concentration of Cations			SAR (mol/m^3) ^{1/2}
	Na^+ (mol/m^3)	Ca^{2+} (mol/m^3)	Mg^{2+} (mol/m^3)	
Tap water in the lab, UW	1.78	0.55	0.33	1.90
City tap water in Sheridan, WY	0.63	0.14	0.04	1.47
Synthetic CBNG co-produced water (type I)	19.63	0.80	0.43	17.70
Synthetic CBNG co-produced water (type II)	17.85	0.25	0.10	30.17
CBNG co-produced water in the field study area	13.03	0.14	0.09	27.07

filtered ($0.20 \text{ }\mu\text{m}$) and analyzed for Na^+ using an Inductively Coupled Plasma (ICP) Spectroscopy (Thermo Jarrell Ash, Model P300).

2.2. Adsorption kinetics study

A Na^+ adsorption kinetics study was conducted using a batch equilibration technique (Zhao et al., 2008, 2009) and four different zeolite size fractions ($1.3\text{--}1.5$, $1.5\text{--}1.7$, $1.7\text{--}2.0$, and $2.0\text{--}2.5 \text{ mm}$). Twenty grams of BR zeolite from each particle size fraction was added to 500 ml of synthetic CBNG water (type I) in reaction vessels and the solutions were mixed at 60 rpm using a mechanical stirrer (Phipps & Bird, Model No. 300). The vessels were sampled at 0, 30, 60, 120, 180, 300, 420, and 660 min by collecting a 1 ml aliquot of solution that was filtered through a disc filter (SFCA/PF, $0.20 \text{ }\mu\text{m}$) attached to a syringe. The samples were then diluted to 25 ml with DI water and analyzed for Na^+ , Ca^{2+} , and Mg^{2+} using ICP Spectroscopy.

2.3. Field demonstration

The field demonstration was designed to evaluate the following experimental conditions in triplicate: (1) city water without zeolite, (2) city water with zeolite, (3) CBNG water without zeolite, and (4) CBNG water with zeolite. The field demonstration site was located adjacent to the University of Wyoming Research and Extension Center in Sheridan, Wyoming. A private drilling company drilled twelve boreholes in three rows (four to a row). The boreholes in each row were located approximately 8 m from each other and the rows were spaced approximately 8 m apart. Each borehole was approximately 1.8 m deep and had a diameter slightly greater than 20 cm. Falling head permeameters were constructed using 3 m sections of 15 cm diameter schedule 40 polyvinyl chloride (PVC) pipe. The pipes were emplaced in the boreholes by hydraulically advancing each one approximately 5 cm into the soil. Since the boreholes were only 1.8 m deep this resulting in a $\sim 1.2 \text{ m}$ riser. The annulus around each pipe was filled with bentonite effectively sealing them off from the surface.

Six of the twelve boreholes were randomly selected to receive 3 kg of BR zeolite, which formed a permeable reactive barrier of approximately $8\text{--}10 \text{ cm}$ in thickness directly above the soil. Based on the results from the adsorption isotherm study this amount of zeolite can treat approximately 180 L of CBNG co-produced water with an SAR value of $30 (\text{mol/m}^3)^{1/2}$ reducing it to below $10 (\text{mol/m}^3)^{1/2}$. The remaining six boreholes did not receive zeolite and served as controls. Automatic data logging pressure transducers (Level TROLL 500, In-Situ, Inc.) were calibrated and installed in the bottom of each borehole to measure water levels with time. A separate pressure transducer was attached to the outside of one of the risers to record ambient temperature and barometric pressure.

Fig. 1. Sorption of Na^+ by BR zeolite at different equilibrium concentrations in 48 h for NaHCO_3 and NaCl solutions.

Approximately 53 L of CBNG water was used to fill six of the boreholes (three with zeolite and three without) and the other six were filled with ~ 53 L of tap water. Once the boreholes were filled they were covered with plastic to prevent the addition of rainwater and reduce evaporation. After a period of 38 days the boreholes were refilled with the appropriate water (Phase II). Following the completion of the field demonstration intact soil cores were collected from the bottom of each of the boreholes using 5 cm diameter by 1.2 m long polyethylene pipes. Soils corresponding to depths of 0–5, 5–15, 15–30, 55–65, and 95–105 cm were extruded from the cores and composited for further analysis. Approximately 100 g of the composited soils were used to prepare saturated paste extracts (USDA, 1954). The saturated paste extracts were further diluted and analyzed for major cations (Na^+ , Ca^{2+} , and Mg^{2+}), EC and pH.

3. Results

3.1. Adsorption isotherm

Adsorption of Na^+ (mg/g) by BR zeolite was determined for different equilibrium concentrations (mg/L) of Na^+ in NaHCO_3 and NaCl solutions (Fig. 1). Results indicated that sorption of Na^+ in BR-zeolite was higher for NaHCO_3 than NaCl for all initial concentrations of Na^+ (625, 1,250, 2,500, 3,750, and 5000 mg/L). The isotherm curves revealed that the Na^+ adsorption could be well described using the Langmuir equation (Eq. (1)):

$$q = \frac{q_{\max} K C}{1 + K C} \quad (1)$$

where q is the Na^+ adsorbed (mg/g), $q_{\max}$ is the maximum adsorption capacity (mg/g) of the solid phase, K is the Langmuir constant, and C is concentration (mg/L) of Na^+ in the solution at equilibrium. Upon rearranging Equation (1), Equation (2) is obtained:

Table 2
Maximum adsorption of sodium, Langmuir Coefficients and R squared values.

Reaction	$q_{\max}$ (mg/g)	K	R^2
BR zeolite with NaHCO_3	21	0.0012	0.99
BR zeolite with NaCl	18	0.0006	0.96

Fig. 2. Langmuir Adsorption Isotherm models for adsorption of Na^+ by BR zeolite from NaHCO_3 and NaCl solutions at different equilibration concentrations.

$$\frac{C}{q} = \frac{1}{K q_{\max}} + \frac{C}{q_{\max}} \quad (2)$$

By plotting C/q vs. C , the slope of the line ($1/q_{\max}$) was used to determine $q_{\max}$ and the intercept ($1/(K q_{\max})$) used to determine K . The values of $q_{\max}$, K , and R^2 for NaHCO_3 and NaCl were calculated (Table 2) using the equations for a straight line (Fig. 2) and the maximum sorption capacities of 18 and 21 g/kg were determined for the NaCl and NaHCO_3 solutions, respectively. The adsorption of Na^+ by BR-zeolite at different equilibration concentrations was also fitted to the Freundlich equation:

$$X/m = K_f C_e^{1/n} \quad (3)$$

where X is mass of adsorbate (mg), m is mass of adsorbent (g), K_f is Freundlich coefficient, C_e is the equilibrium concentration (mg/L), and $1/n$ is a constant. This equation was also converted into linear form to determine the values of n , K_f , and R^2 for NaHCO_3 and NaCl (See Table 3).

The coefficient of determination (R^2) for NaHCO_3 and NaCl indicated that both models fit the adsorption of Na^+ by BR zeolite well although the Langmuir model was slightly better. Similar results were shown by Zhao et al. (2008, 2009). The Langmuir and Freundlich adsorption coefficients were greater for NaHCO_3 than NaCl . It is likely that the larger adsorption coefficients and maximum adsorption ($q_{\max}$) values for NaHCO_3 can be attributed to the precipitation of Ca^{2+} due to the formation of calcium carbonate (CaCO_3) and its release from zeolite into the solution. The formation of CO_2 and resulting decrease in solution pH may also contribute to increased Ca^{2+} and Mg^{2+} desorption resulting in greater adsorption of Na^+ on exchange sites.

The following chemical and physical processes result in the cation exchange reaction between Na^+ and zeolite:

Table 3
Freundlich constants n , K_f , and R squared values.

Reaction	n	K_f	R^2
BR zeolite with NaHCO_3	1.93	0.29	0.96
BR zeolite with NaCl	1.64	0.08	0.92

Fig. 3. Change of Na⁺ concentration (mg/L) and SAR (mol/m³)^{1/2} with time (min) for BR zeolite particle sizes 1.3–1.5 mm, 1.5–1.7 mm, 1.7–2.0 mm, and 2.0–2.5 mm.

Ion exchange reactions continued until an equilibrium state was reached. It is suspected that the equilibrium condition occurred earlier with NaCl because the concentration of Ca²⁺ in solution (desorbed from the zeolite) increased with time and did not form a precipitate. However, Ca²⁺ desorbed from zeolite in the presence of NaHCO₃ can precipitate (Equations (7)–(9)) which keeps the concentration of Ca²⁺ in solution lower, thus shifting equilibria to the right.

3.2. Adsorption kinetics

As shown in Fig. 3, greater Na⁺ sorption rates for the surrogated CBNG co-produced water (Type I) occurred with smaller sized zeolite particles. Although Zhao et al. (2008) stated that in porous materials such as zeolites the majority of reactive sites are on internal surfaces, adsorption was found to be directly related to the particle surface area. The greatest efficiency was found with the smallest particle size (1.3–1.5 mm), which removed about 72% of Na⁺ in the first 30 min of reaction (Table 4). The SAR value of the simulated CBNG water was reduced from 30 to below 10 (mol/m³)^{1/2} in the first 30 min of reaction, resulting in SAR values of 4.2, 5.5, 5.4 and 9.0 (mol/m³)^{1/2} corresponding to zeolite particle sizes of 1.3–1.5, 1.5–1.7, 1.7–2.0, and 2.0–2.5 mm, respectively (Fig. 3 and

Table 4
Initial and final SAR values and Na⁺ removal percentage as a function of BR zeolite particle sizes after 30 min.

Particle size (mm)	1.3–1.5	1.5–1.7	1.7–2.0	2.0–2.5
Initial SAR (mol/m ³) ^{1/2}	30.0	30.0	30.0	30.0
Final SAR ((mol/m ³) ^{1/2} after 30 min)	4.2	5.5	5.4	9.0
Na ⁺ removal percentage (% after 30 min)	72	68	66	59

Table 4). These results are comparable to Huang and Natrajan (2006) who reported a similar relationship among adsorption rates and particle size. In addition, the diffusional resistance to mass transport within larger particle-sized zeolites is generally higher than that of smaller particle-sized zeolites (Airolidi and Critter, 2003).

3.3. Field demonstration

Daily water levels within the boreholes and the amount of water infiltrated were plotted for each of the experimental conditions over time (Fig. 4). As shown the water level decreased at a faster rate for the boreholes containing CBNG co-produced water and zeolite than for those containing CBNG co-produced water without zeolite. The slow rate of change for the boreholes containing CBNG co-produced water without zeolite as compared to other experimental conditions suggests that Na⁺ had a detrimental effect on soil infiltration but that zeolite was able to mitigate at least some of the impact. As shown in Fig. 5, the average maximum Na⁺ loadings throughout the field demonstration were 0.60 g, 1.31 g, 6.94 g, and 28.5 g of Na⁺ for the boreholes with city water and zeolite, city water without zeolite, CBNG co-produced water without zeolite, and CBNG co-produced water with zeolite, respectively. Based on

Fig. 4. Daily water levels (m) in boreholes of different experimental conditions over time (days). Phase I ended on day 27 and Phase II began on day 28 and ended on day 68.

Fig. 5. Cumulative mass loading (mg) of Na⁺ through boreholes of different experimental conditions over time (days).

Table 5
Mass loading of Na⁺ through boreholes.

Experimental conditions		Na ⁺ (mg)
City tap water	Boreholes with zeolite	559
	Boreholes without zeolite	1312
CBNG coproduced water	Boreholes with zeolite	28500
	Boreholes without zeolite	6936
Zeolite capacity (3000 g)	From Langmuir model	54000–63000
Impact of zeolite	Mass of Na ⁺ that was possibly absorbed by the zeolite	50% (approximately)

Fig. 6. A Phase I and II comparison of water levels in boreholes with city tap water (left) and CBNG co-produced water (right) and no zeolite as a function of time.

the results from the NaHCO₃ adsorption isotherm study, 3 kg of BR-zeolite can adsorb approximately 63 g of Na⁺. The mass loading of Na⁺ through boreholes with CBNG co-produced water and zeolite was greater than the mass loading through boreholes with CBNG co-produced water without zeolite by approximately 76% (Table 5). The results indicate that zeolite effectively mitigated some of the negative infiltration effects of high SAR (CBNG co-produced water). However, the presence of zeolite appears to have resulted in slightly lower permeability for the low SAR water (city water).

The water levels in the city water boreholes without zeolite had similar daily water levels indicating that the infiltration of water through the boreholes did not change significantly between Phase I and II (Fig. 6). Consequently, it appears that the SAR of the city water (SAR = 1.47 (mol/m³)^{1/2}) had little effect on the soil's permeability. Although the water levels in the boreholes with CBNG co-produced water and zeolite were slightly lower in Phase II as compared to Phase I, the slopes of the lines (i.e., infiltration rates) were very similar to the city water boreholes without zeolite. The water levels in the boreholes with city water and zeolite were also similar in Phases I and II (Fig. 7). However, as previously mentioned the infiltration rates were slightly lower than the city water boreholes without zeolite. Although a slight reduction in permeability was expected it is possible that the condition was exacerbated by the clogging of soil pores by small zeolite particles thereby reducing the porosity of the soil's upper layer (Al-Busaidi et al., 2008). The infiltration rates for the boreholes with CBNG co-produced water with zeolite were much greater than the infiltration rates for the boreholes with CBNG co-produced water without zeolite. Water levels in the CBNG co-produced water boreholes without zeolite indicate a significant reduction in soil permeability from Phase I to II. The Phase I results indicate an average of 79% of the water from the boreholes with CBNG co-produced water and zeolite had infiltrated into the soil in 14 days, approximately four times as much water as the boreholes without zeolite (19%). The Phase II results indicated a loss of water from the boreholes with CBNG co-produced water and zeolite of 60%, approximately 10 times the loss of water from the boreholes with CBNG co-produced water without zeolite (6%) during the same period of time. A statistical analysis of the hydraulic conductivity data indicates a significant difference (95 CI) with respect to the means for Phase I and II and a significant difference with respect to the variances for Phase I.

The soil paste extract data for SAR, EC, and pH is summarized in Table 6. Bivariate correlations of SAR, EC, and pH found that there was only a moderate negative correlation between SAR and EC

Fig. 7. A Phase I and II comparison of water levels in boreholes with city tap water and zeolite (left) and CBNG co-produced water and no zeolite (right) as a function of time.

($r = -0.62$) and EC and pH ($r = -0.68$). However, SAR and pH ($r = 0.96$) showed a strong positive correlation (both SAR and pH decreased with depth while EC increased with depth). Fig. 8 shows that SAR decreased with depth for each of the experimental conditions, except for the CBNG co-produced water boreholes with zeolite, which showed slightly greater values for 5–15 cm ($\text{SAR} = 8.8 \text{ (mol/m}^3)^{1/2}$) than 0–5 cm ($\text{SAR} = 6.4 \text{ (mol/m}^3)^{1/2}$). The higher SAR near the surface resulted from the mass loading of Na^+ and its accumulation in the soil due to cation exchange (Burrow et al., 2002; Ganjegunte et al., 2004). The data also shows that SAR values for the CBNG co-produced water boreholes without zeolite were higher than the boreholes with zeolite, except at the 5–15 cm depth. The EC results in Fig. 9 show the opposite correlation for EC which increased with depth for all of the boreholes except the city water boreholes without zeolite from 0 to 5 to 5–15 cm (1.6 dS/m to 1.2 dS/m).

Table 6
Case summaries of field experimental conditions.

Experimental conditions		Experimental results		
Treatment	Depth (cm)	SAR ($\text{mol/m}^3)^{1/2}$	EC (dS/m)	pH
CBNG coproduced water but no zeolite	0–5	8.3	0.9	7.4
	5–15	7.4	0.9	7.3
	15–30	5.8	1.3	7.1
	55–65	1.6	1.4	6.3
	95–105	1.1	1.6	6.1
CBNG coproduced water and zeolite	0–5	6.4	0.8	7.3
	5–15	8.8	1.1	7.3
	15–30	2.9	1.4	6.9
	55–65	1.0	1.9	6.1
	95–105	0.8	2.2	6.1
City tap water but zeolite	0–5	0.6	0.7	6.3
	5–15	0.5	1.4	6.3
	15–30	0.9	1.9	6.2
	55–65	0.8	2.2	6.3
	95–105	0.8	2.3	6.3
City tap water and no zeolite	0–5	3.1	1.6	6.6
	5–15	0.8	1.2	6.3
	15–30	0.5	1.7	6.2
	55–65	0.8	2.2	6.2
	95–105	0.9	2.3	6.2

These results suggest that major ions other than Na^+ were leached from the soil. The introduction of CBNG co-produced water rich in NaHCO_3 may have also resulted in the precipitation of Ca^{2+} and Mg^{2+} salts in the soil to insoluble carbonates, reducing the amount of soluble salts (and EC) in the soil. The EC values for the city water boreholes without zeolite were greater than the CBNG co-produced water without zeolite suggesting that soluble salts were leached from the upper layers of soil as a result of the application of city water.

4. Conclusions

Laboratory studies with BR-zeolite indicated the adsorption of Na^+ on BR-zeolite followed the Langmuir adsorption model with differences in sorption characteristics using NaHCO_3 and NaCl . Adsorption kinetic studies found Na^+ was inversely related to the size of the zeolite particles with significantly greater adsorption for

Fig. 8. Distribution of SAR as a function of depth for different experimental conditions.

Fig. 9. Distribution of soil EC as a function of depth for different experimental conditions.

smaller particles. Results of the field demonstration suggest that BR-zeolite is capable of mitigating some of the soil permeability effects caused by high SAR. Infiltration rates were similar for the city water boreholes with and without zeolite. However, the CBNG co-produced water boreholes showed a significant difference relative to zeolite with much higher infiltration rates for the boreholes containing zeolite. Post field demonstration soil analyses revealed that SAR and pH values decreased with depth while the EC increased. The soil analyses suggest that the infiltration effects resulted from relatively high Na^+ concentrations and SAR in the co-produced water. Although the results are encouraging and suggest that treatment with BR-zeolite can be a viable method for mitigating the effects that high sodicity CBNG co-produced water, further research is necessary to evaluate the feasibility of zeolite lined evaporation ponds for the management of CBNG co-produced water.

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