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Effectiveness Evaluation of Vapor Corrosion Inhibitors for Tank Bottom Plate Corrosion Control

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ABSTRACT

Soil-side corrosion of above ground storage tank bottoms is a major challenge for midstream operators owning tank farms. In North America, most above ground storage tanks include active cathodic protection (CP) systems to protect the soil-side of the tank bottoms from corrosion. However, CP systems could fail leading to unprotected tank bottom, and occasionally extensive corrosion has been observed even with an active CP system in place. In addition, a tank bottom without a CP system could experience elevated corrosion including pitting corrosion. Vapor corrosion inhibitors (VCIs) are being promoted as alternative corrosion control measures. An industry-sponsored study was conducted to evaluate effectiveness of the VCIs in mitigating the tank bottom corrosion. Specifically, the study was conducted to determine whether the VCIs are effective in mitigating corrosion comparable to a working CP system for tank bottoms or not. Several laboratory-scale experiments were conducted, and experimental data were rigorously analyzed. It was found that the VCIs are effective in mitigating corrosion when vendor specific recommended dosages are used. The pitting corrosion significantly decreased with application of the VCIs, but corrosion rates were not mitigated to the extent specified in NACE SP0193 and NACE SP0169 for demonstrating adequate CP.

Key words: Vapor Corrosion Inhibitors, Aboveground Storage Tank, Bottom Plate, Pitting Corrosion.

INTRODUCTION

Soil-side corrosion of the bottom plates of aboveground storage tanks is a major concern and maintenance issue in the fossil fuel industry. Literature information[1,2,3] show that soil-side corrosion could occur at elevated rates and cathodic protection (CP) alone may be insufficient. This is because CP could partially or completely degenerate, or CP may not reach all areas of the bottom plate. To address these issues, vapor corrosion inhibitors (VCIs) are being promoted as alternative corrosion control measures to mitigate tank bottom corrosion. An industry consortium sponsored a study[4] to independently evaluate the effectiveness of the VCIs. The objectives of the study were to evaluate effectiveness of the VCIs in mitigating the soil-side tank bottom corrosion, and to determine if the VCIs' effectiveness is comparable to a working CP system. Overall scope of the study[4] included literature review, laboratory experiments, and limited field testing to evaluate the effectiveness of VCIs. This paper was developed from the report and describes the work on evaluating effectiveness of the VCIs for the tank bottom plate corrosion control.

VCIs have been used for corrosion mitigation for numerous applications for several decades, but their application for the tank bottom plate corrosion control is relatively recent. VCI vendors have devised specific methods to apply VCIs into a tank sand pad. Application methods are dependent on the tank operating conditions which could include a tank being in-service, out of service, and during construction. The application methods rely upon the process of chemical volatilization and diffusion for distribution of the inhibitor chemistry throughout a tank sand pad. VCIs' volatilization eliminates the need to have a direct access to the tank bottom plate surface. VCIs could be injected and distributed in the tank sand pad for an in-service tank, whereas VCIs could be applied at the tank pad surface for an out of service tank. The most common ways to introduce VCIs into the tank pad include liquid slurry injection (prepared by mixing potable water with VCI) and dry powder application. A VCI chemistry must be contained in the tank pad to be available for corrosion control. A typical AST construction includes a concrete support ring wall surrounding the tank sand pad that is underlain with a containment liner. The tank floor plates are typically A36 steel and are constructed on the sand pad surface, then the plates extend onto the concrete ring wall. The chime of the tank in contact with the ring wall can be sealed with commercially available sealants. This creates sufficient containment under the ASTs for the VCI chemistry to be available long-term. When the inhibitor is delivered and released either within interstitial space or at the pad surface, volatilization coupled with molecular diffusion occurs till equilibrium determined by the partial vapor pressure and concentration gradients is reached. Mechanism for corrosion control is formation of a monomolecular layer throughout the soil-side surface of the bottom plate. Inhibitor molecules adsorb on the steel surface to suppress both metal dissolution and the reduction reaction, in other words both anodic and cathodic processes.

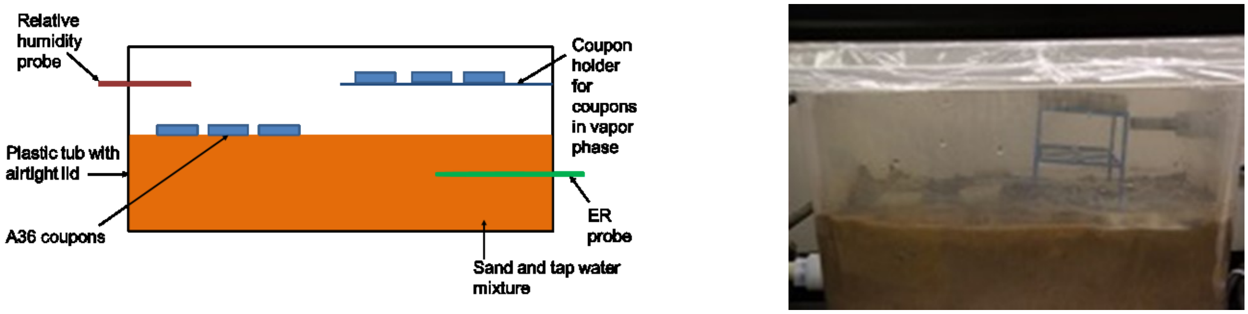
EXPERIMENTAL

Several laboratory-scale experiments were conducted to determine the efficacy of the VCIs in mitigating tank bottom plate corrosion. Specifically, seven experiments were conducted to study the effect of VCIs in mitigating general and preventing pitting corrosion of the above-ground storage tank (AST)-type carbon steel, typically A36 grade carbon-steel. Two commercially available VCIs were tested and are identified as: (i) VCI-A, and (ii) VCI-B. Field sand samples, from an existing tank foundation, were procured. The tank bottom plate at the sand sampling site experienced severe soil-side pitting corrosion, therefore, the field sand samples were considered corrosive. Control and VCI effect experiments were setup in plastic tubs. The tubs were filled with the field sand, dosed with VCIs, and sealed to prevent escaping of the VCIs. A36 grade carbon steel coupons were placed in contact with sand, and in the vapor space of the tubs.

Moisture content of the field sand was determined by using the weight loss method. Field sand samples from an out-of-service tank site were collected in six 5-gallon pails. A sand sample for each pail was collected, weighed, and then dried over a period of 8 days. The moisture content in the sand samples varied between 6.29 to 11.73 percent; average moisture content was approximately 8.44 percent. The sand from the six pails were mixed and then used to setup the experiments. The bacterial activity of the sand samples was also measured. The overall bacterial activity was found to be 10^6 CFU/g of sand.

The control and VCI effect experiments were setup in plastic tubs. A schematic diagram of the experimental system is in Figure 1. Each experimental system consisted of a transparent plastic tub container with an airtight lid. Several tubs were used to setup the experiments. Each tub was approximately half-filled with sand plus water mixture. Twelve coupons were placed inside each tub.

The coupons were fabricated using the A36 grade carbon steel. Each coupon was cut from a one-inch (2.54 cm) diameter A36 rod. Further, each coupon was potted in epoxy, polished, and engraved with unique identification number.



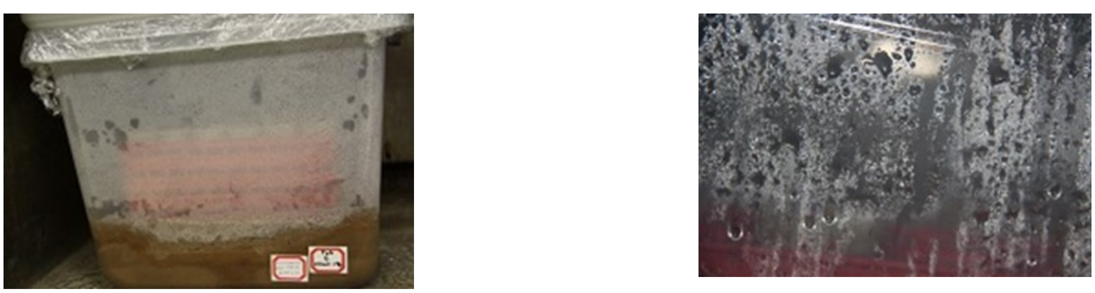
(a) (b)

Figure 1. (a) Schematic of container for the control and VCI effect experiments, (b) image of an experimental setup

Seven experiments were setup and included a control experiment and three VCI effect experiments with each of the two VCIs: (i) control experiment without VCI, (ii) VCI effect experiment with 100% VCI-A dose, (iii) VCI effect experiment with 10% VCI-A dose, (iv) VCI effect experiment with 1% VCI-A dose, (v) VCI effect experiment with 100% VCI-B dose, (vi) VCI effect experiment with 10% VCI-B dose, and (vii) VCI effect experiment with 1% VCI-B dose.

VCI dosages for the VCI effect experiments were calculated as per the manufacture recommendations. One VCI manufacturer uses a proprietary formula to estimate dosage for a given tank sand pad characteristics while the other VCI manufacturer dosage recommendations are based on surface area. VCI manufacturer technical experts were consulted to estimate the dosages. VCI dosing in the experiments involved mixing the VCI chemistries with potable water, and dosing the sand pad with the mixture (potable water + VCI). The amount of potable water plus VCI in each VCI effect experiment was such that water saturation level was approximately 75 percent. Potable water was also added in the control experiment to attain 75 percent saturation. The dosing step was in-between laying of the sand in the plastic tubs; this process simulated dosing of an in-service tank.

The VCI effect experiments were conducted for 12 months. Fifty percent of the coupons were extracted from each experiment after 6 months of exposure, and the remaining were removed after 12 months. The coupons were extracted through a narrow opening, and quickly, thus minimizing loss of the VCIs.



(a) (b)

Figure 2. Image of an VCI effect experiment tub (a) three weeks after start, (b) near end of the experiment, showing visible water condensation at the tub walls

It was important to keep the VCI concentration constant through the experiments duration. However, it was not possible to measure the VCI concentration directly. Nonetheless, moisture level in the tubs could be monitored by way of observing water condensation at the tub walls. The water condensation indicated that the interior environments of the tubes were contained and there were no exchanges between ambient and tubs' environments. Images of a tub immediately after the start and before the end of the experiment are presented in Figure 2. As seen in the figure, condensate water remained on the tub's wall for the entire duration of the experiment. This was used to infer that the VCI concentrations remained constant inside the tubs for the duration of the experiments.

EXPERIMENTAL DATA AND RESULTS

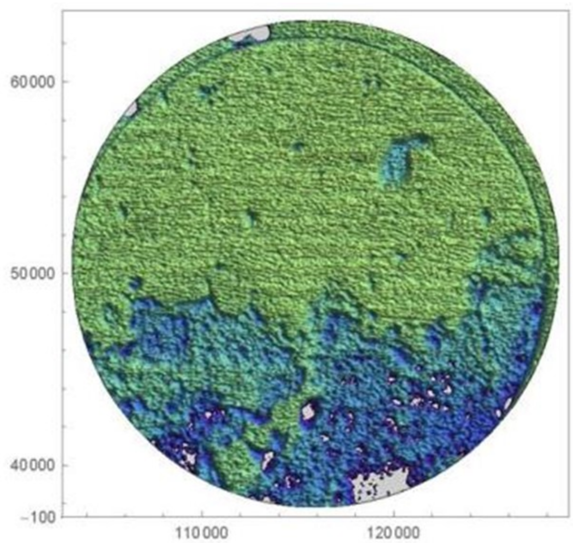
Vapor corrosion inhibitor (VCI) effectiveness values were calculated after retrieving the coupons, and analyzing them for corrosion rates by estimating surface average and pitting corrosion. A comprehensive surface analysis of the coupons was key to determining both surface average and pitting corrosion rates. Corrosion across the coupons' surfaces was nonuniform and varied from coupon to coupon. A laser profilometry technique was used to measure depths of various pits on the coupons. The techniques involved scanning the coupon surfaces with a laser profilometer, accounting for bulk surface curvature and incline, and statistically analyzing the collected data to estimate pit depths. The technique also enabled to quantitatively characterize pitting corrosion, including pit surface area, pit depths, and surface coverage of the pits. An example output of the laser profilometer-based technique is presented. A coupon was exposed to the sand-only environment for 6 months. The coupons developed several localized corrosion spots. The coupon and the laser-scanned images are presented in Figures 3(a), 3(b), and 3(c). Figure 3(b) shows the digital reconstruction of the coupon as compared to the coupon surface image in Figure 3(a). The technique quantified the pitting corrosion by estimating the following parameters: corroded volume and mass, corroded area, fraction of the corroded surface, average penetration, deepest penetration, penetration standard deviation, and cumulative distribution of the penetration depth. These parameters for the coupon in Figure 3(a) are listed in Table 1.

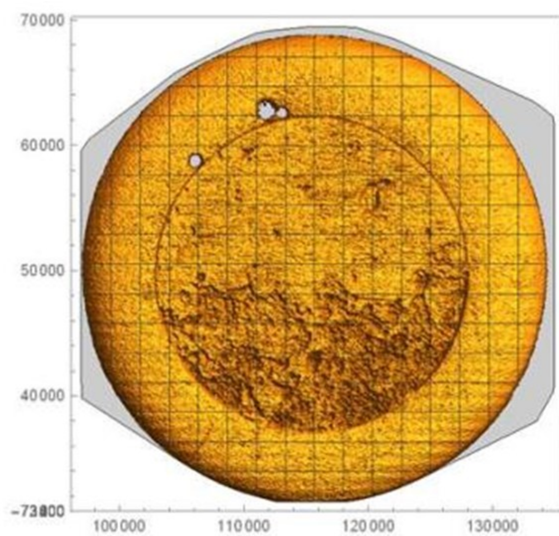
Table 1. Parameters related to quantifying corrosion for coupon in Figure 3(a)

Parameter	Value
Fraction of corroded surface	0.648
Corroded area	328.4 mm^2
Corroded volume	10.71 mm^3
Average penetration	32.61 μm
99 percent quantile penetration	160.1 μm
Surface average corrosion rate	41.9 μm/yr (1.65 mil/yr)*
Deepest penetration rate	317.5 μm/yr (12.5 mil/yr)* - (based on 99 percent quantile penetration)
* 1 mil/yr = 1 mpy = 25 μm/yr	

A cumulative depth distribution profile was developed for each coupon. The cumulative depth distribution is the probability of the pit depth not exceeding a given value. For example, if the value of the cumulative distribution at 160.1 μm is 0.99. Thus, the probability that the depth does not exceed 160.1 μm is 0.99. Alternatively, the probability that the depth will exceed 160.1 μm is 1−0.99=0.01. This information, i.e., 99 percent quantile penetration, was used to estimate the maximum pitting corrosion rates with high degree of confidence.

(a)





(b) **(c)**

Figure 3. (a) Image of the A36 coupon after 6 months of exposure, and (b) false color map and (c) digital image constructed using the laser-profilometer data.

The corroded volume, A36 density, coupon surface area, and exposure time for each coupon were used to estimate the surface average corrosion rate, and 99 percentile pit depth and exposure time to estimate the pitting corrosion rate. The pitting corrosion rate of a coupon provide an indication of severity of the corrosion, whereas the surface average corrosion rate provides an indication of extent of the corrosion.

Each experiment had 12 coupons, 6 of them were in direct contact with sand, and the remaining 6 were placed in the vapor space of each tub experiment. Each set of three of the six coupons in contact with the sand and in vapor space were extracted after 6 months, and the remaining after 12 months. Only three of the vapor phase coupons exhibited corrosion. Therefore, only three vapor phase coupons were analyzed using the laser profilometer technique.

Sand-Contact Coupons

Digitally reconstructed images of the sand-contact coupons are presented in Figures 4 and 5 after 6 and 12 months of exposure, respectively. The corrosion rate data for the sand-contact coupons are listed in Table 2 (sand and sand + 100% VCI), Table 3 (sand and sand + 10% VCI), and Table 4 (sand and sand + 1% VCI). Each table has data for 6- and 12-month coupons for each electrolyte and corrosion type, thus six corrosion rate values for each combination of electrolyte and corrosion type. In addition, a combined average corrosion rate of the 6- and 12-month coupons and corresponding standard deviation was calculated for each electrolyte and corrosion type. These average values and standard deviations of the averages are listed in the respective tables and are graphically presented in Figures 6−8.

Averages of the surface average corrosion rates for the sand, sand + 100% VCI-A, and sand + 100% VCI-B electrolytes are presented in Figure 6(a), and averages of the pitting corrosion rates presented in Figure 6(b). In Figures 6(a) and 6(b), the surface average corrosion rates for the three electrolytes are within 1.0 mpy (25.4 µm/yr) of each other; however, the pitting corrosion rates range between 6.9 to 13 mpy (175.3 to 330.2 µm/yr). The pitting corrosion rates for the sand-only coupons ranged between 7 to 24.6 mpy (177.8 to 624.8 µm/yr). The pitting corrosion rates in sand + 100% VCI-A decreased compared to sand-only, and ranged between 2 to 5.3 mpy (50.8 to 134.6 µm/yr). The pitting corrosion rates in sand + 100% VCI-B also decreased compared to sand-only, and ranged between 3.7 to 11.4 mpy (94.0 to 289.6 µm/yr). Effect of the VCIs is also evident in the surface average corrosion rates. The surface average corrosion rates ranged between 0.95 to 2.16 mpy (24.1 to 54.9 µm/yr) for the sand-only electrolyte. The surface average corrosion rates decreased in the sand + 100% VCI-A compared to sand-only electrolyte, and ranged between 0.16 to 0.76 mpy (4.0 to 19.3 µm/yr). Similarly, the surface average corrosion rates also decreased in the sand + 100% VCI-B compared to sand-only electrolyte and ranged between 0.47 to 1.63 mpy (11.9 to 42.4 µm/yr).

Averages of surface average for the sand-only, sand + 10% VCI-A, and sand + 10% VCI-B electrolytes and presented in Figure 7(a), and averages of the pitting corrosion rates are shown in Figure 7(b). In Figures 7(a) and 7(b), the surface average corrosion rates for the three electrolytes are within 0.7 mpy (17.8 µm/yr) of each other, however, the pitting corrosion rates range between 13.1 to 14.8 mpy (332.7 to 375.9 µm/yr). The pitting corrosion rates ranged between 8.1 to 26.2 mpy (205.7 to 665.5 µm/yr) in the sand + 10% VCI-A, and 10.5 to 23.7 mpy (266.7 to 602.0 µm/yr) in sand + 10% VCI-B. These pitting corrosion rate ranges indicate that the severity of the pitting corrosion not mitigated at 10% of the recommended dose values. However, a comparison of the surface average corrosion rates with and without VCI showed that extent of corrosion slightly decreased with the VCI usage.

Averages of surface average for the sand, sand plus 1% VCI-A, and sand + 1% VCI-B electrolytes are presented in Figure 8(a), and averages of the pitting corrosion rates in Figure 8(b). The pitting corrosion rates ranged between 6.1 to 17.8 mpy (154.9 to 452.1 µm/yr) in the sand + 1% VCI-A, and 7.0 to 10.6 mpy (177.8 to 269.2 µm/yr) in sand + 10% VCI-B. These pitting corrosion rate ranges indicate the severity of the pitting corrosion is somewhat lower at 1% dosage compared to sand-only electrolyte, but a statistical analysis was needed to quantify significance of the decrease. Similarly, a comparison of the surface average corrosion rates with and without VCI showed that extent of corrosion slightly decreased with the VCI usage, but a statistical analysis was needed to quantify significance.

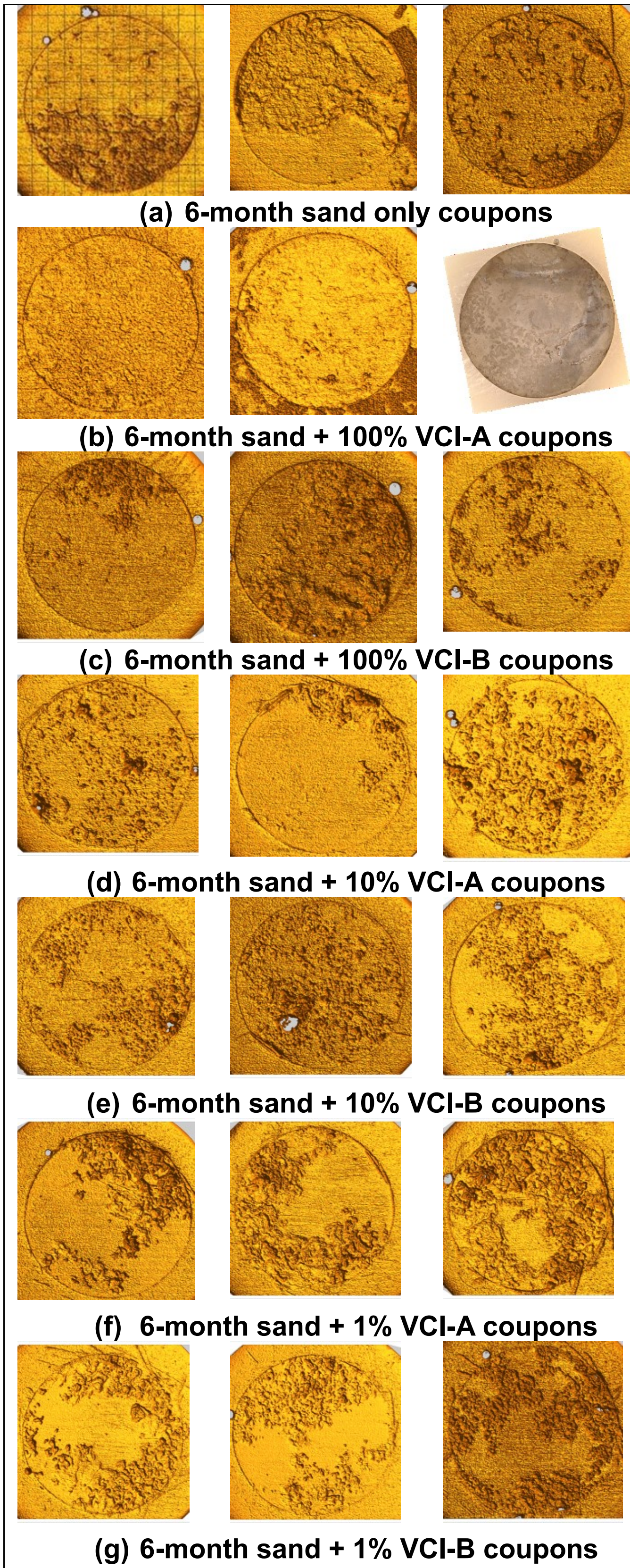


Figure 4. Digitally reconstructed images of the sand-phase coupons after 6 months of exposure

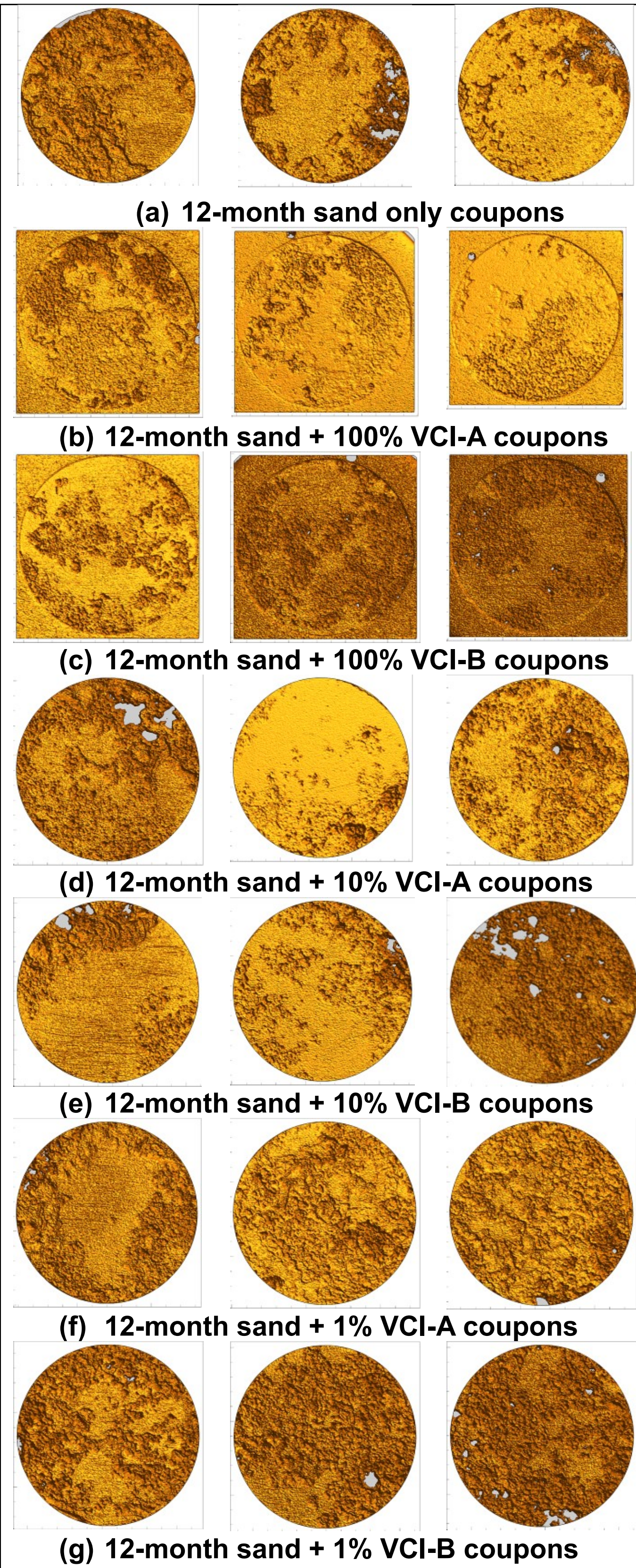


Figure 5. Digitally reconstructed images of the sand-phase coupons after 12 months of exposure

Table 2. Corrosion rates for sand-contact coupons in sand and sand + 100% VCI

Corrosion Type	Corrosion Rate (mil/yr)*					
	Sand Only		Sand + 100% VCI-A		Sand + 100% VCI-B	
	6-month coupons	12-month coupons	6-month coupons	12-month coupons	6-month coupons	12-month coupons
Overall Surface Average	1.65	0.95	0.16	0.56	0.47	0.53
	1.90	1.14	0.74	0.53	1.63	0.47
	2.16	1.09	0.51	0.50	0.62	0.52
	Average**	**1.48**	**Average****	**0.50**	**Average****	**0.71**
	± std***	**± 0.49**	**± std*****	**± 0.19**	**± std*****	**± 0.46**
Pitting (maximum)	12.5	7.0	2.0	4.5	7.8	5.3
	9.7	13.3	3.7	5.3	11.4	3.7
	24.6	11.4	2.9	3.9	9.1	3.9
	Average**	**13.08**	**Average****	**3.72**	**Average****	**6.87**
	± std***	**± 6.07**	**± std*****	**± 1.16**	**± std*****	**± 3.09**

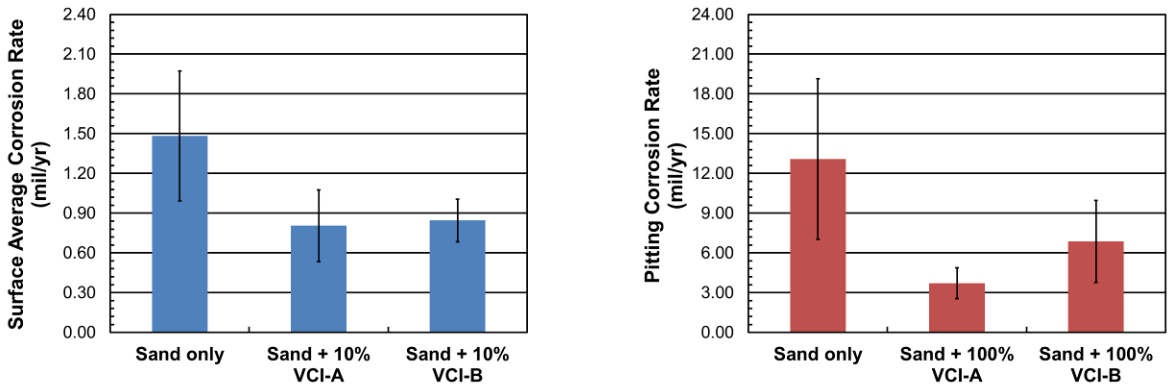
*1 mil/yr = 25 μm/yr
**Average values are calculated for 6 coupons for each electrolyte and corrosion type combination
***std denotes standard deviation of the data used to estimate average value

Table 3. Corrosion rates for sand-contact coupons in sand and sand + 10% VCI

Corrosion Type	Corrosion Rate (mil/yr)*					
	Sand Only		Sand + 10% VCI-A		Sand + 10% VCI-B	
	6-month coupons	12-month coupons	6-month coupons	12-month coupons	6-month coupons	12-month coupons
Overall Surface Average	1.65	0.95	0.92	0.86	0.75	0.75
	1.90	1.14	0.57	0.62	1.16	0.77
	2.16	1.09	1.27	0.59	0.76	0.88
	Average**	**1.48**	**Average****	**0.81**	**Average****	**0.85**
	± std***	**± 0.49**	**± std*****	**± 0.27**	**± std*****	**± 0.16**
Pitting (maximum)	12.5	7.0	26.2	13.0	14.3	10.5
	9.7	13.3	15.4	13.0	23.7	15.0
	24.6	11.4	22.0	8.1	14.3	10.8
	Average**	**13.08**	**Average****	**16.28**	**Average****	**14.77**
	± std***	**± 6.07**	**± std*****	**± 6.64**	**± std*****	**± 4.78**

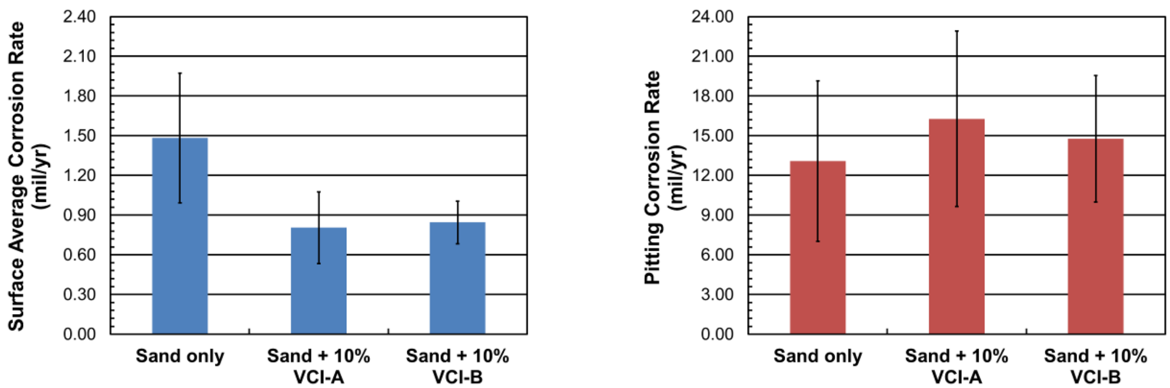
*1 mil/yr = 25 μm/yr
**Average values are calculated for 6 coupons for each electrolyte and corrosion type combination
*** std denotes standard deviation of the data used to estimate average value

A statistical analysis was conducted to determine the significance of difference between sand and sand + VCI electrolyte corrosion rates. Statistical method used was Student's t-test, which is based on the hypothesis that there is no statistically significant difference between the corrosion rates for the two electrolyte parameters used in the t-test—that is, that they are essentially identical to each other in terms of the coupon corrosion rates. The statistical result calculated by the test, P value, is the probability that the hypothesis is true. If the P-value is equal to or less than 0.05, it indicates a low probability that the two electrolytes resulted in similar corrosion rates—that is, it means there is a statistically significant difference between the two electrolyte corrosion rates.



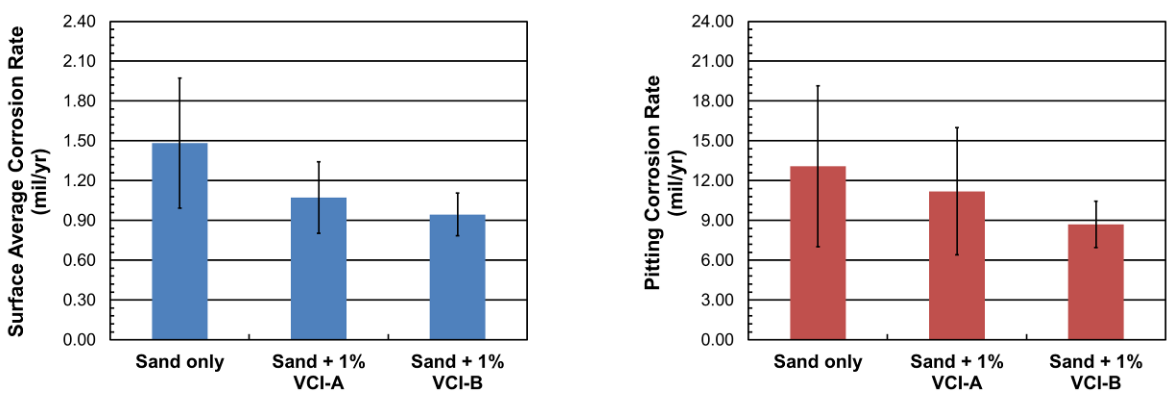
(a) (b)

Figure 6. Average of (a) surface average, and (b) pitting corrosion rates for sand, sand + 100% VCI-A, and sand + 100% VCI-B. The black line in each bar represent standard deviation.



(a) (b)

Figure 7. Average of (a) surface average, and (b) pitting corrosion rates for sand, sand + 10% VCI-A, and sand + 10% VCI-B. The black line in each bar represent standard deviation.



(a) (b)

Figure 8. Average of (a) Surface average, and (b) pitting corrosion rates for sand, sand + 1% VCI-A, and sand + 1% VCI-B. The black line in each bar represent standard deviation.

Table 4. Corrosion rates for sand-contact coupons in sand and sand + 1% VCI

Corrosion Type	Corrosion Rate (mil/yr)*					
	Sand Only		Sand + 1% VCI-A		Sand + 1% VCI-B	
	6-month coupons	12-month coupons	6-month coupons	12-month coupons	6-month coupons	12-month coupons
Overall Surface Average	1.65	0.95	1.53	0.74	1.20	0.69
	1.90	1.14	1.37	0.77	1.12	0.79
	2.16	1.09	1.10	0.92	1.03	0.84
	Average**	**1.48**	**Average****	**1.07**	**Average****	**0.95**
	± std***	**± 0.49**	**± std*****	**± 0.32**	**± std*****	**± 0.20**
Pitting (maximum)	12.5	7.0	17.8	6.1	10.5	6.8
	9.7	13.3	11.8	7.2	10.6	7.7
	24.6	11.4	15.8	8.5	9.6	7.0
	Average**	**13.08**	**Average****	**11.20**	**Average****	**8.70**
	± std***	**± 6.07**	**± std*****	**± 4.78**	**± std*****	**± 1.74**

*1 mil/yr = 25 μm/yr
**Average values are calculated for 6 coupons for each electrolyte and corrosion type combination
*** std denotes standard deviation of the data used to estimate average value

The P-values calculated using Student's t-test are listed in Table 5. Input data for Student's t-test included corrosion rates obtained from 6- and 12-month coupons for different electrolytes. In applying the t-test, each electrolyte and corrosion type combination was considered. The following conclusions are drawn based on the statistical analysis:

- Dosing of the sand with 100% VCI-A resulted in a statistically significant reduction in both surface average and pitting corrosion rates compared to sand only electrolyte,
- Dosing of the sand with 100% VCI-B resulted in statistically significant reduction in surface average corrosion rate compared to sand only electrolyte, however, reduction in the pitting corrosion rates compared to sand only electrolyte is only marginal with 94% confidence, and
- At 10% and 1% VCI of recommended dosage, the pitting corrosion in the VCI dosed sand is statistically similar to the sand-only electrolyte, indicating that VCI effectiveness vanished at these dosages.

The data in Tables 2-4 and Figures 6-8 coupled with the statistical analysis highlight the following. Pitting corrosion is the main hazard for tank leakage and failures. None of the VCI dosages were sufficient to reduce the corrosion rates less than 1 mpy (25.4 μm/yr), i.e., corrosion is not mitigated equivalent to the CP levels specified in NACE SP0193[5] and NACE SP0169.[6] Specifically, as per NACE SP0169, commonly accepted benchmark for sufficient CP is when corrosion rate is less than 1 mpy (25.4 μm/yr). However, a 100% dose of VCI-A reduces the pitting corrosion rate to one third that of the native rate. Similarly, a 100% dose of the VCI-B reduces the pitting corrosion rate to half that of the native rate. These reduction in pitting corrosion rates with 100% recommended dose do provide an extension of the life span of the tanks before repair or replacement is required.

Vapor-phase coupons

The vapor phase coupons were visually analyzed for corrosion prior to laser profiling of the surfaces. It was observed that most vapor phase coupons showed little or no signs of corrosion. Images of the 6- and 12-month coupons exposed to the vapor space of various electrolytes are presented in Figures 9 and 10, respectively. Some coupons showed significant corrosion compared to the others. Corrosion

Table 5. Student's t-Test P-values for comparison of sand and sand + VCI corrosion rates

Corrosion Rate	Comparison Between Electrolytes	P-Value* From the Student's t-Test	Statistically significant difference (Yes/No)
Surface Average Corrosion	Sand and Sand + 100% VCI-A	0.003	Yes
	Sand and Sand + 100% VCI-B	0.02	Yes
	Sand and Sand + 10% VCI-A	0.02	Yes
	Sand and Sand + 10% VCI-B	0.02	Yes
	Sand and Sand + 1% VCI-A	0.12	No
	Sand and Sand + 1% VCI-B	0.05	Yes (marginal)
Pitting	Sand and Sand + 100% VCI-A	0.012	Yes
	Sand and Sand + 100% VCI-B	0.06	No (marginal)
	Sand and Sand + 10% VCI-A	0.40	No
	Sand and Sand + 10% VCI-B	0.61	No
	Sand and Sand + 1% VCI-A	0.56	No
	Sand and Sand + 1% VCI-B	0.14	No
*P-value of 0.05 or less indicate statistical significant difference			

on some coupons placed on plastic racks occurred because the plastic stand and coupons shifted location during tests, which resulted in some coupons directly contacting the plastic bars of the racks. This led to formation of crevices, and thus crevice corrosion occurred on some coupons. The coupons that were judged to experience severe crevice corrosion (in form of pitting under crevices) were analyzed using the laser profilometer data. The surface average and pitting corrosion rate data of the 12-month coupons are listed in Table 6. As listed in Table 6, the surface average corrosion rates of the three coupons (two sand-only and one sand plus 10% VCI-B coupons) are less than 1 mpy (25.4 μm/yr), and the pitting corrosion rate of the coupons are less than 5 mpy (127 μm/yr). The listed data also indicate that pitting corrosion in the crevices could be mitigating by exposure to VCIs, however, this phenomenon needs to be further investigated.

Table 6. Surface average and pitting corrosion rate of the few vapor phase coupon

Coupon exposure time	Electrolyte	Surface Average Corrosion Rate (mil/yr)*	Pitting Corrosion Rate (mil/yr)*
12 month	Sand only	0.45	3.97
12 month	Sand only	0.40	4.64
12 month	Sand + 10% VCI-B	0.24	2.52
*1 mil/yr = 25 μm/yr			

(a) 6-month sand only coupons

(b) 6-month sand + 100% VCI-A coupons

(c) 6-month sand + 100% VCI-B coupons

(d) 6-month sand + 10% VCI-A coupons

(e) 6-month sand + 10% VCI-B coupons

(f) 6-month sand + 1% VCI-A coupons

(g) 6-month sand + 1% VCI-B coupons

Figure 9. Images of the vapor-phase coupons after 6 months of exposure

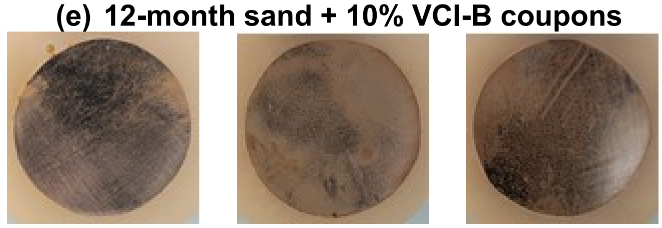
(a) 12-month sand only coupons

(b) 12-month sand + 100% VCI-A coupons

(c) 12-month sand + 100% VCI-B coupons

(d) 12-month sand + 10% VCI-A coupons

(e) 12-month sand + 10% VCI-B coupons



(f) 12-month sand + 1% VCI-A coupons

(g) 12-month sand + 1% VCI-B coupons

Figure 10. Images of the sand-phase coupons after 12 months of exposure

Visual examination of the coupons that were not analyzed using laser profilometer suggest that vapor phase corrosion of A36 carbon steel is negligible, and the presence of VCI may further reduce pitting corrosion tendencies. The majority of the metal surfaces remained in the pre-test conditions, i.e., as shiny as before commencing the experiments. Some images of the coupons in Figures 9 and 10 may not appear shiny. This was due to contrast ratio selected to photograph the coupons.

CONCLUSIONS

Several experiments were conducted to evaluate two commercially available VCIs for their performance on soil-side corrosion mitigation of tank bottom plate. It was determined that

- dosing of the sand electrolyte with 100% VCI-A resulted in a statistically significant reduction in both surface average and pitting corrosion rates compared to sand-only electrolyte,

- dosing of the sand electrolyte with 100% VCI-B resulted in a statistically significant reduction in surface average corrosion rate compared to sand only electrolyte; however, the reduction in the pitting corrosion rates was only marginally significant, with 94% confidence,

- since pitting is the main hazard for tank leakage, the vendor recommended VCI dosages were not sufficient to lower pitting corrosion rates less than 1 mpy, i.e., the corrosion rates were not mitigated to the extent specified in NACE SP0193 and NACE SP0169 for demonstrating adequate CP. However, a 100% dose of recommended value with VCI-A reduces the pitting corrosion rate to one third that of the native rate. Similarly, a 100% dose of VCI-B reduces the pitting corrosion rate to half that of the native rate. These reduction in pitting corrosion rates do provide an extension of the life span of the tanks before repair or replacement is required, and

- at 10% and 1% VCI of the recommended dose values, the pitting corrosion in the VCI-dosed sand is statistically similar to the sand-only electrolyte, i.e., both VCI-A and VCI-B were not effective at these 10% and 1% VCI dosages.

Overall, the VCIs selected in this study were found to be effective in mitigating pitting corrosion of A36 grade carbon steel exposed to corrosive sand, provided the VCI dosages were in accordance with the recommended values. The VCIs significantly reduced the tendency of pitting corrosion, but the corrosion rates were not mitigated to the extent specified in NACE SP0193 and NACE SP0169 for demonstrating adequate CP. None the less, use of VCIs could provide corrosion mitigation, and thus service life extension, for the tanks without active CP systems or where CP systems have either failed or degenerated.

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