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Corrosion Of Metals - Mapping Of The Environment In Iceland

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Summary: **Iceland is an island in the middle of the Atlantic Ocean, at a latitude of 63 - 66 °N, and is in the main path of low pressure systems in this part of the world. The country is dominated by a mountainous central part (highest peak 2119 m) and glaciers, with lowlands mainly along the south and west coasts. The climate is therefore characterized by a wet and windy south-western part and a colder-dryer northern part. The corrosion environment ranges from a wet, chloride-rich area in south, to a dry and colder area in the north. In fact, the biggest desert in Europe, is in Iceland. In the windy environment, pollution is seldom a problem for people or materials. The corrosive environment is now being mapped by weathering of small test pieces at 15 different locations in Iceland; the test pieces are made of steel, zinc, aluminium, galvanized steel, and surfaces with different types of paint. The first-year results have been analysed, and show a spread in weathering for zinc between 1.4 - 3.9 mm and for steel between 1.5 - 36.1 mm . This paper discusses project design and presents first-year results of the study.**

Keywords. Corrosion, metals, atmospheric corrosivity.

1 INTRODUCTION

1.1 The country and climate

Iceland is an island in the North Atlantic Ocean. The middle is uninhabitable highlands, and the built environment, thus, mainly along the coast. The climate is marine-influenced and geographic location is in the route of frequent low pressure systems that move over the ocean. Accompanying the low pressure systems are prevailing wind directions of southwest to southeast and this, in combination with mountains and a few glaciers, results in wide climate variation within the country.

The climate is windy and moist, and precipitation is very common on the south coast. The highlands, especially north of the glaciers, is very dry, with the area north of the largest glacier, being the biggest desert in Europe. The energy use for heating and electricity is environmentally friendly, as it involves geothermal energy and electricity from hydro power stations.

Heavy industry is on a small scale (three factories so far are located near Reykjavik). The number of cars per capita in Iceland is very high and pollution from them is noticeable in the capital city, Reykjavik, on the few calm days each year. In periods of gentle southeasterly winds, polluted air from Europe comes to Iceland. However, the air is mostly clean, due to the windy climate and rather minimal local pollution. Information on air pollution in Iceland is limited and measurements are mainly done to assess the pollution from traffic in the capital.

1.2 The market

Almost all building materials, except cement and rock materials, have to be imported to Iceland, and this obviously applies especially to all metals. The annual import of metals for the building industry is approximately 310 kg/capita, and other annual imports (transport vehicles, etc) about 185 kg/capita. Of this annual import, approximately 370 kg/capita of metals end up in a corrosive environment of some kind. Metals are recycled to some extent or about 0.2 kg/capita.

In the building industry, metals are mainly used for reinforcing concrete, various types of claddings, for pipes, etc. Almost all roofs are covered with corrugated sheets of either steel or aluminium, and walls of older wooden houses are likewise commonly covered with corrugated steel. In the last years, cladding of concrete walls in new buildings has become more popular. Import of metal cladding materials each year amounts to about 700,000 m^2. Hydro power stations are placed at different locations around the country and it has proven effective to develop a wide-ranging network of high voltage lines to even-out electrical disturbance in the distribution net. The high voltage electrical cables and masts are in environments, which have very different corrosive characteristics. Some are quite near the sea, in constant salt spray, and others are in the highlands.

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Iceland’s market is small and far away from other markets, so transport costs easily run high. In this context, and generally speaking, it is important to obtain the best longevity of materials as possible, e.g. by limiting corrosion of metals. Therefore, corrosion speed and corrosive agents must be evaluated. Mapping to show the background atmospheric corrosion rate is likewise essential to be able to follow changes over time, but also to be able to inform the market about how the conditions relate to other known parts of the world.

Corrosiveness of the environment can be estimated using two different methods: direct measurements, or evaluation of atmospheric agents in accordance with ISO 9223. This paper presents results from measurements of first-year corrosion and compares them to mapping of the climate.

2 CORROSION AND WEATHERING TEST PROGRAM

Samples sized 100 mm x 150 x 2 mm were mounted in fasteners of polymer materials on a backing panel of plywood, such that the distance from the backside of the sample to the plywood sheet is 17 mm with 15 mm between different sample materials. The samples are placed at 15 test locations, each rack with a mounting board of size 530x860 mm at a height of 3 - 4m above ground, oriented to face south at an angle of 45° in accordance with EN ISO 8565. The test pieces are of technically pure, low carbon steel (C=0.05%) , zinc-coated carbon steel, zinc (> 99,9% pure), aluminium (1050 A and AlMg3) and different types of painted steel samples. Plans are to demount samples for evaluation after 1, 3, 5 and 10 years. The measurements consist of recording the corrosion of the metals and evaluating the condition of paints. The project started in 1999, and therefore, results to date are limited to one year’s corrosion.

The test locations are shown on Figure 1, and numbering of them is listed in Table 1.

The results for corrosion rate of steel and zinc after one year are shown in Table 1.

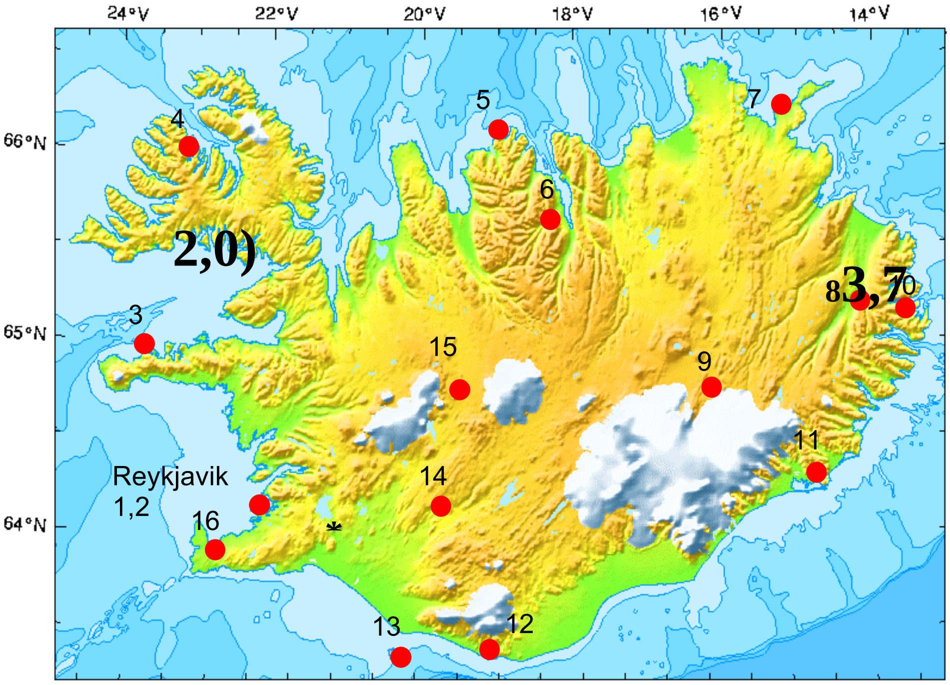

Figure 1. Map of Iceland showing exposure test locations

* Irafoss (see text)

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Table 1. Corrosion rate of carbon steel and zinc after one year's exposure

No.	Location	Corrosion rate (µm /first yr.)		Climate 1)
		Carbon steel	Zinc	measured
1.	Reykjavik 1	20.7	2.3	1
2.	Reykjavik 2	18.6	2.7	2
3.	Olafsvik	21.5	2.7	2
4.	Bolungarvik	15.8	2.0	1
5.	Siglufjordur	13.0	1.4	1
6.	Akureyri	5.5	1.6	1
7.	Thorshofn	17.0	1.6	2
8.	Egilsstadir	3.7	2.5	1
9.	Kverkfjoll	1.5	1.6	3
10.	Neskaupsstadur	12.8	3.9	1
11.	Hornafjordur	24.9	1.6	2
12.	Vik i Myrdal	18.7	2.3	1
13.	Vestmannaeyjar	36.1	2.3	1
14.	Burfell	22.3	2.6	1
15.	Hveravellir	4.2	2.2	1
16.	Svartsengi	35.3	2.7	2
	Average	16.98	2.25	
	Standard deviation	10.256	0.632	
	Variation	0.604	0.281	

1) Climate measured :
1 at weather station
2 at a nearby location (< 20 km)
3 distance to weather station > 100 km

3 THE CLIMATE AND CORROSIVE AGENTS IN ICELAND

The atmospheric corrosion of metals is discussed at length in the literature. The standard ISO 9223 specifies the key factors and Haagenrud (1997) gives a very good overview.

The climate factors used in the project are measured by the Icelandic Metrological Station at, or nearby, most of the test stations. Measurements of temperature, humidity, wind-speed and direction are logged automatically each 1 or 3 hours, and in some instances precipitation is also available. From the start, it was clear that some spot measurements of air pollution would be needed, but it was decided to wait for initial results on corrosion to see where to concentrate the main effort.

For the exposure locations, the climatic factors of importance in this context can be described as follows.

Temperature

The climate is temperate and at the corrosion locations, the yearly average temperature varies locally from 0.6 (location 15) to 6.4 °C (location 12). Temperature is seldom higher than 20 °C, or lower than -20°C.

Moisture

The weather is humid at the coast all around the island, but drier in deep fjords and some places in the highland. At the coast, the average monthly values vary slightly and the yearly average value of relative humidity (% RH) is the interval of 78 - 83 % RH and slightly higher in the highlands.

Time of wetness (TOW)

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TOW according to the definition of ISO 9223 (T>0°C, RH>80%) is in the interval 1449 hrs. (location 10) to 6324 hrs. (location 13).

Rain

Climate in southwest is wet, but noticeably drier in the north. The yearly precipitation at the locations is from 860 mm (location 15) to 3375 mm (locations 12) .

Wind

The climate is windy all year round. The average yearly wind speed at the locations is measured in the range of 3 - 10 m/s, with one location at each extreme, but usually the value for average wind speed is 4.7 – 7.1 m/s The prevailing wind directions are southeasterly to southwesterly .

SO_2

SO_2 is considered one of the major corrosive agents of steel and zinc. Iceland has little SO_2 pollution, as almost all house heating is done either by geothermal energy, or electricity from hydro power stations. The island is very sparsely populated (2.7 km^2/inhabitant), and the average wind speed is high. Thus, problems concerning air pollution are uncommon and only limited measurements are made of these agents. SO_2 is only measured regularly in Reykjavik, and the yearly mean, near a heavily travelled road was measured in 1991 as 3.2 $\mu g/m^3$. In general, the measured value in Reykjavik can probably be considered as a maximum value for Iceland, if one excludes local climate near two aluminium factories. Exposure location 16 is located near a geothermal power station, with a known high concentration of corrosive agents (SO_2) in the steam.

Salinity

It is known that salinity greatly affects the speed of corrosion, and even in highly populated areas this effect can be more than that from SO_2, especially as the content of SO_2 is decreasing in many places, as discussed by Haagenrud (1997) and reported in '*Hot Dip Galvanizing*' (2001). The chloride deposited is only measured regularly at two places in Iceland: in the capital Reykjavik, and at Irafoss which is inland from the south coast.

Salinity Cl^- (mg/m2,d)

	yearly mean	highest monthly mean
Reykjavik (1985)	19.8	53.0
Irafoss (1985)	10.0	15.2

It is known that salinity concentration is highest at the southwest parts of the country and lowest in the northeast parts (south to southwesterly winds prevail in Iceland). Salinity is carried by wind over great distances and in southern storms, saline deposit is observed on structures on the north coast, despite highlands in the middle of the country that, depending on direction of wind from coast to coast, have an average height of 400 - 600 m . Concentration of salinity in air due to wind must depend on many factors, including topography, wind speed and direction, as well as distance from location to sea in line with the wind direction. A study of salinity, which takes into account how salinity transfers from sea to air, and the effect of this on the corrosiveness of the climate, was reported by Cole *et al*. (1999) and wind speed was found to be a very important variable.

4 CORROSIVITY CLASSES ISO 9223: 1992

The standard, ISO 9223, classifies the atmosphere according to direct measurement of corrosion rates on one hand, and on the other, the value of climatic parameters (time of wetness, sulfur dioxide and airborne salinity).

Based on measured corrosivity, the corrosion class for steel in Iceland is in the range 2 - 3 and for zinc, 3 - 4. Classification based on information about the climate gives the corrosivity class for both steel and zinc as ranging from 3 to 4 (or even 5). The two methods thus, do not give exactly the same result, as steel corrodes slightly slower than expected from the climatic classification.

5 DOSE RESPONSE FUNCTIONS FOR CORROSION SPEED IN ICELAND

The models of the effect of different climatic factors on the corrosion of metals, or dose response functions, easily become complicated, and it is probably most economic to simply measure the effect by mapping corrosivity in the area in question. Scientifically, however, the models are of great interest as an aid in understanding effect of climate on materials and as damage functions.

In the literature, Haagenrud (1997) showed an overview of dose response functions. These functions are based on a different number of climatic variables and the composition of them is somewhat different, and so is even the number of variables. In most of the functions, (in fact all, except one) the SO_2 plays a major role, though humidity, time of wetness (TOW), sulphur (S) and clorides (Cl-) are also used as variables. The correlation coefficient (multiple linear correlation) found for the different models varies between 0.67 and 0.94.

When the dose response functions were tested on the data from our project, with different values for the unknown factors (S , SO_2, H+, Cl- etc.) based on an intelligent guess, it was apparent that the functions are poor estimators for corrosion speed in Iceland. The reason for this is probably that the SO_2 content is usually low, and thus, not a main factor in the corrosion. On the other hand, salinity is high at times. The measured corrosion rate of steel is much higher at the seashore, than at locations inland, but the corrosion of zinc is not as dependant on location. For the first years results therefore only the corrosion of steel will be modeled in dose response funtions.

For corrosion of steel, the airborne salinity and moisture, or time of wetness, are probably the main factors. Salinity comes from the sea, and most of the test sites are at the seashore. Lacking measurements of salinity, these can probably be estimated by the wind speed and distance from the shore. In the multiple regression models, the effect of salinity is therefore estimated by two methods;

- the average wind speed in directions from the sea divided by distance from shore
- the average wind speed from sea, multiplied by the fraction of time these wind directions prevail.

Different multiple regression models were tested on the data, but the two shown gave best results:

Model 1 : $\text{Corr } (\mu\text{m/first yr}) = 23.031\ (w_{sa}/L)^{0.2627}\ (TOW)^{0.4704}$

Model 2 : $\text{Corr } (\mu\text{m/first yr}) = 10.055 + 3.942\ (TOW) + 4.539\ (TOW)(w_{sa}/L)$

where	w_{sa}	average wind speed (m/s) from direction of sea
	L	distance from shore (km)
	TOW	time of wetness in accordance with ISO 9223 (T>0°C, RH>80%), as a fraction of total time

	Standard error of estimate	Correlation coefficient R
Model 1	6.02	0.829
Model 2	6.28	0.812

Model 1 has certain similarities with the model shown by Cole *et al.* (1999), model 2, on the other hand, is of the more traditional type used by many, as revised by Haagenrud (1997). It is interesting to note that two so different models show similar quality of fit to the data, more datapoints (higher number of test locations) would be of of help to decide the appropriate damage function.

Taking the frequency of wind directions from sea into account did not improve the models, on the contrary, the fit became considerably worse. The calculated corrosion rate, in accordance with model 1, is compared with the measured rate in Figure 2. As can be seen from the figure and the values for standard error and the regression coefficient, the regression model fits the measured results quite well. Both models improved considerably, if location 14 was excluded, but this is considered to depend on local reasons as explained next page and not that the point is an outlier of some kind.

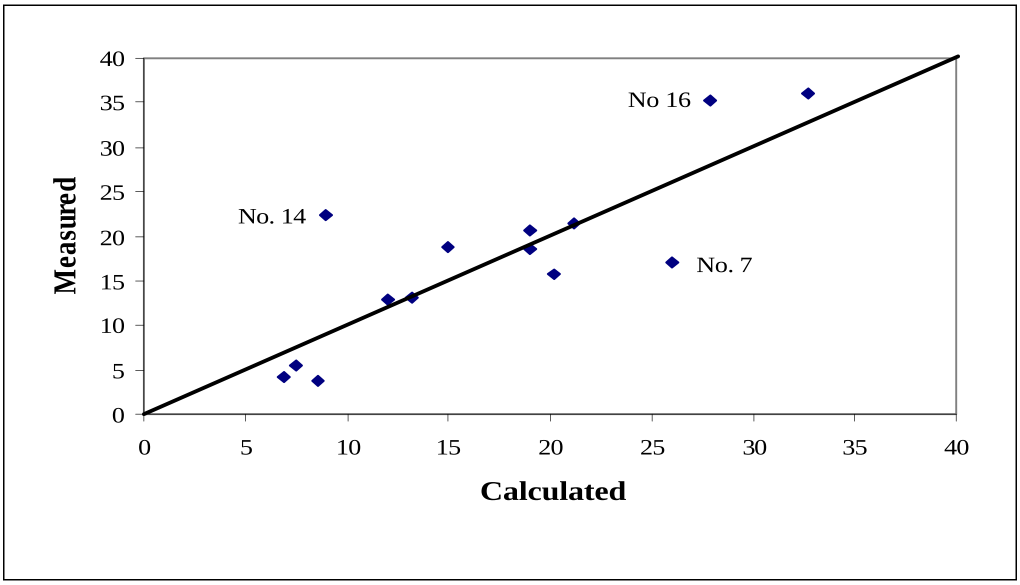

Figure 2. Corrosion of weathering steel (mm/first yr.)-Model 1
comparison between calculated and measured values

6 DISCUSSION

Even these initial, first-year results give information about the atmospheric corrosion in Iceland which makes comparison with other countries much easier. The corrosivity of the atmosphere is in classes 2 - 4 (ISO 9223). Dose response functions in the literature do not seem to be appropriate for Icelandic conditions, which shows the impact of corrosive agents in different countries can be very different. Airborne salinity seems to be a very important factor in corrosion of steel in Iceland. The measured corrosivity shows great variability and it is evident that this can be explained in different ways. The atmospheric conditions vary greatly between the test locations and the measured samples are few. For instance, results are not sufficiently evenly spread to positively determine if the two highest returns are part of the distribution, or are exceptions (outliers). However, these two points are not the results showing the greatest errors in the regression models, and can probably anyway be explained by differences in climate.

The regression models show a poor fit for the thre points no. 7, 14 and 16. For exposure site no. 7 the calculated value is higher than the measured value. The location is unsheltered on the north-east coast and the model probably overestimates the effect of wind from the sea. The exposure site no. 14 is on the other hand about 50 km inland and the calculated corrosion is lower than the actual one. The surface of the area from shore to the site is very even and without any hills, the model underestimates the effect of wind from sea in this topography and at this distance. Number 16 is underestimated in the calculations. The exposure site is located near a geothermal power station, where it is known that the steam is very corrosive. How and whether this affects the testing site also, is not clear at the moment.

The two sides of the sample are not entirely in the same situation, one being more sheltered than the other. The corrosion is measured as weight loss of the sample, and then calculated as weight loss (or reduced thickness) on unit area, based on the size of the sample and taking into account both sides. But, it is not certain the samples corrode evenly on both sides, at all locations (closed tube specimens are a better solution). The effect of rain washing the samples clean, or of salinity deposited only on the outward (upper) side of the sample, must have different effect on the corrosion, depending on frequency of rainy days, etc. On the whole, the timing effect for different series of agents (time series), at different locations, can play a major role in the corrosivity of the atmosphere.

7 CONCLUSIONS

Corrosion of metals, especially steel, in Iceland varies videly for different locations, with the main corrosive factor seemingly being airborne salinity. The corrosion rate has only been measured over one year, but the project will continue for a total of ten years. The content of salinity will be measured at some places, to obtain knowledge about what values to expect, and concentration of SO_2 will be measured at location 16 and one other for comparison. These measurements will probably be made periodically, and over limited time. Further data processing of the effect of climate on corrosivity of metals in Iceland will continue when the results after three year's weathering have been gathered. In the continuation of the project, the question of different corrosion on the two sides of the sample will be examined. The time series for climatic factors of different locations will also be studied.

The first samples for assessment of painted surfaces will be demounted at the 3-year timepoint but some of the samples already show some faults, assumed to be mainly due to sandstorms.

8 ACKNOWLEDGEMENT

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