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Blocking saline fluids using bentonite clay liners: an approach to reduce corrosion

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ABSTRACT

Saline water, or any chloride-rich fluid, can cause corrosion in steel-reinforced concrete substructures. Corrosion occurs when heavily reinforced foundations are subjected to an aggressive environment containing harmful salts. Coastal areas are considerably affected by the corrosion of steel, whether within concrete elements or in direct contact with soils. Corrosion of pipes and underground storage tanks is also a major concern. This study aims to reduce the risk of corrosion by using clay liners to intercept the flow of water and thus reduce aggressive fluid contact. It also investigates the ability of clay to interact with harmful chemical components in fluids. Field experiments compared two clay materials with water exposure to thin layers of bentonite clay and local clay liners. The water exposed to the surface of the liner was allowed to drain and was collected in a water tank. This procedure was repeated for several weeks. The electrical conductivity measurements of the two clay liners were monitored and compared. Water chemistry was investigated before and after exposure to the liner materials. This study confirmed that bentonite liners of low permeability were more efficient in reducing corrosion than the local clay liner.

Keywords: Salinity; Bentonite; Clay liner; Chemistry; Corrosion

1. Introduction

The coastal areas in the Kingdom of Saudi Arabia are considerably affected by the corrosion of steel, whether near the ground surface, embedded in concrete, or in direct contact with soil. Facilities in these areas are often subjected to an aggressive environment containing harmful salts, resulting in corrosion. The degradation of pipes and underground storage tanks due to corrosion is a major concern nowadays, especially in industrial cities. Numerous studies have been conducted to protect steel using epoxy coats or other additives to produce impervious concrete. Other protective coats, such as bitumen or paints, are also applied. This study aims to reduce the risk of corrosion by using clay liners to intercept the flow of water and thus reduce aggressive fluid contact. It also investigates the ability of clay to absorb harmful chemical components in fluids. Wrapping pipes or tanks with a composite of geotextile and clay can provide good protection. Various clay liners can be investigated to select the best alternative.

Underground fluid storage steel tanks and steel pipelines at or below the ground surface are subject to corrosion due to severe exposure conditions. The impact of corrosion on the lifetime of these facilities is severe unless a protective plan is well established to make the losses as minimal as possible. Materials such as corrosion-resistant alloys and cheaper carbon steel and methods such as corrosion reduction techniques have been commonly used. These approaches provide corrosion-resistant products that can be either very expensive or not sufficiently effective to eliminate corrosion completely. The use of corrosion-resistant alloys may not always be favorable upon considering capital and operational costs. The long-term sustainability of underground steel tanks and pipes can be achieved by using creative approaches that will enhance protection against corrosion.

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The exposure environment can be improved by reducing the fluid chemical aggression in the surrounding medium.

The corrosive environment is the most serious factor related to the corrosion of steel. This environment can be mild or very hostile. International specifications for protecting steel reinforcement within concrete establish a limit of allowable maximum chloride content. The corrosion at coastal sites or remote offshore locations is of great concern.

Carbon dioxide, hydrogen sulfide, and oxygen can cause internal pipeline corrosion in the presence of water. The corrosion rate is highly related to aqueous solutions in the environment. Corrosion inhibitors can be either thin films placed on the pipes or chemical compounds added to a fluid to reduce the rate of corrosion. Chemical corrosion inhibitors can be very effective in reducing corrosion rates. Temperature and pressure also influence the corrosion rates.

Winning et al. [1] stated that corrosion inhibitors can be very effective against CO_2 and H_2S, but not against oxygen. A very high inhibitor concentration may be required to achieve better results. The factors affecting corrosion rates include the presence of oxygen, carbon dioxide, and hydrogen sulfide, in addition to pressure, temperature, the amount of water, and flow characteristics.

McMahon and Groves [2] presented the Corrosion Inhibitor Guidelines handbook, which describes the basic process and parameters affecting the corrosion rate, corrosion inhibitor delivery rate, and concentration in water. Gregg and Ramachandran [3] stated that, in the presence of water, corrosion due to carbon dioxide increases with temperature until a corrosion layer is formed. They noted that, with an increase in the pressure of carbon dioxide, corrosion increases. They also studied the influence of flow and velocity on the corrosion process. Studies on corrosion and inhibitors can be found in reviews by many researchers [4–8].

Srinivasan [9] surveyed recent advances in the use of natural clay for removing biological, organic, and inorganic contaminants from drinking water. Natural clays were observed to be capable of removing contaminants with very high removal ratios for toxic trace metals and organic matter. Other studies concerned with modifying clay to increase its adsorbent capacity to remove contaminants other than metals from drinking water are currently ongoing [9]. Larchéa et al. [10] highlighted the influence of severe exposure on corrosion. The proposed high ambient temperature and biofouling as major factors influencing corrosion, in addition to high chloride content, high pressures, and dissolved oxygen content. Cheng et al. [11] studied vapor inhibitors for corrosion protection in humid and saline, natural, and industrial environments and concluded that the selection of appropriate corrosion inhibitors shall be based on cost, the ease of availability, worker safety, and chemical stability. Wang et al. [12] studied extensive data and concluded that a good relationship exists between corrosion and soil properties when corrosion data are classified based on soil aeration.

From the literature review, it can be concluded that the corrosion of carbon steel pipelines or underground carbon steel tanks due to carbon dioxide or hydrogen sulfide can be significantly reduced using chemical corrosion inhibitors. A corrosion rate of 0.1 mm/year can be typically achieved if treatment is performed using relevant chemical materials. Chemical corrosion inhibitors may not be effective against corrosion caused by the presence of oxygen, a high rate of flow, or elevated temperature. Abrasive solids within the fluids can also aggravate pre-existing corrosion. The performance of pipes and underground water tanks is dependent on the surrounding environment. The chemical composition, constituents of fluids passing through soils, and pressure and temperature have a significant influence on the corrosion process.

The chloride ion ingress can react with iron to form iron chloride. With the introduction of water or oxygen, iron chloride may convert to iron hydroxide in an anodic reaction:

$$2Fe \rightarrow 2Fe^{2+} + 4e$$

$$2Fe^{2+} + 4Cl^- \rightarrow 2Fe\ Cl_2$$

$$2Fe\ Cl_2 + H_2O \rightarrow Fe(OH)_2 + 2Cl^-$$

Chloride ions that reach the steel reinforcement by diffusion or capillary suction can initiate corrosion. Pereira and Hegedus [13] presented a model for chloride diffusion and reactions through the porous concrete.

2. Materials and methods

2.1. Materials

2.1.1. Sand

Sand is the main constituent of clay liners. The sand material used in this study was a fine- to medium-grained material abundant in the desert areas close to the site. The sand is classified as SP "poorly graded sand" following the unified soil classification system, or ASTM D 2487. Upon examining the coefficient of curvature and the coefficient of uniformity, the material was determined to be not within the uniformly graded sand range. The specific gravity of the sand used was 2.65. Fig. 1 presents the grain size distribution of the sand.

2.1.2. Local clay

Table 1 presents the index properties, specific gravity, and soil classification of Al-Qatif clay. Table 2 presents the chemical properties of Al-Qatif clay. The moisture–density relationship of the clay–sand mixtures was investigated for 15% clay by weight in accordance with ASTM D 698. The maximum dry density and optimum moisture content obtained from a Proctor test were 18.0 kN/m^3, and 15%, respectively.

2.1.3. Bentonite clay

The commercial bentonite HY Oil Companies Material Association (OCMA) was selected for use in this study. Tables 3 and 4 present the physical and chemical compositions of the HY OCMA bentonite, respectively. The maximum dry density and optimum moisture content obtained from a Proctor test were reported to be similar to those of the local clay.

2.1.4. Testing procedure

The use of liners as a protective measure against corrosion is based on two main aspects: to reduce the fluid material

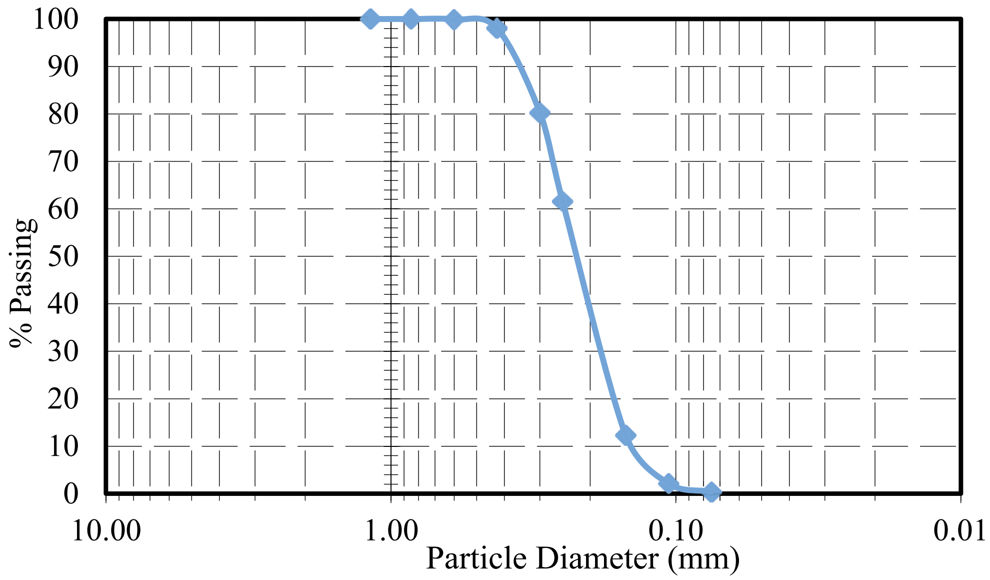

Fig. 1. Grain size distribution of the sand.

Table 1
Properties of Al-Qatif clay

Property	Value
Specific gravity, GS	2.71–2.75
Liquid limit, LL (%)	137–140
Plastic limit, PL (%)	45–60
Plasticity index, PI (%)	95–99
Unified soil classification system	CH

Table 2
Chemical composition of Al-Qatif clay

FeO_3, %	<0.1
K_2O, %	2.2
Na_2O, %	<0.1
Al_2O_3, %	6.3
MgO, %	<0.1
SiO_2, %	17.3
TiO_2, %	<0.1
CaO, %	0.9

Table 3
Typical physical properties of bentonite

Property	Value
Specific gravity, GS	2.6–2.7
Liquid limit, LL (%)	480
Plastic limit, PL (%)	50
Plasticity index, PI (%)	430

Table 4
Typical chemical composition of OCMA-grade bentonite

FeO_3, %	2.9
K_2O, %	0.1
Na_2O, %	1.9
Al_2O_3, %	17.0
MgO, %	4.6
SiO_2, %	55.2
TiO_2, %	<0.1
CaO, %	0.9

passing through the liner and to reduce the aggressive chemicals carried by the fluids. Two types of liners were considered in this study: a bentonite liner and a local clay liner. Each liner was 100 mm thick and consisted of 15% clay by dry weight of sand. The first section, or section 1, refers to the bentonite liner; the second section, or section 2, refers to the local clay liner. Water was supplied from the main water tank using polyvinyl chloride pipes attached to flow meters and valves (Fig. 2). Fig. 3 shows the typical field data logger and 5TE sensors used in this study. The water penetrated a clean sand layer before accumulating on the surface of the liner. It was then allowed to drain under a very gentle slope and was collected using an underground water tank placed below the liner. Water samples were collected from the main tank and from the surface of the bentonite and local clay liners.

2.1.5. Chemical test methods for water

The following chemical water tests were conducted in this study: pH (ASTM D 1293) [14], total dissolved solids (TDS; ASTM D 5907) [15], chloride content (ASTM D 512) [16], sulfate content (ASTM D 516-90) [17], nitrate content

(ASTM D7781) [18], calcium (ASTM D 511) [19], magnesium (ASTM D 512) [16], sodium (ASTM D 4191) [20], potassium (ASTM D 4192) [21], and iron (ASTM D1068) [22].

2.1.6. Electrical conductivity at the mid-layer of the liners

The two constructed sections were fitted with electrical conductivity sensors (5TE) at the mid-layers of the liners. The EM 50 is a five-port, self-contained data logger housed in a weatherproof box and can communicate through a cable to the 5TE sensors and a PC.

2.1.7. Hydraulic conductivity of bentonite clay and local clay liners

Clay liners with low hydraulic conductivity are used as clay barriers to control the flow of fluids for waste control and other applications. Clay liners were observed to be useful to reduce the aggressive chemical exposure that may cause steel to corrode, including steel embedded in the concrete or in direct contact with soil. Chloride-induced corrosion is caused by the transfer of chloride ions by diffusion or direct flow. Liners designed for environmental requirements usually have a limited hydraulic conductivity of 10^{-7} m/s [23]. This value can be achieved using different proportions of sand and clay depending on the porosity of sand, the percentage of clay, and the type and mineralogy of clay. Other parameters such as the micro fabric and the chemical composition of clay can have a significant influence. The water retention of bentonite is high relative to that of most local clays. It can absorb more water within its internal tetrahedral and octahedral sheets. Dafalla and Al-Mahbashi [24] studied the retention capacity of bentonite and local clay liners with the same materials used in this study by utilizing soil water characteristics equipment. The air entry value (AEV), residual water content (Wr), and residual suction (Rs) are the main parameters obtained for constructing the soil water characteristics curve.

Fig. 2. Supply main tank and liner sections tested in the field.

Fig. 3. Typical field data logger and 5TE sensor view.

The AEV is a low suction pressure at which air starts entering into clay and occupies spaces within the soil pores. The water content decreases with the increase in the suction pressure until a point defined as the residual Wr. The moisture content beyond this point will remain constant. Ws is the optimum compaction water content. Table 5 presents the parameters related to the two liners compared in this study. The greater the water retention of the liner, the lower is its hydraulic conductivity.

The hydraulic conductivity for the 15% local clay liner and the 15% bentonite clay liner are reported to be between 4.156×10^{-8} cm/s and 6.780×10^{-8} cm/s, and higher than 10^{-8} cm/s, respectively. The test took a long time for bentonite clay liner than for the local clay liner.

3. Test results and discussion

Corrosion of steel embedded in concrete appears as a weak thin layer of iron oxides formed due to chloride ingress through concrete or due to the introduction of carbon dioxide from the atmosphere. Table 6 presents the hydraulic conductivity for 15% local clay liner.

Table 5
Soil water characteristics curve control points for sand–clay mixtures

Mixture	15%B	15%Q
AEV (kPa)	208	70
Wr (%)	1.2	0.85
Ws (%)	22.5	14.5
Rs (kPa)	10,000	20,000
R^2	0.989	0.972

Dafalla and Al Mahbashi [24].

Table 6
Hydraulic conductivity for 15% local clay liner

Clay content (%)	15	15
Dry unit weight (kN/m^3)	17.9	17.7
Moisture content (%)	17	20
K_{20} cm/s	4.157×10^{-8}	6.780×10^{-8}

The focus of this work is the chemical interaction between the fluid and the two types of selected clays commonly used in liners. The first defense against corrosive fluid is the hydraulic conductivity of the barrier. As less fluid passes through the well-sealed liner, the vulnerability of steel to corrosion is low. Fig. 4 presents a 24 h comparison of the electrical conductivity at mid layers for the two liners used.

The obtained pH value indicates a general alkaline medium for the water supplied through the main tank or the water collected from the surface of both the bentonite and local clay liners. Random values in the range of 7.7 to 8.3 were observed in tests conducted during the first two months. Lower alkalinity was observed for the local clay liner and the bentonite liner for the period of July to August (Fig. 5). In general, the more acidic the medium, the more likely it is the occurrence of corrosion. The bentonite liner is expected to perform better than the tested local clay liner.

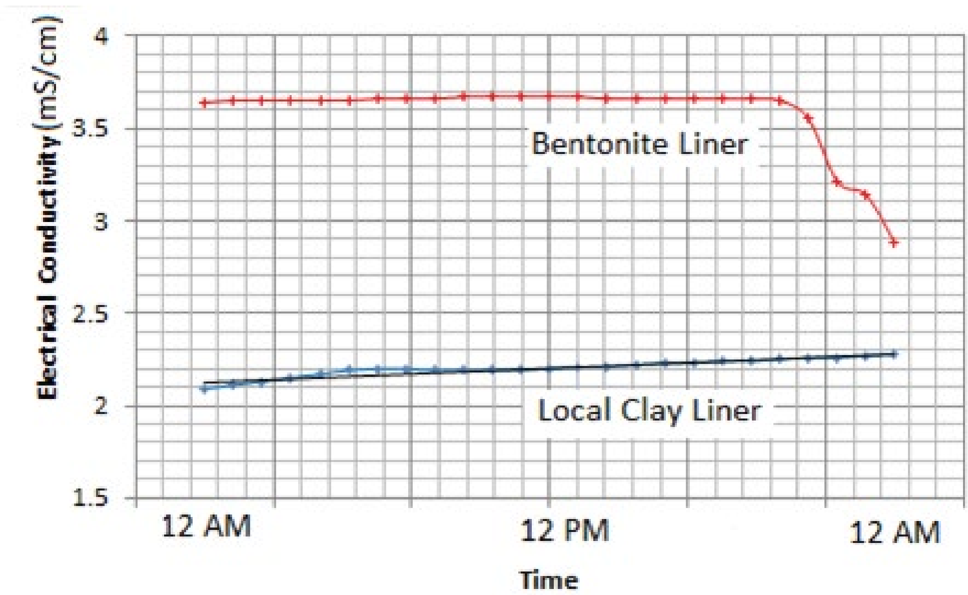

Fig. 4. 24 h comparison of the electrical conductivity of the two liners.

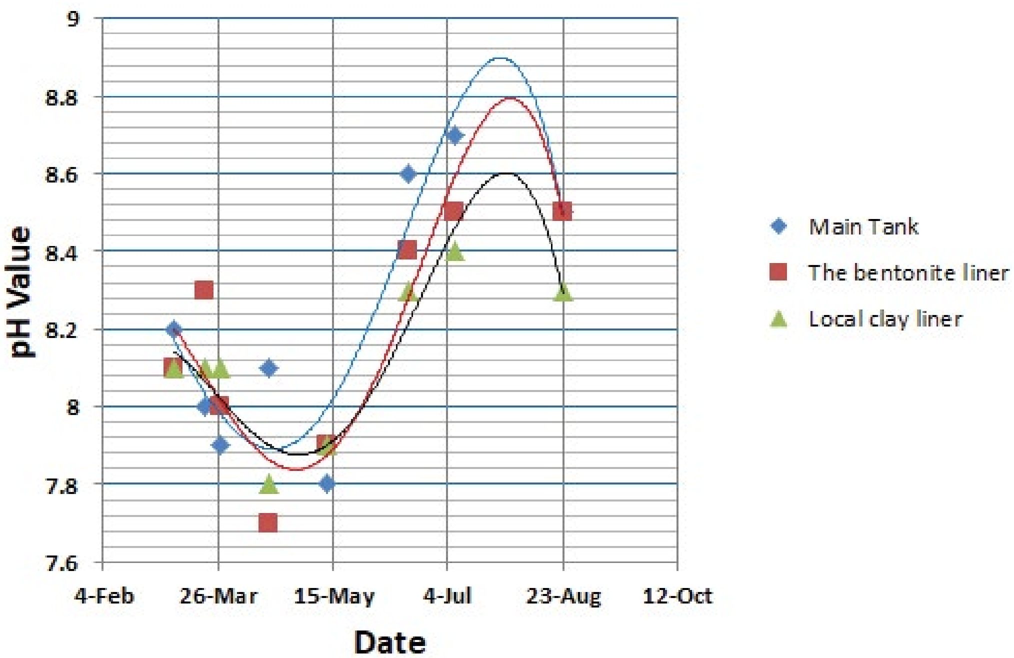

Fig. 5. Change in pH value over the testing period.

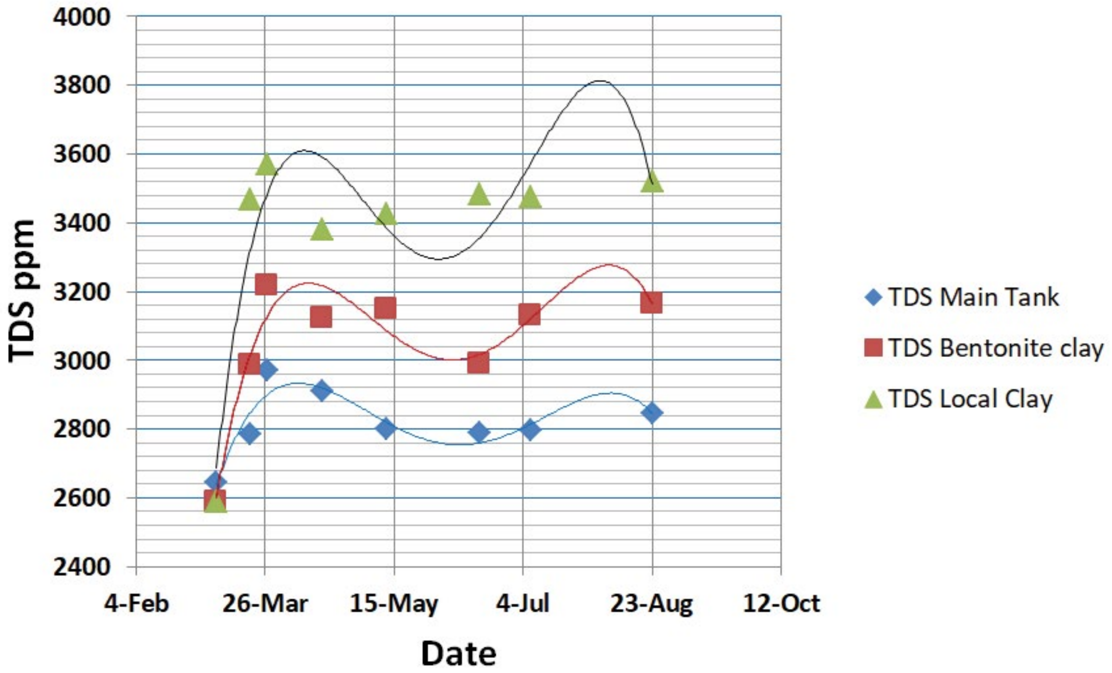

Fig. 6. Change in TDS value over the testing period.

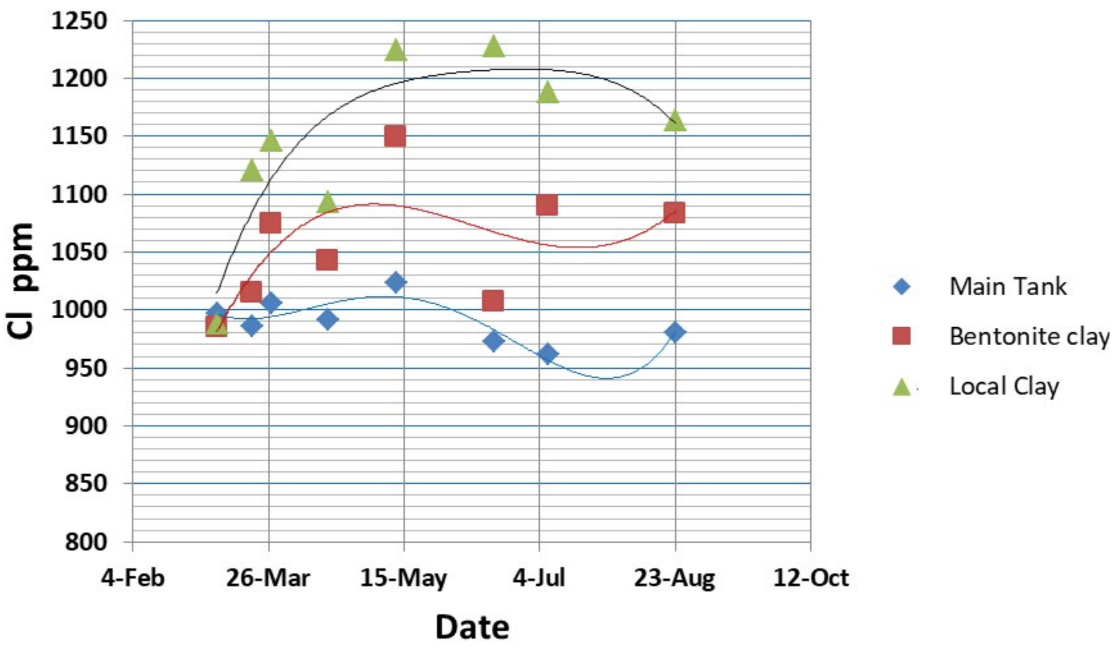

Fig. 7. Change in chloride content over the testing period (ppm).

The TDS reported for the local clay liner was approximately 10% higher than that of the bentonite liner. The supply water in the main tank indicated TDS values in the range of 2,600 to 2,900 ppm (Fig. 6).

The chloride content in the main tank water supply was maintained below 1,020 ppm. However, when water was delivered to the liner, the increase in chloride content of the local clay liner was much higher than that measured for the bentonite clay liner (Fig. 7). Chloride-induced corrosion can be triggered when the chloride content in aggregates for use in concrete is above 500 ppm (British Standard 8110, Part 1; 1985).

The increase in sulfate content for the water collected from the local clay liner was almost twice that measured for

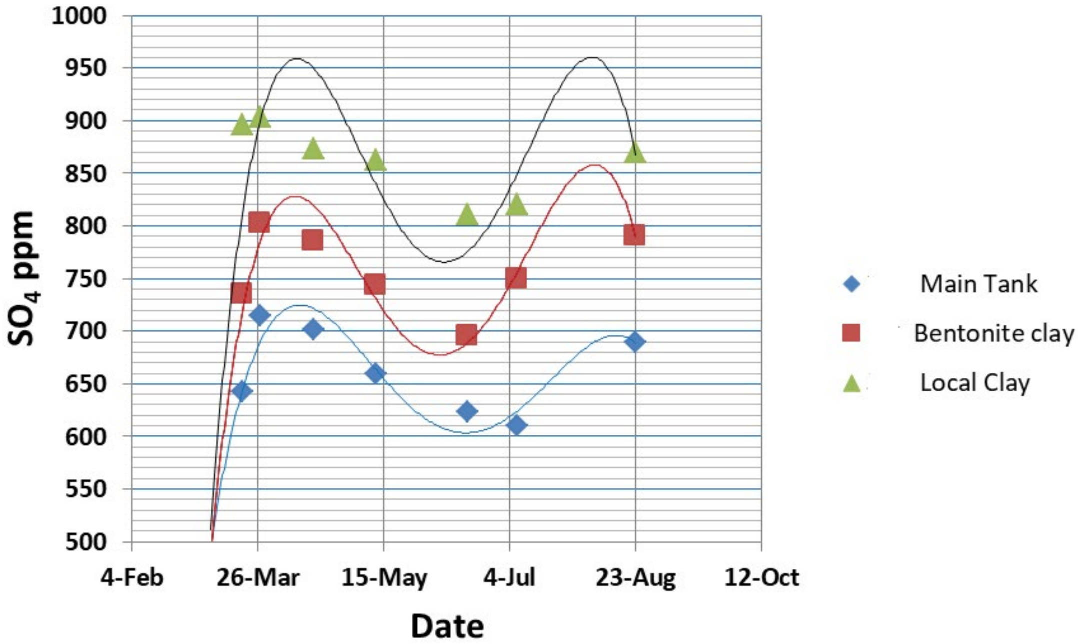

Fig. 8. Change in sulfate content over the testing period (ppm).

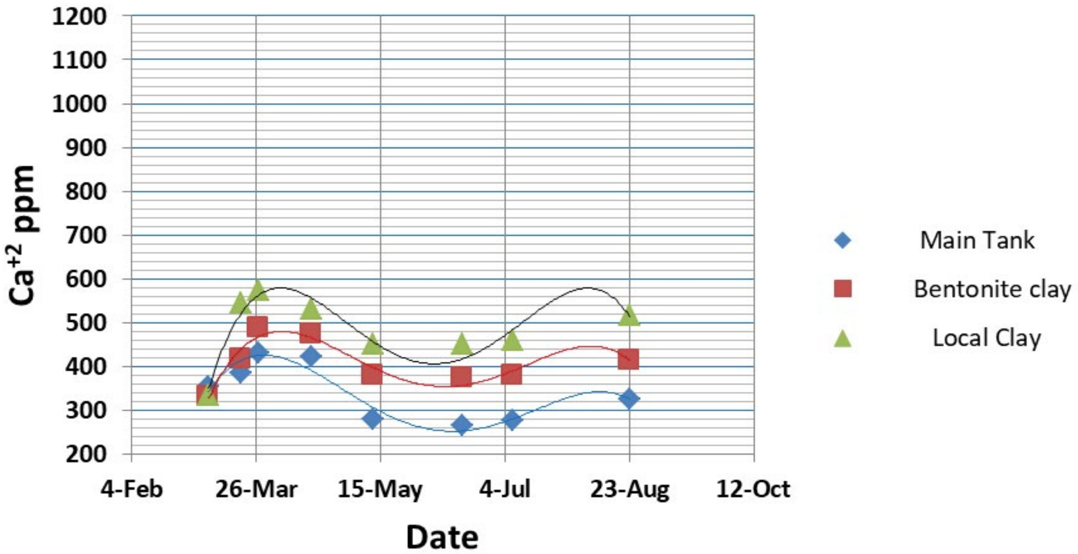

Fig. 9. Change in calcium content over the testing period (ppm).

the bentonite clay liner. Fig. 8 shows the increase in sulfate content during the test period. The sulfate-resisting cement type *V* is usually used for concrete in direct contact with high sulfate content. There is no direct correlation between corrosion and sulfate content.

The increases in calcium and sodium contents were of the order of 150–200 ppm. Notably, the bentonite liner lost smaller amounts of calcium and sodium owing to the flow of water. Figs. 9 and 10 show a uniform increase in these two elements during the tested period. Fig. 11 presents a bar diagram comparing TDS, Cl^-, SO_4^-, Ca^{++}, Mg^{++}, and Na^+.

From a comparison between the results of this work and those of the published literature and past studies, it can be concluded that clay liners have good potential for reducing corrosion via a reduction of the severe exposure level. These results are consistent with reference [9] regarding the removal of inorganic contaminants and with reference [25] regarding the influence of pH and temperature.

The scope of this study is limited to underground facilities and the subsurface environment. This study focused on comparing two liners with different types of clay tested in specific environmental settings.

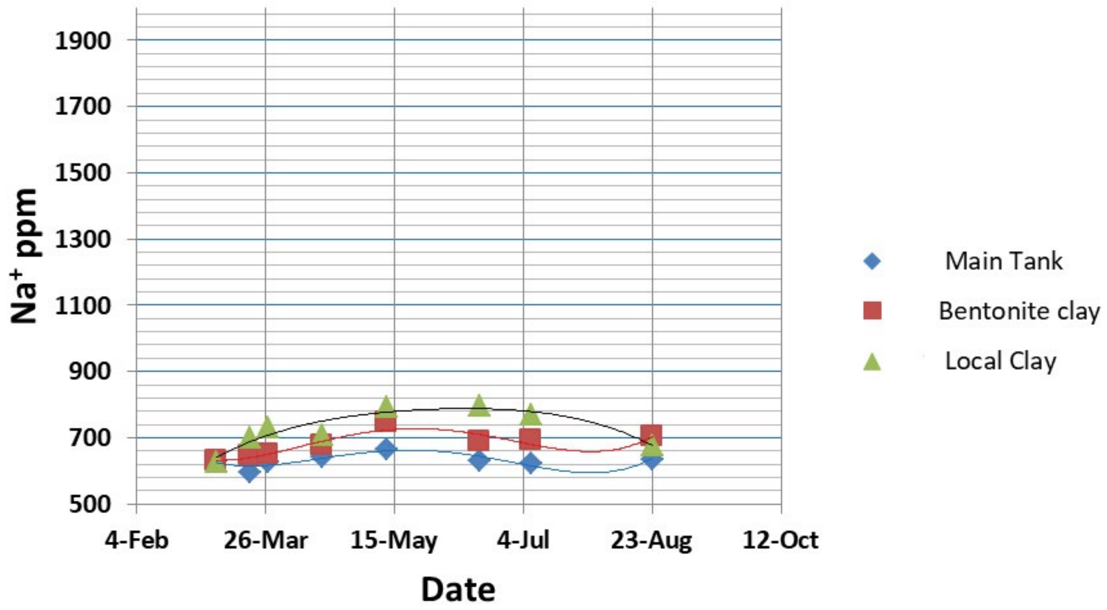

Fig. 10. Change in sodium content over the testing period (ppm).

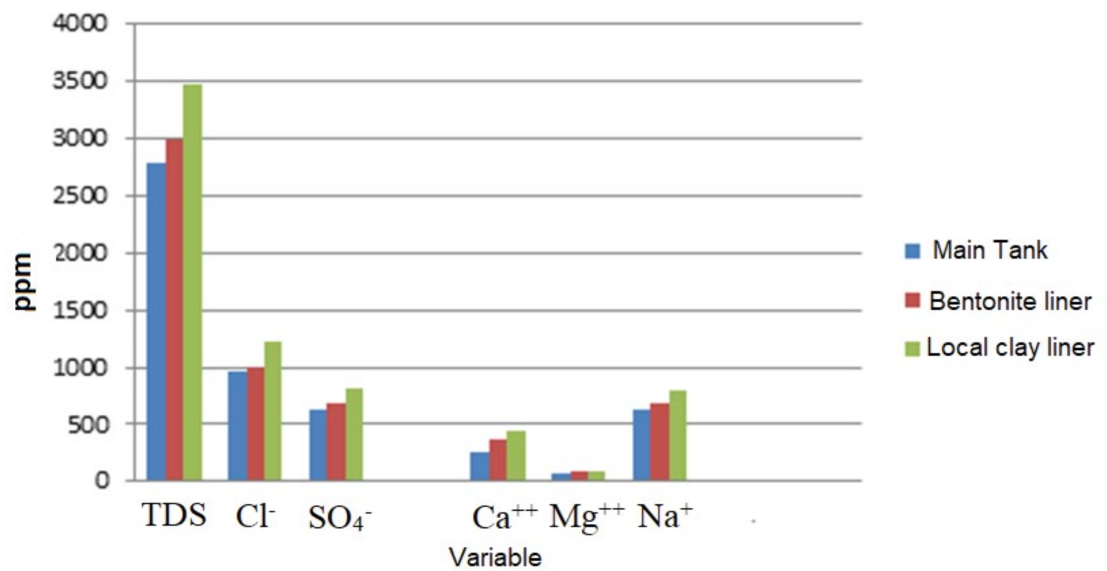

Fig. 11. Bar diagram comparing TDS, Cl^-, SO_4^-, Ca^{++}, Mg^{++}, and Na^+.

4. Conclusion

This study used clay–sand liners as a protecting barrier against corrosion. Two types of clay liners were compared to examine their chemical interactions with saline fluid. The pH level indicated an alkaline medium for the clay–water interaction for the two selected clay liners. The bentonite clay liner was observed to add slightly more TDS and chlorides to the water introduced compared with the local clay liner. Similar results were reported for sulfate, calcium, magnesium, and sodium contents. The low hydraulic conductivity of bentonite clay liners is attributed to the affinity of bentonite to absorb water and retain a semi-liquid clay paste within its voids. The chemical and physical properties of the clay used in liners can be utilized to produce a better barrier against saline water flow and reduce the aggressive chemical nature of fluids penetrating the liner.

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