RESEARCH ARTICLE

FACTORS INFLUENCING ATMOSPHERIC CORROSION RATES IN ABU DHABI

*Paul Rostron and Chaima Belbarak

Chemical Engineering, The Petroleum Institute, Abu Dhabi

ABSTRACT

Samples of carbon steel were exposed to the atmosphere in Abu Dhabi and corrosion rates measured every month for one year. Various angles of repose from 0° to 45° were selected, as well as a comparison between north facing and south facing. The samples were heavily contaminated with airborne dust, even though they were 15 m above grade. The salt content of the dust was high ~2000 ppm) and is believe responsible for the high corrosion rates observed in a country where there less than 30 mmyr^{-1} of rain. Comparison between top and bottom surface was also made as well as an investigation of the chloride content of the dust. The study produced a protocol that can be rolled out to the whole of the UAE to produce a corrosion map of the UAE.


INTRODUCTION

Atmospheric corrosion is a well understood phenomena and there is extensive literature on the subject[x]. The measurement of atmospheric corrosion is subject to many industry standard testing protocols. In this research we are using these standard tests to investigate and try to understand the unusually high atmospheric corrosion observed in Abu Dhabi. Abu Dhabi is a city on the southern shore of the Arabian Gulf, in the country of the United Arab Emirates. As the Capital city of the UAE it is extensively built up and supports apopulation of approximately 1.2 million. Current plans are for a rapid expansion (by 2020) to 3.4 million. The city is an island separated from the mainland by a narrow channel. A cursory examination of structures around the city indicates that atmospheric corrosion rates seem to be very high[pictures 1-5]. Coated structures face an extremely aggressive environment and once coating failureoccurs rapid corrosion of the underlying structure begins. However, a cursory examination of the climate suggests that corrosion should not be a problem (ABES). The region is dominated by a hot, dry desert, with barren sand dunes. No rivers exist and there is almost no natural vegetative cover. Average rainfall, at less than 3 cm per year is extremely low. The low rainfall might initially suggest that corrosion should not be an issue in this region, as without an electrolyte, atmospheric corrosion rates are limited to a light tarnishing caused by direct oxidation. And yet we see a strong corrosion threat. The typical rainfall pattern for Abu Dhabi.is shown in chart 1. Typically, rainfall of less than 1 or 2 mm per month is observed. This is usually highly localized from occasional thunderstorms. Often the rain is sufficient to cause

the surface to get wet, but not enough to cause water to flow. In this paper we seek to measure the corrosion rates for uncoated metal samples exposed to this environment in an attempt to identify the source of the very high corrosion rates observed, and to suggest remedial actions that can be taken. Only one test location was chosen as the aim of this phase of the project is to identify the structural factors which might affect corrosion, namely; angle of repose, time of year, north/ south facing direction and a comparison between top surface and the underside of a test coupon. Once the effects of these factors and the best way to perform the measurements have been worked out, the project will be rolled out for a corrosion rate map of the UAE, similar to a recent study in Kuwait (ACMK) several metals were tested, but in this paper we focus on the effects of atmospheric exposure on 2mm thick mild steel samples.

Chart 1: Average annual temperature for Abu Dhabi. Source, reference 3
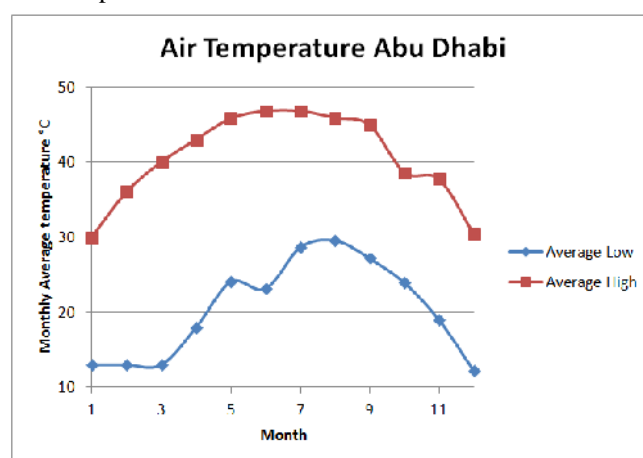
Corresponding author: Paul Rostron,
*Chemical Engineering, The Petroleum Institute, Abu Dhabi.*

METHODOLOGY

Uniform, representative samples of different metals were prepared and cleaned as per ASTM standard: STP 435. (MCA) Each sample was cut from 2mm thick sheet metal and the edges ground to dimensions of 5.0 cm x 7.0 cm. for each test parameter, three identical samples were use to provide average results.   After cutting out the coupons, the edges of the coupons were ground off to remove any shear affected edges. The effect of shear cutting would have left the edges anodic to the cathodic sheet, distorting the results. Clean degreased samples were supported by rubber washers to prevent galvanic corrosion on racks and exposed to the environment for different durations. Samples were exposed for monthly, 6 monthly and yearly exposures at 0°, 30° and 45° angle of repose. The default position was south facing, but an additional set of samples were set at 30° facing North. The sample were held in a wooden frame and secured to it by means of two insulating washers (each 5mm thick) at each corner. The washers were secured to the frame by galvanised zinc nuts, bolts and washers, with great care to ensure that there was no metallic connection between the metal securing system and the coupon. The underside was open to the air. The rubber washers were tightly bolted to ensure there was no possibility of crevice corrosion and in all of the sample, no evidence of crevice corrosion was noticed. Since this research was the initial plan for a corrosion map of the UAE, only one test location was chosen. The testing location was chosen to be away from intervention, so the roof of a building was chosen. The height above grade was approximately 15 m. This allowed the samples to be exposed to the true airborne dust, uncontaminated with wind blown sand grains. After exposure, the samples were cleaned using ASTM standard G1(CPACR) to determine the weight loss experienced. One of the great problems with the cleaning process is that the process has to be sufficiently aggressive to dissolve the corrosion products without removing any of the un-corroded metal, which would over estimate the corrosion rate. To minimize this, our cleaning protocol incorporated severalmitigation strategies which went beyond the standard approach. Firstly, before each series of un-corroded samples were tested, the operator would apply the cleaning protocol to a blank sample.

This was repeated several times until the operator could clean the samples without removing any metal from the blank sample. This cleaning protocol was then used on the test specimens in exactly the same way. Data for this procedure showed no mass difference in sampled cleaned in this way. All masses were recorded using the same analytical balance to avoid balance calibration issues. The sensitivity of the balance used in all of the mass measurements was 0.1 mg, so the error in any experiment was the level of detection which can be calculated as 3×10^{-5} mmyr^{-1}Experimental errors were further reduced by using relatively large (5 cm x 7 cm) test panels. Finally, for reproducibility, each variable was repeated using three identical test panels to determine an average result. The cleaning method chosen in this series of experiments was cathodicallyprotection acid etching. Coupons of carbon steel were immersed in 10% Sulfuric acid and the samples were made negative by connection to an external DC power supply. Graphite anodes were placed around the sample to ensure uniform current density. A protection voltage of -1.5-2.0 V was applied by external power source. The CP effectiveness

was tested by measurement of a coupon to solution potential using a copper- copper sulfate reference electrode and a true RMS multimeter (having internal impedence of > 10 MΩ). The driving voltage on the power supply was adjusted using a rheostat, such that the coupon to copper sulfate reference electrode potential was in the range -850 mV$_{CSE}$ - 1100 mV$_{CSE}$. Samples were immersed in the acid etch solution for 20 minutes, followed by light scrubbing with green pan scourers. For particularly difficult to remove deposits the process was repeated until clean grey metal was achieved. Blank (un-corroded) samples exposed to this protocol lost less than 0.00005g per cycle. In a qualification test, one sample was exposed to the cleaning protocol for 15 times and the mass loss was measured to be 0.2 mg. We were thus able to develop a highly reproducible and effective cleaning protocol within the industry standard, but it was highly labor intensive and time consuming. Whilst effective it would not be viable as a commercial method.

RESULTS AND CALCULATIONS

As expected, the carbon steel samples showed a relatively high rate of corrosion. During the study, there was relatively little effect month by month. October showed a higher corrosion rate, but otherwise the rate observed was relatively constant across the year. The results are summarized in Graph 1, for both the monthly results and the one year exposure samples. The one year exposure coupon showed a lower overall corrosion rate.
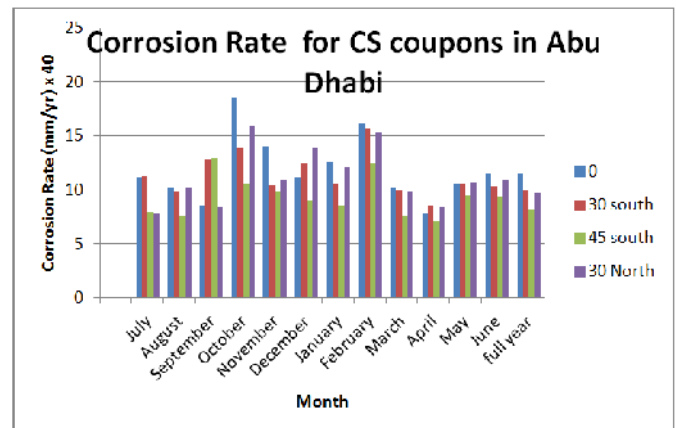
Graph 1. Corrosion rates for carbon steel samples by month

Upon examination of the test samples the following observations were made:

- Even after only one month of exposure, all of the samples were covered in a layer of fine dust, deposited from the air. There were no sandstorms during the trial, so this dust was the ubiquitous dust found around Abu Dhabi. The high location of the testing site, on the roof of a 3 story building (roof height~15 m above grade) meant that the dust was not due to local wind effects whipping up surface dust.
- The corrosion was uniform across the coupon surface.
- There was a significant difference between the top surface and the bottom, with the top surface showing a thick layer of hard adherent rust. The underneath was only lightly rusted with a loose flaky rust.

- The one year exposure coupons had an extremely hard and difficult to remove corrosion product. The inner layer was black indicating the formation of magnetite. The corrosion rate was lower than the average of the monthly corrosion rate due possibly to the slightly protective scale.

To calculate the penetration rate from (corrected) mass loss measurements, the following calculation was performed:
Penetration rate = Kw/ATD

Where K =3.45 x 10^6 for penetration rates in mpy (mils per year) and K = 8.74 x 10^4 for penetration rate measurements in $mmyr^{-1}$.

W= weight loss (g)A = surface area of the sample (cm^2)
T = time of exposure (hours), D= metal density

Further analysis

Topside versus underside corrosion rate comparison

The difference in corrosion rate between top surface and bottom surface was clearly a significant difference, and therefore experiments were performed to quantify this difference. Identical coupons of carbon steel cut from the same stock sheet were cleaned and degreased as per our protocol, and then one side protected from the environment using a lacquer paint. The samples were left to dry thoroughly overnight in an oven at 40 °C and then exposed in the 0° elevation position, oneseries of samples with the exposed side uppermost and the other set with the exposed side underneath. The samples were exposed for one month and then the corrosion product removed as before, but with extra care to ensure no damage to the lacquer. After cleaning the lacquer was inspected to ensure no damage and then the mass loss measured. The comparative trial showed that 95% of the corrosion occurs on the top surface of the metal, with corrosion on the underneath a very minor element.

Airborne dust compositional analysis

Dust samples were collected for analysis to try to understand the effect it has on atmospheric corrosion rates. One hypothesis for the high corrosion rates is that the dust is somehow responsible. Firstly, the dust fizzes in the presence of hydrochloric acid, the gas released causes lime water to cloud, indicating that at least a part of the dust is a carbonate, most likely calcium carbonate as could be predicted since the majority of rocks present are limestone. The dust also contains traces of silica. Dust samples were also analyzed for chloride concentration and the chloride results are recorded in Table 1.

Table 1. Dust chloride concentration

Month	[Chloride] (ppm)
June	1842
July	1795
August	1844
September	1783
October	1943
November	2034
December	355
January	1447
February	2035
March	1832
April	1792
May	2025

In addition to dust samples falling onto the coupons, dust from various locations around the test site were also analysed for chloride content. The problem with these samples is one is unsure as to the amount of time they have sat on the surface. Also, any rain may have leached chlorides out of them. Two types of dust were identified at ground level: a very fine powdery dust, very similar to the dust accumulated on the coupons, and a coarse, sandy material, only seen at ground level and not found on rooftops. Both types were analysed for chloride content and the data appears in Table 2. Dust found on galvanised steel structures contained very little chlorides, but the galvanised steel structures suffered from extensive corrosion. It is possible that the chlorides are incorporated into a hard adherent layer that was not scraped off, resulting a low chloride measurement. The fine powdery dust had a very similar chloride content to that found on the coupons. The wind blown sand had a lower chloride content, primarily because there was a higher silica content.

Table 2. Chloride content in different deposits around the area of interest

Location	Chloride concentration, ppm (average of 3 readings)
Ground level fine dust scraped from a windowsill	1882
Ground level wind blown sand in lee of kerbstone	475.3
Roof level Dust collected from flat painted surface	2505
Roof level dust scraped from flat corroded galvanised steel AC duct	52.18
Concave depression in galvanised steel AC duct	72.43

Calculation example

Samples of dust were collected by means of a conical flask and filter funnel. This trapped airborne dust and any rain. Accurately weighed samples of the dust were added to distilled water and titrated against a silver nitrate solution($1.252x10^{-3}$M) using potassium chromate (VI) indicator.

Typical calculation (for September)

For a dust sample of 0.1508 g, an average titration volume of 6.05 mL was recorded 1.254E-3 M Ag^+ X 6.05/1000 L X35.453 g/molCl X 1/0.1508 g dust = 1780 ppm Cl^-

DISCUSSION OF RESULTS

The uniform corrosion rates observed for the carbon steel samples were remarkably consistent. There was little seasonal variation.Very little corrosion was found on the undersides of the coupons. There is some evidence in the data that Fall and Spring achieve higher corrosion rates. During these seasons, the weather undergoes a change from hot to cold and vice versa, and is often accompanied by night time fog. The foggy days could be responsible for the higher corrosion found during these times. During the rest of the year, the relative humidity varies from a daytime low of <50% to a night-time high of >80%. During the day, the humidity is low enough for any salt deposits to dry out completely and be blown around by the strong winds that occur in the late afternoon. At night the humidity is high enough (>70%) for salt deposits to form a saturated brine on the surface of the sample, causing rapid

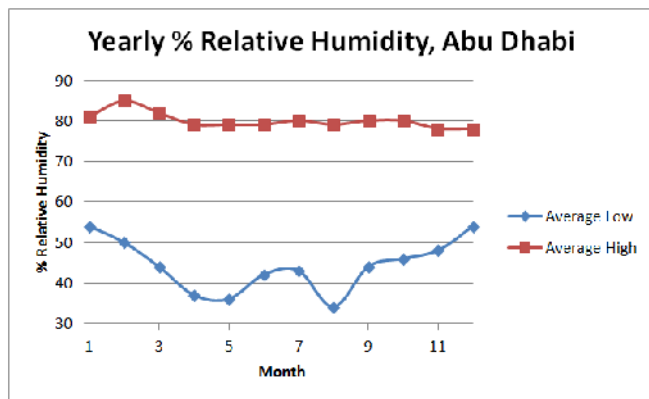corrosion. Government data [3]on average high and low humidity bears this out and is shown in chart 2.

Chart 2. Average annual Relative Humidity for Abu Dhabi. Source, reference 3

The angle of repose had a slight effect on corrosion rates. The steeper the angle the lower the rate of corrosionwas observed. We can assign this effect to the reduced ability of angled coupons to allow dust to settle on them. This result was also reinforced by the comparison of top versus underside corrosion rates, with 95% of the corrosion of a flat sample occurring on the top side. Looking around Abu Dhabi we see many examples of the effect of salt contamination causing corrosion.

- In Picture 1: we see a cast aluminium door handle showing extensive top surface corrosion.
- In Picture 2: a rarely used walkway has suffered complete failure of the coating and extensive corrosion of the tread surface after 3 years exposure.
- In picture 3: we see a HVAC exhaust duct. Constructed out of 316L stainless steel, it shows extensive pitting corrosion after only 2 years exposure. Run off showing salty deposits are clearly visible.
- In picture 4: Galvanized steel HVAC duct showing penetrating failure after 3 year's service.
- In picture 5: the roof of a car after one month's dust deposition. Corrosion on the flat surface also evident. The rest of car shows no corrosion at all.

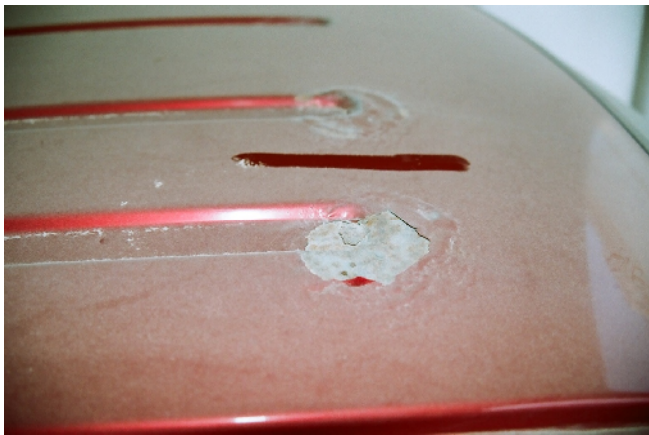**Picture 1. Cast door handle showing extensive top surface corrosion**

Picture 2. A rarely used walkway.Total coating failure. Age of structure: 3 years

Picture 3. 316L SS HVAC duct showing salt rime and pitting. Two years old

Picture 4. Galvanised steel HVAC duct showing corrosion failure after 3 year's exposure

Picture 5. One month of dust deposition on the roof of a car in Abu Dhabi.Also showing corrosion spots after 5 years exposure. Rest of car has no corrosion evident at all

Conclusion

Abu Dhabi has some very unusual weather. It is a hot dry desert, with minimal rainfall. However, the coastal location means that there is often high relative humidity, especially at night. During the daytime, the high temperature tends to result in low humidity. The temperature is high enough for salt to dry out completely, and be blown around by the strong onshore winds which develop in the late afternoon. However, when the temperature falls at night, the lower temperature causes the humidity to rise above 70% and the salt is now deliquescent, and produces a thin film of brine on any dust contaminated surface. Occasionally, fog banks at temperatures in excess of 30 °C are formed. Coupled with the relatively high salt content of the airborne dust and we have a recipe for rapid corrosion of exposed steel structures. We recommend that the environment should be considered a marine one, and coatings formulations used with this in mind. Regular cleaning of structures should be performed, with the aim to clean off the dust deposits. Not only is the dust unsightly, but we have shown it to be a significant source of corrosion. No work has been reported to date on the chloride concentration of airborne dust in the UAE. Further work, looking at producing a corrosion map of the UAE should also look at the chloride content of airborne dust around the country to identify any correlation. Further work is planned to extend this investigation to other areas around the UAE, with the aim of producing an isocorrosion map of the country. This work has set the groundwork for this study by showing that a country wide study should focus on the following sample: a flat coupon, coated on the underside.

The exposure should be at a minimum one month, with six months to a year being preferred and care should be taken to mitigate seasonal variation. Seasonal variation in corrosion seems to be slight, but further work looking at the weather could yield interesting results. However, since this cannot be controlled we have decided to use results averaged over 6 months for the isocorrosion mapping project.

Cleaning protocols

There are two standard approaches to cleaning off rusted carbon steel without removing metal; inhibited 10% sulfuric acid, and cathodically protected carbon steel in 10% sulfuric acid. Both methods are recommended in ASTM and NACE standards. (CPACR and LCTM) In this research the cathodic protection approach was used, coupled with light scrubbing using a green pan scourer. It may be that the corrosion product we observed was an unusuallyhard, baked rust, but it was found that the rust took a great deal of effort to remove, with more than one hour per sample often required to remove it. It is proposed that any future study looks at better cleaning protocols. One system to consider is blast cleaning with either solid carbon dioxide, or sodium bicarbonate, which are promoted as not damaging the steel (these cleaning protocols are advertised as not creating a blast profile).

REFERENCES

1 Annual Bulletin of Environmental Statistics 2009 published by Statistic Centre Abu Dhabi, PO box 6036, Abu Dhabi2010. Accessed as a pdf 20 march 2012 from:http://www.scad.ae/SCAD%20Publications/Annual%20Bulletin%20of%20Environmental%20Statistics%202009%20English.pdf.
2 Metal Corrosion in the Atmosphere, STP 435, ASTM International, West Conshohocken, PA, 1968, pp360-391.
3 high and low relative humidity for Abu Dhabi, http://www.ncms.ae/climate/climateData.asp?id=26 website accessed 20 march 2012.
4 "Cleaning Protocols for Atmospheric Corrosion Rates", ASTM G1.ASTM International, West Conshohocken, PA.
5 TM0169: "laboratory Corrosion Testing of Metals", NACE International, Houston TX, USA, 2000.
6 "Atmospheric Corrosion Mapping of Kuwait" H.M. Shalaby, F. Al-Sabti and K. Al-Muhanna, Kuwait Institute for Scientific Research, paper 07342, CORROSION 2007, March 11 - 15, 2007.
7 ATMOSPHERIC CORROSION OF MATERIALS, S. SYED *Emirates Journal for Engineering Research,* 11 (1), 1-24 (2006).

****