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Performance indicator of the atmospheric corrosion monitor and concrete corrosion sensors in Kuwait field research station

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Abstract. Two field research stations based upon atmospheric corrosivity monitoring combined with reinforced concrete corrosion rate sensors have been established in Kuwait. This was established for the purpose of remote monitoring of building materials performance for concrete under Kuwait atmospheric environment. The two field research sites for concrete have been based upon an outcome from a research investigation intended for monitoring the atmospheric corrosivity from weathering station distributed in eight areas, and in different regions in Kuwait. Data on corrosivity measurements are essential for the development of specification of an optimized corrosion resistance system for reinforced concrete manufactured products. This study aims to optimize, characterize, and utilize long-term concrete structural health monitoring through on line corrosion measurement and to determine the feasibility and viability of the integrated anode ladder corrosion sensors embedded in concrete. The atmospheric corrosivity categories supported with GSM remote data acquisition system from eight corrosion monitoring stations at different regions in Kuwait are being classified according to standard ISO 9223. The two nominated field sites where based upon time of wetness and bimetallic corrosion rate from atmospheric data where metals and rebar's concrete are likely to be used. Eight concrete blocks with embeddable anodic ladder corrosion sensors were placed in the atmospheric zone adjacent to the sea shore at KISR site. The anodic ladder corrosion rate sensors for concrete were installed to provide an early warning system on prediction of the corrosion propagation and on developing new insights on the long-term durability performance and repair of concrete structures to lower labor cost. The results show the atmospheric corrosivity data of the environment and the feasibility of data retrieval of the corrosion potential of concrete from the embeddable sets of anodic ladder corrosion sensors.

Keywords: field research station; atmospheric corrosivity sensors; corrosion sensors for concrete

1. Introduction

Atmospheric corrosion accounts for the highest overall cost and metal loss of all the fundamental corrosive environments. It is defined as a thin aqueous layer between the surface of the corroding material and the atmosphere. Three phases, solid (corroding substrate), liquid (thin aqueous layer) and gaseous (atmosphere) and the interfaces between these phases are therefore important and can be used in corrosion monitoring principles. Corrosion monitoring in outdoor

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and indoor atmosphere poses specific challenges related to characterizing corrosion damage generally taking place at a low rate in a short practical time frame. Metals, alloys and metallic coatings may suffer atmospheric corrosion when their surfaces are wetted (Husain 2001). The nature and rate of attack depends upon the properties of surface formed electrolytes, particularly with regard to the level and type of gaseous and particulate pollutants in the atmosphere and the duration of their action on the metallic surface. Categorization of corrosivity of atmosphere provides a basis for the selection of materials and protective measures in atmospheric environments subject to the demands of the specific application particularly with regard to service life (ISO 9223, 2012). Unfortunately, the area of atmospheric corrosion monitoring for the State of Kuwait, especially in predictive capability, has not benefited much from recent advances in atmospheric corrosion field. The main difficulty has been thought to be the desert climatic condition of Kuwait and that the amount of electrolyte condensed on a metal surface is too limited for reliable measurement of electrochemical parameters. The recent advancement of cost effective micro-sensors based on modern vacuum deposition technology makes the fabrication of micro-sensors practical and form the base for recent corrosion sensor development. This technology is found to be useful for studying atmospheric corrosion under Kuwait environment, where reactions take place in ultra-thin, localized condensed water layer on metal surfaces (Husain *et al.* 2003, Cole *et al.* 1995, Guttman *et al.* 1968)

Electrochemical probes of various types have been used in atmospheric corrosion studies for approximately twenty years. However, until recently, the majority of studies had employed pairs of dissimilar metals, galvanically coupled. Such measurements attempts to estimate the “Time of Wetness” (TOW) parameter, i.e. the time period during which the test probe is wetted either by condensation or by rainfall. It is usually assumed that significant corrosion damage occurs only during these periods. The measurement of the galvanic corrosion current can be carried out using a sensitive current to voltage converter (zero resistance ammeter or ZRA) with operational amplifier (OPM). It is usual to record the total period during which the output of this device exceeds a preset limit, this being time of wetness parameter. Commercial probes are now available which utilize interlaced gold plated fingers on fiber-glass substrate. This simple approach does not give the actual corrosion rate, although a reasonable estimate can usually be made of the total metal loss over a period of time. (King *et al.* 1999, Leygraf *et al*. 2000)

Nowadays, it is possible to record the magnitude of the coupling current. Integration over the time of test then gives the total charge passed. This can be converted to the metal loss due to corrosion, using a suitable empirically obtained scaling factor. This factor is dependent on both cell geometry, the electrode material and on the exposure conditions. An estimate of the corrosion rate can then be made; since it is possible to theoretically predict that the corrosion current density will be proportional to the inverse of the cell resistance, measured by the corrosion rate sensor (Michailovsky 1982). The linear polarization measurement technique comprised of two identical electrode and relies on the application of a small (<20 mV) potential across the sensor test cell, measuring resultant current, or vice versa.

The main objective of this study was to demonstrate that the Corrosivity of Kuwait marine industrial atmosphere is measurable using sensitive electrochemical techniques and that these can be used in conjunction with continuous monitoring of physical and chemical parameters and computer analysis of the data to pinpoint the time periods and parameter combinations which give rise to increased corrosion rates

The knowledge of the effects of the various naturally occurring combinations of pollutants and meteorological parameters could then be used in conjunction with continuous electrochemical monitoring to predict on a continuous basis the corrosivity of the site atmosphere with respect not only to mild steel but also to other structural building materials and electronic devices.

2. Kuwait atmospheric corrosivity station

The Kuwait Atmospheric Corrosivity Monitor has been designed by the CISRO Manufacturing and infrastructure Technology Australia (6). This unit records the environmental parameters that are important for corrosion. Used in combination with pollutant monitoring equipment such as ISO Salt Candle, estimates of the Corrosivity of the environment can be made.

The system shown in Fig. 1 includes a bimetallic corrosion sensor. This enables the unit not only to provide ISO time of wetness (TOW) and Grid (TOW), but also the corrosion rate of the bimetallic sensor. The wetness grid and surface temperature sensors are seen here attached to a stainless steel plate.

The incorporated GSM modem with power supply (10-18 V DC) allows:

- Remote downloading of data with data logger engine specified as Data Taker DT50
- SMS messaging (including interrogation)
- Alleviates need for fixed telephone line

Specifications of Probe Sensors. Relative humidity and Temperature sensors type: Vaisala Humitter,

Temperature accuracy better than ±0.6℃ and RH accuracy better than ±5%

1. Wetness grid: Gold finger-jointed grid mounted on sintered alumina
2. Bimetallic corrosion sensor: Gold/Zinc, or Copper/Aluminum
3. Surface temperature sensor: PT100

Salt Candles. The wet Salt Candles allows accurate measurement of fluoride, chloride, nitrite, bromide, phosphate and sulfate cations; and lithium, sodium, ammonium, potassium, magnesium and calcium anions. The candles as described in ISO 9225 are used to trap and collect air-borne pollutants to determine the corrosive effect of the atmosphere in an area. They consist of a bottle containing a 40% glycerol solution and gauze wick that protrudes above the bottle. An aliquot of this solution is then analyzed for chloride ions according to ISO 9225. Alternatively an aliquot of the solution can be analyzed for the rate of deposition of many ions using Ion Chromatography. The deposition rate is expressed in (mg/m^2 day).

3. Corrosion rate sensor for concrete

Online sensors monitoring means sensors embedded in concrete for monitoring of temperature, resistivity, alkalinity (pH), chloride, corrosion potential, corrosion rates and in combination with continuous data acquisition. (Norberg 1993, Vera *et al*. 2009)

An online sensor for structural performance monitoring has been identified and accepted by many leading institution as an important facility that can influence strategic building aging performance significantly through better diagnostics, inspection and management of failure initiation in concrete (Ye *et at*. 2012, 2013). Many strategic building structures such as bridges, motorways, off shore structure and oil piers, cost billions of dollars when through classical inspection is carried out. They require special attention and advanced inspection techniques such as to establish and develop an early warning system before visible crack initiation/propagation or corrosion damage can occur.

Generally, reinforced structures must be inspected regularly and observed damages have to be repaired. The classical way to control of such huge reinforced concrete structures is typically performed by visual inspection; with non-destructive testing (NDT) for time-to-corrosion measurement combined with destructive testing and limited coring. As soon as structural problems are observed, a more thorough and expensive analysis is performed. Consequently, corrosion occurring at structurally sensitive locations may never be detected until the corrosion related damage becomes large and visible, which might lead to problem with costly maintenance or complete replacement. Online-monitoring could represent an alternative way with higher accuracy of detection of damages and, thus, lower overall costs. (Schiegg *et al*. 2010, Soleymani *et al.* 2004 Mccarter *et al*. 2004).

In this study a research effort is made to establish the atmospheric corrosion rate sensors and the embeddable anodic ladder corrosion sensors for concrete, the corresponding responses acquired by the station are reported in this study.

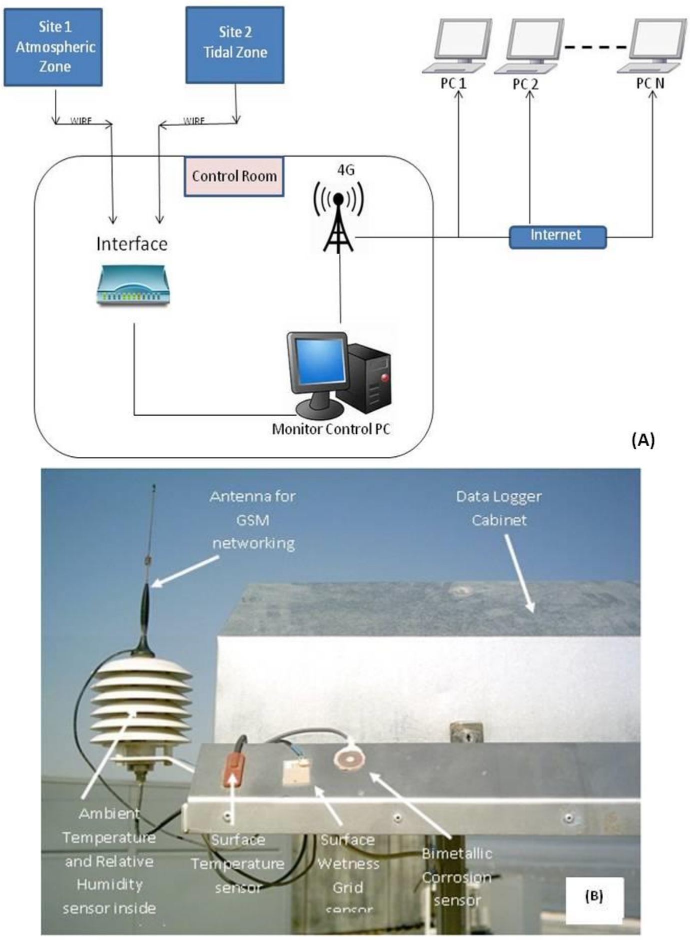


Fig. 1 Atmospheric Corrosivity Monitoring Station in Kuwait (a) Network of sensors and data transmission units (b) Sensor Components

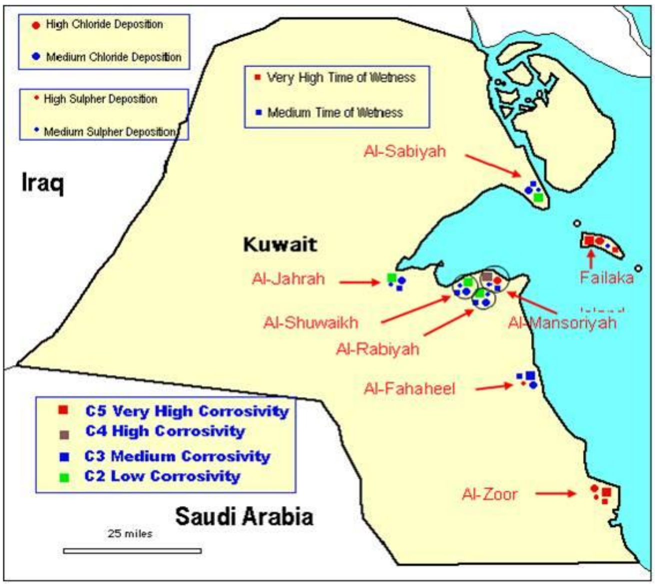


Fig. 2 Atmospheric Corrosivity map of Kuwait with color coded site corrosivity points

Fig. 3 Anodic ladder corrosion sensors installed in concrete blocks for atmospheric zone at KISR field research station

In this study, the complete set up for the installation of corrosion sensors for concrete blocks, Fig. 3, includes anode ladder type corrosion sensor, corrosion monitoring data logger (CMDL) for corrosion signals, wireless bridges, and electrical protective enclosures. The data was collected by wireless connection through global system for mobile communication (GSM) line and was continuously stored by data acquisition system available in the laboratory. The effectiveness of applying corrosion inhibitors (CI) in concrete for resisting chloride and sulphate induced corrosion was studied using corrosion sensors in this task. Type I and Type V cement and two corrosion inhibitors were used for the preparation of concrete mixes. Eight concrete mixes were prepared with different combinations of water-cement ratio, type of cement, and type of corrosion inhibitor.

5. Results and discussion

It has been decided for the purpose of this paper to limit the presentation of the Atmospheric Corrosivity monitor data to Sabia Station and Al Zoor Station only to one cumulative daily data plot instead of a series of progressively more detailed plots of all areas in Kuwait. Figs. 4 and 5 present the daily averages for of bimetallic corrosion, time of wetness (TOW), relative humidity RH with air and surface temperature. The plot represent the exposure period from 4 Aug 2004 to 23 Feb 2005 (i.e., 7 months). The months of exposure were split into two variables with the first three months as one variable and the last four as another. This is because initial examination of the plots of the data indicated a distinct difference in rates of change for the two periods of time (see Figs. 4 and 5). The atmospheric corrosion rate has shown that the electrochemical data reflect the same trends as the TOW, RH and surface temperature and gave useful information concerning seasonal changes of corrosion rates. The trends of seasonal data has indicated that as the temperature increases RH decreases and the layer formed by dew became thinner and thinner until all surface electrolytes has disappeared.

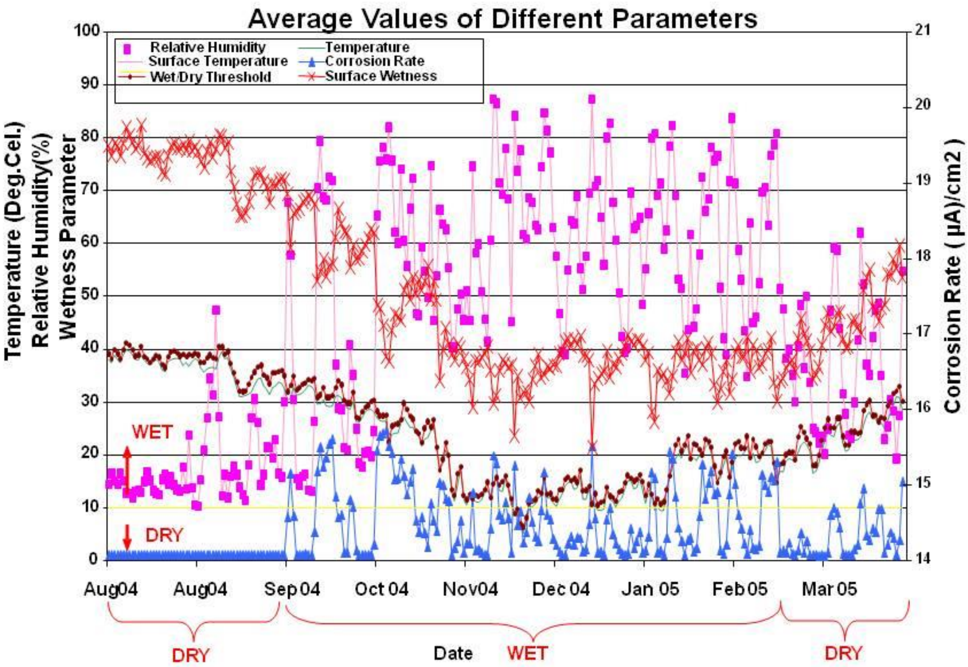


Fig. 4 Atmospheric corrosivity data for Sabia Station North of Kuwait, showing, bimetallic corrosion, TOW, R.H, surface temperature and air temperature

The following Figs. 6-8 lists atmospheric corrosivity data obtained to characterize the daily, weekly, and hourly performance of the corrosivity monitor located at Sabia and Al Zoor stations.

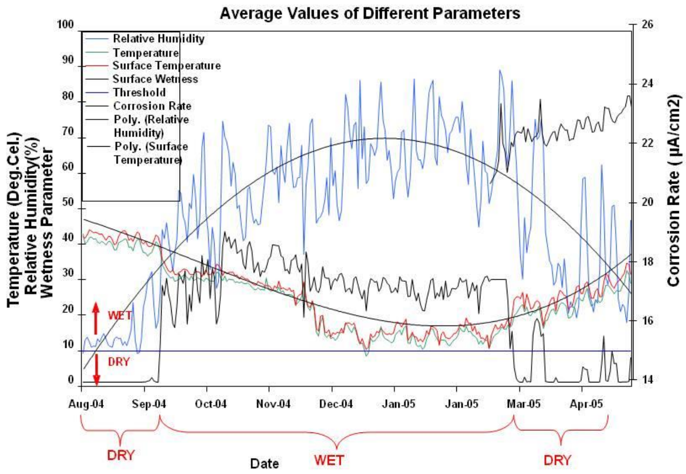


Fig. 5 Atmospheric corrosivity data obtained for Al-Zoor Texaco Station Site South of Kuwait, showing, bimetallic corrosion, TOW, R.H, surface temperature and air temperature

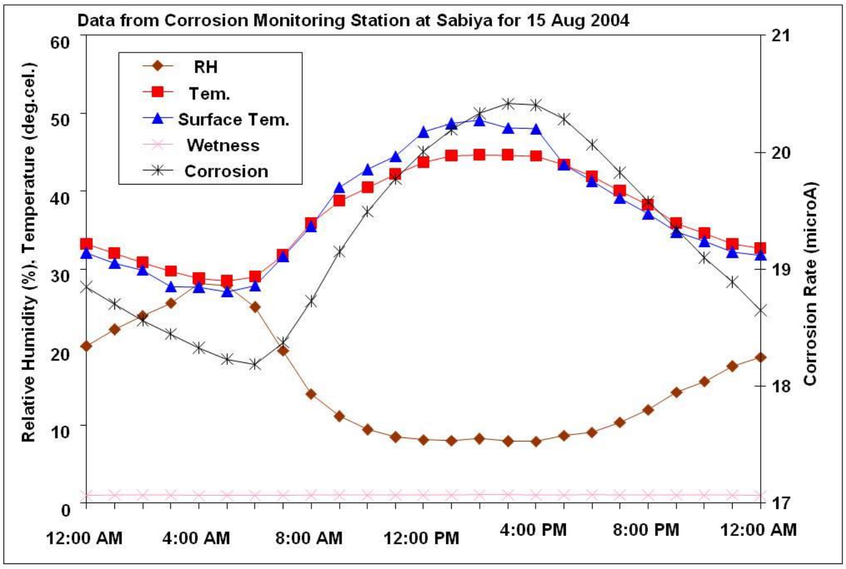


Fig. 6 Atmospheric data for Sabia on showing one day profile of RH, Temperature, Surface Temp, wetness, and corrosion rate

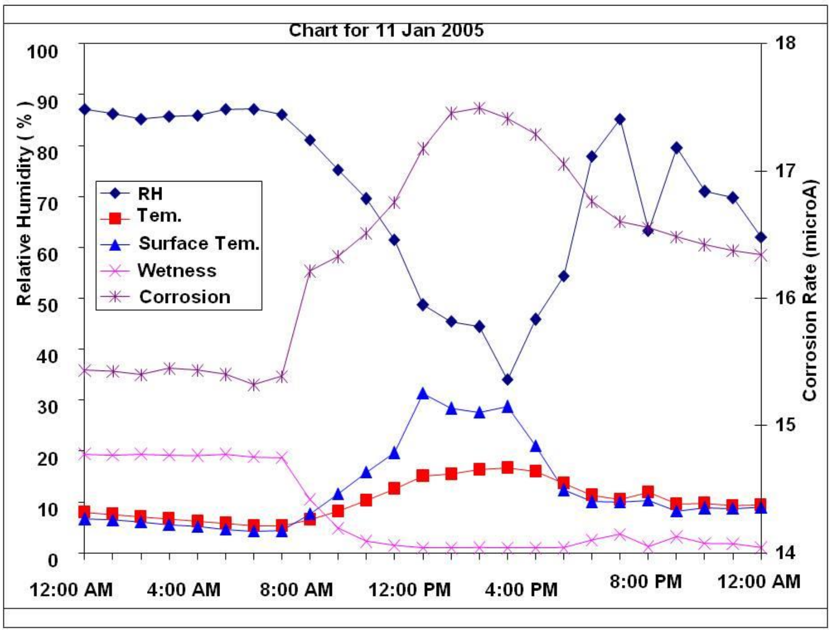
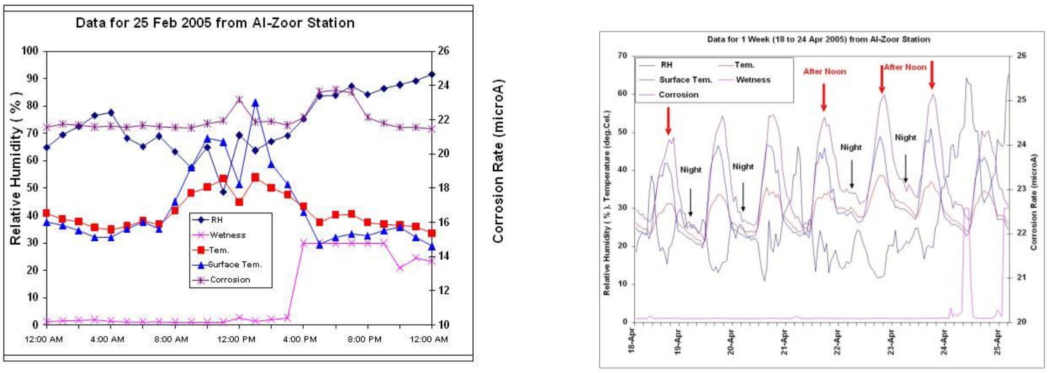


Fig. 7 Atmospheric data for Sabia on 10 & 11 January 2005, showing two days hourly profiles of RH, Temperature, Surface Temp, wetness, and corrosion rate



(a) (b)

Fig. 8 Atmospheric data for Al Zoor area on 25 February &18 to 24 April 2005, showing (a) one days and (b) two weeks hourly profiles of RH, Temperature, Surface Temp, wetness, and corrosion rates

Tables 1 to 4 present the classification of different locations in Kuwait based on time of wetness, deposition rate of SO_2, deposition rate of Chlorides and overall categorization of corrosivity, respectively. Table 5 summarizes these findings along with the average corrosion rate obtained from bimetallic sensors.

Table1 Classification of time of wetness

Time of wetness		Category	Locations in Kuwait
Hours per year (h/a)	%		
$T \leq 10$	$T \leq 0.1$	T_1	
$10 < T \leq 250$	$0.1 < T \leq 3$	T_2	
$250 < T \leq 2500$	$3 < T \leq 30$	T_3	Fahaheel, Sabiyah, Rabiyah, Mansoriya, Shuwaikh(KISR), Jahra
$2500 < T \leq 5500$	$30 < T \leq 60$	T_4	
$5500 < T$	$60 < T$	T_5	Failaka, Al-Zoor

Table 2 Classification of pollution by sulphur-containing substances represented by SO_2

Deposition rate of SO_2 mg/(m^2.d)	Concentration of SO_2 μg/m^3	Category	Locations in Kuwait
$P_d \leq 10$	$P_c \leq 12$	P_0	
$10 < P_d \leq 35$	$12 < P_c \leq 40$	P_1	Al-Rabiyah, Al-Sabiyah, Al-Jahra, Mansoriya, Shuwaikh, Failaka
$35 < P_d \leq 80$	$40 < P_c \leq 90$	P_2	Al-Zoor, Fahaheel
$80 < P_d \leq 200$	$90 < P_c \leq 250$	P_3	

Table 3 Classification of pollution by airborne salinity represented by chloride

Deposition rate of chloride Mg/(m^2.d)	Category	Locations in Kuwait
$S \leq 3$	S_0	
$3 < S \leq 60$	S_1	Al-Rabiyah, Fahaheel, Sabiyah, Al-Jahra, Shuwaikh
$60 < S \leq 300$	S_2	Mansoriya, Failaka, Al-Zoor
$300 < S \leq 1500$	S_3	

Table 4 Categories of corrosivity of the atmosphere

Category	Corrosivity	Locations in Kuwait
C_1	Very low	
C_2	Low	Al-Sabiyah, Al-Jahra, Shuwaikh, Al-Rabiyah,
C_3	Medium	Fahaheel
C_4	High	Mansoriya
C_5	Very high	Failaka, Al-Zoor

Table 5 Deposition rate of chloride and SO_2 along with the time of wetness and average corrosion rate for different sites in Kuwait

Site	Deposition Rate of Chloride (mg/m2.day)	Deposition Rate of SO2 (mg/m^2.day)	Time of Wetness (%)	Corrosivity Category	Remarks (Corrosivity of Site)	Average corrosion rate (μA/cm^2)
Al-Zoor	150.00(S2)	35.02(P2)	62(T5)	C5	Very High	27.42
Failaka	79.80(S2)	25.95(P1)	87(T5)	C5	Very High	25.67
Sabiyah	19.00(S1)	17.30(P1)	20(T3)	C2	Low-Medium	17.54

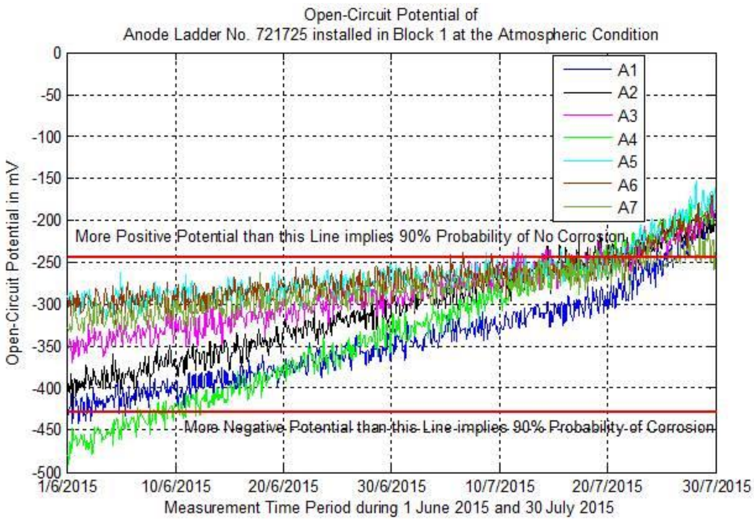
5.1 Anodic ladder corrosion rate for concrete

The data in this part of the study will be limited to corrosion potential (Ecorr) to show data acquisition capability of the sensors**.** Figs. 9, and 10 present the variation of the rebar corrosion potential with time for the selected specimens taken from the concrete blocks exposed to the marine atmospheric environment (Block 1 for OPC and Block 5 for migrating corrosion inhibitor). The mean Ecorr values from duplicate sensors embedded in each block specimens were depicted in the below figures. It has been observed that there is scatter in the potential trends which can be attributed to seasonal variations of temperature or surface electrochemical reaction processes, relative humidity and rainfall. The Ecorr of the blank and the treated specimens showed no significant difference between the rebar corrosion potential trends obtained on each of the two mixes. The difference in the rebar corrosion potential behavior for MCI at 0.4 w/c inhibitor shows more positive corrosion potential with 90% probability of no corrosion. This is clearly indicated in Fig. 10 for the Block 5 specimen from Ecorr sensor retrieved from one of the sensors while the other sensor gave variation in the anode sensors behavior. The trend for block 1 for OPC shows that Ecorr plot is floating between passive and active behavior for both sensors as shown in Fig. 9.

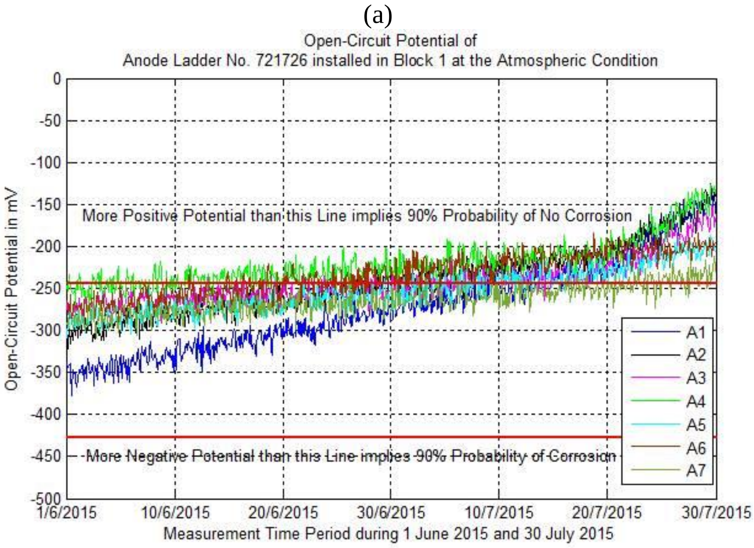
It has been observed in this data that the peaks in the relative humidity curve has affected TOW and caused the high peaks in wetness curve if the temperature is low. It can be roughly said that the high value of humidity (approximately above 50-60%) is responsible for the surface wetness only at lower temperatures (approximately below 35℃). At temperatures approximately above 40°C, the surface doesn’t remain wet even at the higher humidity levels.

As can be seen in the chart for 1 week from Al-Zoor station data, during typical hot days, relative humidity level is generally low (less than 40%) and the surface is not wet. But still we have higher corrosion rate curve which follow temperature curve. Therefore, peaks of temperature curves and corrosion rate curve are observed during afternoon hours and troughs are found at the mid night hours while relative humidity peaks are obtained at mid night time and troughs at afternoon. Even when high humidity and surface wetness is observed during a hot day, corrosion rate curve is found to follow temperature curve rather than the relative humidity curve or the surface wetness curve. This finding is contradicting to most of the observations found in literature

(Mansfeld 1982) where it is stated that most of corrosion activity on the metal surface occur when the surface is wet or when relative humidity is higher than 80 % at temperatures greater than 0°C (t_{80}^{o}). The reason for this contradiction may be due to the fact that most of these atmospheric corrosion studies were conducted in Europe and USA which are rather cold regions. One exception to this, which presents somewhat similar case to our observations in Kuwait, is from (Mansfeld 1982) who has reported the observation of higher corrosion rates during summer and which is proposed to be caused by nitric acid produced by photochemical oxidation of NO_x. This point needs further investigation.

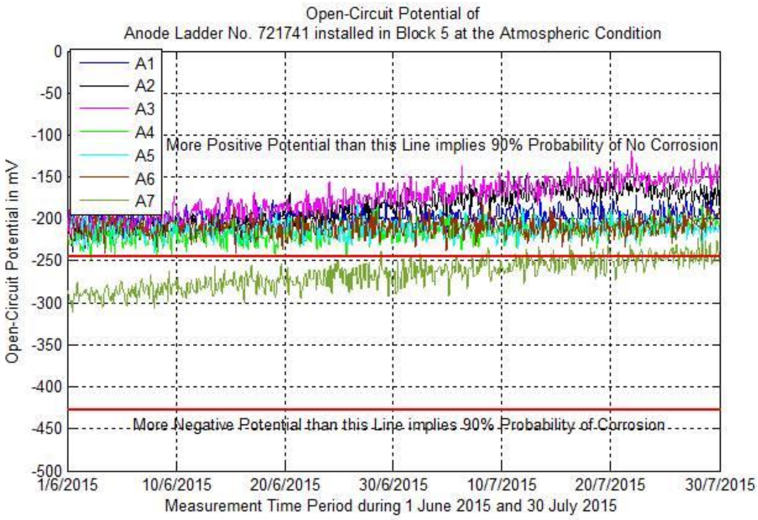


(a)

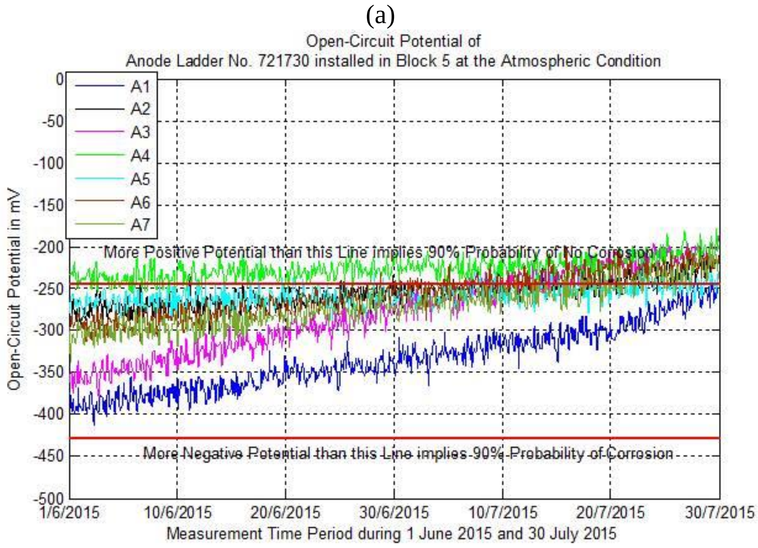


(b)

Fig. 9 Atmospheric Corrosion Potential (Ecorr) versus Time for ordinary Portland cement signals obtained from each sensor (a) and (b)



(a)



(b)

Fig. 10 Atmospheric Corrosion Potential (Ecorr) versus Time for concrete signals obtained from each sensor (a) and (b). (concrete with MCI inhibitor at 0.4 - water to cement ratio)

6. Conclusions

The following conclusions can be drawn from the data obtained by these corrosion monitoring stations.

1) The ambient air temperature and metal surface temperature vary in accordance with each other which are quite obvious. The average difference between the air temperature and metal surface temperature is 3 to 4℃. The interesting thing to note is that during the cold

weather, metal surface temperature is usually less than the air temperature and in hot weather, metal surface experiences higher temperature than the ambient air temperature.

2) Relative humidity exhibits larger variations as compared to temperature variations over same period. The relative humidity trend is usually inversely proportional to the temperature trend. Generally high relative humidity has been observed in the period of cold weather and vice-a-versa. Over a period when temperature goes on increasing, humidity decreases and vice-a-versa.
3) Corrosion rate curve can be said to be directly proportional to the air temperature and surface temperature curves and inversely proportional to the relative humidity curve. Corrosion rates are low in winter (from Sep. to Feb.) and increases with increasing temperatures towards summer.
4) Surface wetness mainly depends on the relative humidity and temperature values.
5) An online monitoring system with sensors for concrete can control the efficiency and detection of defect of cheap repair work. The gathered information will be helpful in establishment of the actual performance and in identification of possible areas for savings.

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