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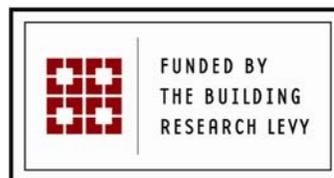## No. 113 (2005)

Stormy Seas, Salt Deposition And Environmental Corrosivity – A Discussion

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Stormy Seas, Salt Deposition and Environmental Corrosivity – A Discussion

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ABSTRACT

At proposed building sites the environmental corrosivity rate of metals does not need to be known to a decimal place, and it may be possible to determine the approximate corrosivity based on observations and existing data bases. Data such as distance to sea, coastline structure, topography, wind speed, wind fetch, seabed profile, surf zone topography and number of stormy days per year should be considered. There is information available that indicates the significance of these factors, but it requires to be investigated under local conditions. The initial surf zone topography in the New Zealand environment has provided results that may account for the high salt content found more than 50 km inland by previous researchers. The results indicate that during low wind speeds of 10 m.s^{-1} the sandy beaches generate more aerosols than the rocky shoreline, and that there is a large proportion of jumbo PM+10 aerosols, which have significantly more volume. The relationship between the size of aerosols and the various surface deposition rate techniques was not determined and further research is required.

REFERENCE

KEYWORDS

Aerosol, buildings, environmental corrosivity, surf zone, transport, meteorology.

ACKNOWLEDGEMENT

INTRODUCTION

Residential buildings near the New Zealand coastline suffer from severe degradation due to the presence of sea salt in the prevailing wind, surface wetness [1] and the humidity, with some mitigation from rain-washing of surfaces. On review of the corrosion literature there has been a common practice for research in coastal regions to determine this correlation between the measured corrosion and exposure variables by regression equations [2-7]. The problem is that empirical fitted experimental data cannot be applied arbitrarily to other geographical locations [8], and given recent weather pattern changes (global warming), the relevance may not be there. Further proof of this failure is found in the review of the single atmospheric corrosivity model of the ISO 9223–9226 [9] series, which has already been shown to have flaws in New Zealand, Australia and the Antarctic [10]. This flaw also appears to prevail into the southern hemisphere where industrial pollution does not have a predominant effect and relatively large coastlines are common.

The environmental corrosivity experienced in New Zealand, a pristine country with low anthropogenic pollution levels, is primarily due to wind-blown chloride deposition and surface wetness / Time of Wetness (ToW) factors [11].

There is a relationship between wind, surface deposition (of salts) and corrosion. Given that there is a likely correlation between chloride deposition, and wind speeds, we can raise the question about the effect of storms. It is probable that storms deliver to the built environment the majority of surface chloride, and subsequent rains result in washing the surfaces while rain sheltered areas continue to corrode at a faster rate. For a sheltered steel surface, it is likely that the instantaneous corrosion rate increases significantly with increasing concentration of chlorides on the surface. It is logical that where moisture or relative humidity is high (80%) [9,12], then corrosion rates would be maintained, or reduced, as corrosion products partially inhibit the corrosion process. With each exposure to aerosol salt deposition and the adsorbed moisture, the corrosion rate is very likely to increase significantly.

Depending upon the environment and other physical factors, it is probable that a sheltered steel surface cycles through a dry (below 80% RH) and wet process regularly. The measured corrosion rates could be considered dynamic. This means the highest corrosion rates occurred when chloride concentrations were high, mobile, chemically available and moisture was present. This is the content of the winds which blow onshore, and which have travelled long distances over the oceans (fetch) prior to storms.

Is it possible that significant corrosion rates of metals in the environment occurs just prior to and following a storm? This paper looks in detail at the issue of wind and the marine aerosols.

AIRBORNE POLLUTION AND CORROSION

Airborne pollution takes many forms as solids, gases, and as aerosols, with the common pollutants being marine salt ($NaCl$ and $MgCl_2$), industrial or anthropogenic pollutants (NH_3, SO_2, NH_4SO_4, NO_x and trace metals), and particulates (inert or carbonaceous) [1]. The pollutants of interest are the marine aerosols which are from wave interaction with the coastline (surf zone) and the aerosols carried from the fetch of the wind over wave bursting oceans [13].
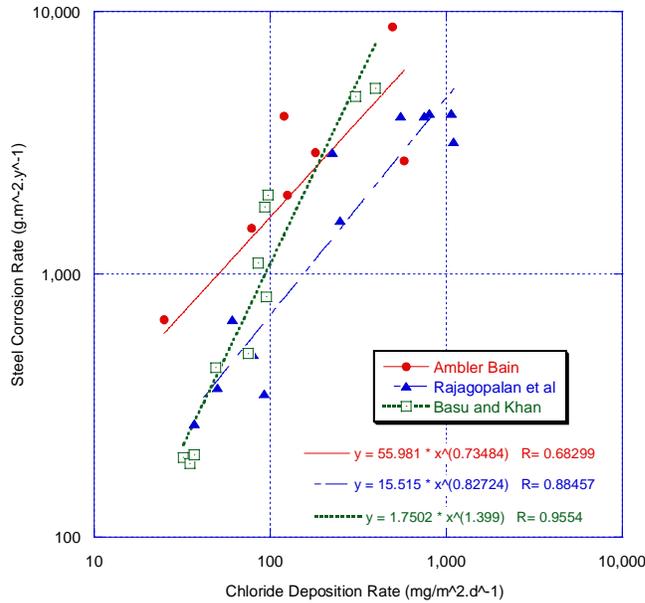
Figure I: Log *vs* log plot [8]
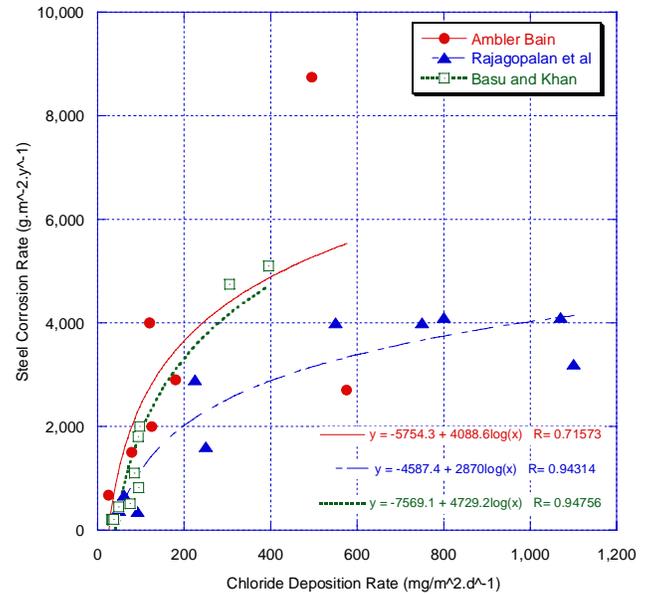**Chloride deposition *vs* steel corrosion rate**

Figure II: Linear *vs* linear plot [8]
Chloride deposition *vs* steel corrosion rate

CHLORIDE AND CORROSION OF STEEL

A significant observation on the corrosion rate of steel in a marine environment concluded that the corrosion rate is very strongly influenced by the quantity of chloride deposited on the surface [14]. There has been an assumption that this is a linear or straight-line relationship, in part due to the way the results have been presented on a log *vs* log plot (Figure I). The same results from Figure I plotted on a linear plot (Figure II) indicate a different condition exists where <u>High</u> surface chloride concentrations greater than 400 to 600 mg m^{-2} d^{-1} are not likely to increase the corrosion rate of steel. A linear corrosion rate does exist where <u>Low</u> chloride concentrations between 0 and 100 mg m^{-2} d^{-1} occur. What is interesting is the <u>Transient</u> region between chloride concentrations 100 to 400 mg m^{-2} d^{-1}, as there is limited predictability of the thresholds of chloride deposition to literally double the corrosion rate. Figure II indicates that good predictability exists in Low deposition rates up to 100 mg Cl$^-$ m^{-2} d^{-1}, and depositions above this are likely to result in significant increases in corrosion rates [15]. Chloride concentrations have been measured using the ISO 9226 Salt Candle and deposition on flat plates have been corrected [8].

AEROSOLS AND MARINE CHLORIDE

All aerosols are grouped into one of four groups based on diameter and termed as Particle Material (PM). These four groups also have generic terms:

A series of simple ratios or equivalence volume for 10µm diameter aerosol $\equiv$ 8 x 5 µm $\equiv$ 64 x 2.5 µm $\equiv$ 1,000 x 1 µm, to provide the same surface chloride on drying. This does not mean we can reject the role of 1µm aerosols, but they only become significant when the numbers are present in large numbers. The interest in this work is primarily on the PM10 and PH2.5 as they represent the largest volume (Table II) of sea water and effectively chloride deposition on to surfaces.

Table 1: **Aerosol definitions and diameter of aerosols [15,16]**

Jumbo (classed as falling or coarse aerosol) Particulates greater than 10 μm in diameter	+10μm diameter
Coarse (classed as falling or coarse aerosol) Particulate Matter 10" – particles less than 10 μm in diameter	$PM_{10.}$ or PM10 (2.5-10μm)
Fine (classed as buoyant or fine aerosol) Particulate Matter 2.5" – particles less than 2.5 μm in diameter	$PM_{2.5.}$ or PM2.5 (1-2.5μm)
Respirable / Thoric (classed as buoyant or fine aerosol) Particulate Matter 1" – particles less than 1 μm in diameter	**Cl** PM_1 or PM1 (0.1-1μm)
TSP Total Suspended Particulates – the total mass of particulate matter measured in units of $μg/m^3$	--

The occurrence of high corrosion rates of steel is most likely to occur with marine aerosol deposition and the most important factor is the size of the aerosol. As noted in Table II, the volume is significantly increased where 10μm or larger aerosols are present. The early corrosion / dose studies of Ambler and Bain considered the fine aerosols (typically 1μm diameter) were inconsequential to the corrosion process, as they contained a low quantity of marine salt, and that the corrosion of metallic surfaces is only caused by salt particles and saline drops of a size more than 10μm diameter, which were termed 'falling type'[16].

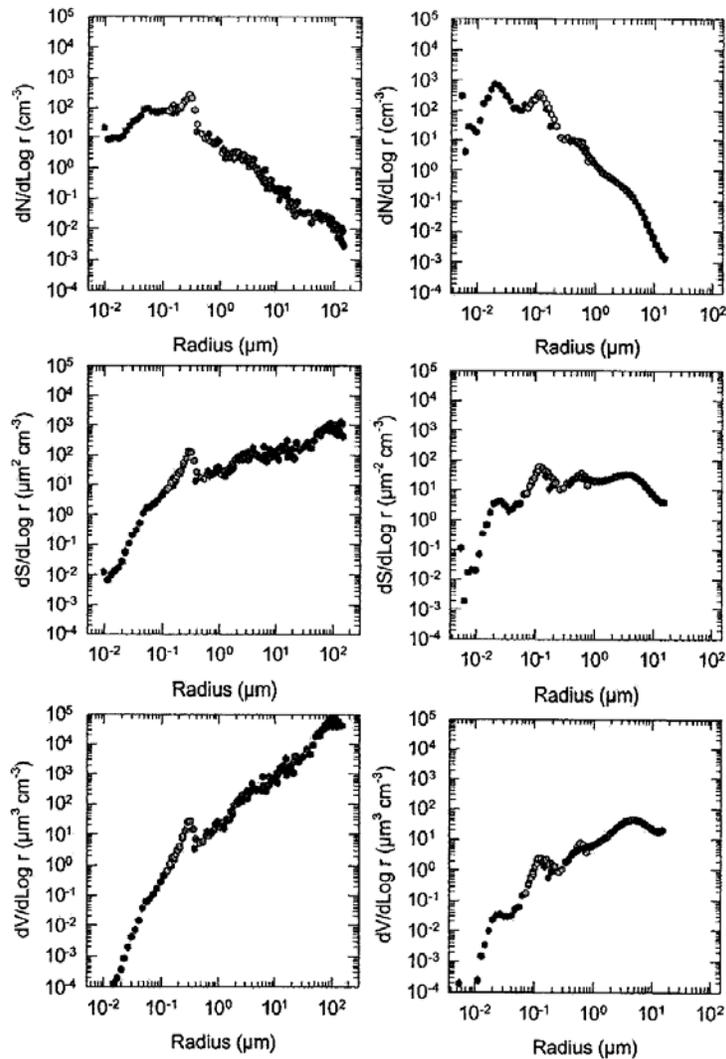**Table 2: Volume of various single aerosol spheres**

Diameter 10μm	V= 524×10^{-9} μL	Diameter 5μm	V= 65.5×10^{-9} μL
Diameter 2.5μm	V= 8.2×10^{-9} μL	Diameter 1μm	V= 0.52×10^{-9} μL

WAVES AND AEROSOLS

There are basically two major regions where aerosols are generated and they are formed out to sea or at the surf zone [17]. The out to sea source is formed by storms, whitecaps and bursting waves, with the wind carrying the aerosols that are formed near the sea surface. At wind speeds that exceed 7-11 m s^{-1}, aerosols are formed by direct tearing from the wave crests (white caps). There is limited data available about the quantity and size distribution of the aerosols formed from this process but the production is determined by the wind speed, which also governs the aerosol dispersion [17,18]. Measurements have indicated that the diameter of aerosols are significantly larger in the surf zone than formed out to sea [30]. It is important to note that the empirical studies and numerical simulations have identified significant discrepancies (orders of magnitude) compared to the model and the effect of the wave can alter the vertical transport of aerosols. It was identified that the spectral shape and amplitude of a wave is varied by wind speeds which have a significant effect on aerosol production [17]. Another approach from an earlier publication (Monahan 1980 in Cole [19]) proposed the use of satellites to measure the instantaneous fraction of the sea covered with white caps (W) for a given period (T) in seconds.

Table 3: Conditions for fully developed seas [21]

Wind velocity km/hr (m.s⁻¹)	Length of fetch (km)	Wind duration (hr)	Average wave height (m)	Wave height max (m)	Wave period (sec)
20 (5.5)	20	2.4	0.3	0.4	4
30	60	6	0.9	1.1	6
40 (11)	140	10	1.6	2.6	8
50	300	16	3	4.5	10
60 (16.5)	500	23	4.5	7	12
75	1200	42	9	14	16
90	2600	69	15	25	20

V=Volume, S=Surface area, N= Number

Figure 3. Plots from O'Dowd et al, showing the number, surface area and volume for maritime aerosol under high humidity at (a) left side wind speed 10 m s⁻¹ and (b) right side wind speed 6 m s⁻¹ [20]

WIND FETCH

'Fetch' is the distance of uninterrupted sea that allows waves to develop. When the wind has been blowing from the same direction, and where there is no rain or cloud to remove the aerosols, large aerosol concentrations or fluxes will develop. The quantity of aerosol is related to wind speed and wave height, as shown in Table III for open seas.

Studies [18,20] have found that onshore sites exposed to long fetch wind will have a high number of fine aerosols and a moderate number of coarse aerosols present in wind speeds ranging from 2-16 m s^{-1}. The 'short fetch' winds, which typically have a lower maximum wind speed (Table III), result in a totally different process occurring and a strong dilution of the aerosol concentration as wind speed increases, while the concentration of fine aerosols is very high, and significantly lower concentration (typically 33% lower) coarse aerosols were measured [18].

This data set [20] in Figure III clearly indicates the effect of wind speed has on aerosol size, number and ultimately volume per unit volume of wind. The area below the two lower plots indicates the total volume that is available for surface deposition. The 10 m.s^{-1} wind has several orders of magnitude aerosol deposit compared to the 6 m.s^{-1} wind. This highlights the importance of large and jumbo aerosols on surface deposition.

SURF ZONE

The marine aerosols that arrive onshore are produced at the surf zone and out to sea and on mixing, and they assume a constant concentration a short distance (metres) onshore. The concentration decreases as a log function from the surf zone because there is only depletion and no additional source to replace the losses, except for any resident aerosols. This has been modelled [22] (Equation 1) and the effect is shown in Figure IV. The model for this is:

$$S = 5252(20/U_h \cdot D)^N \quad (1)$$

Where $N = -0.62e^{0.165Uh}0.037$, S is deposited salt (mg m^{-2}) and Uh is wind velocity on the coast (m s^{-1}) and D is distance from coast (km).
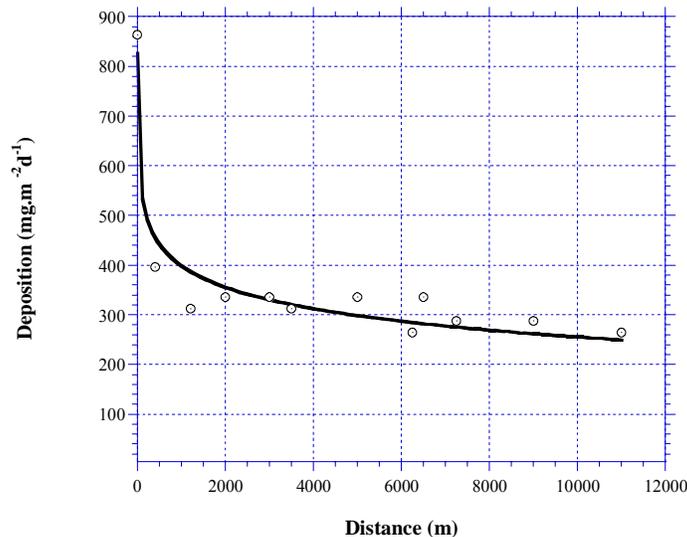

Figure 4: Plot of aerosol deposition on a smooth topography as a function of distance from the sea [22]

It is interesting to note that in Figure IV, the effective deposition rate does not change from 1,000 m to 6,000 m from the shore, and the deposition rates are relatively low at 300 mg m^{-2} d^{-1}. The study in Sweden found that the coastal zones were dominated by coarse particles, and that inland, the small particles dominated [23]. It was noted that in the Arabian Sea, size distribution of aerosols are rarely larger than 100 μm. This was confirmed with the analysis of North East Atlantic measurements [24].

SEABED PROFILE

The seabed profile varies from rapid climbs (cliffs) as commonly found on atolls, and rocky shorelines, to low angle inclines on sandy beaches. Studies have shown that even small increases in the angle of the sandy beach can influence the quantity of marine aerosols generated. The subsequent modelling of this effect of sea bottom profile and aerosol emissions for the same beach identified a logarithmic relationship between total flux and tangent of the slope, and that aerosol concentrations increased in a predictable manner from around 400 m offshore and the concentrations increase to the shore break [25,26]. This is in direct contrast to recent work which claims seabed profiles have no effect [27]. The smooth slope seabeds result in significantly higher aerosol emissions than steep rocky slopes [26]. The seabed profile not only physically changes with seasons, often as a result of storms, but also twice a day there are tides which effectively change the amount of the profile that is exposed to the waves.

WEATHER FRONTS AND SEASONS

The forward surface of weather fronts that occur during changing weather contain at least six times higher concentrations of aerosols compared to the adjacent air mass during the passage of a warm front [23], due to enhanced particle production in the nucleation mode and sunshine. The air masses which have a very distinct and sharp front have significantly greater concentrations. These weather fronts, or just prior to these regions, are areas of very low vertical or mixing turbulence which have difficulty in supporting aerosols, and this results in the significantly higher concentration being present closer to ground levels due to gravitational effects. This low turbulence typically occurs 1.5 – 2 hours before a front, so the aerosol concentrations and size distribution would alter significantly during this period.

The different seasons change the seabed floor profiles, and the amount of onshore wind, which subsequently affects the quantity of aerosols transported inland.

AEROSOL TRANSPORT

The transport by wind of fine aerosols, large aerosols and sea salt particles, results in the increased deposition into the interior of the land mass and accounts for the moderate salt concentrations found in the interior of New Zealand [28]. This is very much influenced by the coastline topography. Typically a rapid decrease in chloride concentrations occurred in the first 2 – 5 km and then a slower decreasing rate further inland [23,29]. Analysis prior to a storm in Säve in Sweden measured a transect from the coast and over forests; measured at 7 km the aerosol concentration of ~12μg.m^{-3} with a percentage reduction of 50% at 20 km, 75% at 80 km, 75-80% at 150 km and generally continued as a straight-line reduction [23].

SUMMARY OF PRIOR INVESTIGATIONS

The creation of aerosols occurs over the seas and at the surf zone and is a function of wind speed and wave action. The further the wind travels, the higher the wind speed, and the larger the waves. This results in a higher concentration of aerosols and more large type aerosols. The open shoreline is either rocky or a beach. The beach shores which are sandy or have a gentle incline give rise to a very high quantity of fine aerosols which can be transported inland, while rocky shorelines where the seabed rises rapidly, typically generates a high proportion of large or jumbo aerosols which are transported only short distances (less than 1 km). Just prior and during storms an exposure to a large increase in aerosol quantity occurs which

is significantly reduced when rain occurs, and clearly seasonal weather patterns have a strong influence on the aerosol emissions [30]. Because of these factors, it is unlikely that a uniform chloride or aerosol emissions would occur at the coast. The first few hundred metres has a significant effect on depleting the large aerosols in the lower speed air stream due to gravity induced fallout. The first 500 m to 1,000 m onshore is effectively an unstable and highly influenced region of chloride deposition, and this is without considering the impact of the coastal terrain or the presence of buildings.

The most severe aerosol depositions in a short period of time occur within 500 m inland of the coastline during high winds and no rain. The peak deposition occurs just prior to a storm front, which has been travelling for an extended period over an ocean, and arrives at a rocky coastline.

At sandy beaches and over a longer period of time, a relatively high volume of fine aerosols are created and transported larger distances inland. The concentration of large aerosols increases with the onset of storm fronts and also increases with larger wave heights.

The New Zealand coastline has a higher wave height (average) exposure than Australia [31] primarily due to a large proportion of coastline being below 40°S latitude and also has a higher exposure to wind.

AEROSOL MEASUREMENT

Aerosol measurement of quantity and size distribution has been conducted using: ISO Salt Candles [9]; Cascade filtration methods over several days; laser particle counters sampling the atmosphere at 600 mL.min^{-1} and conducting distribution analysis every second; and Light Detection And Ranging (LIDAR), which is the optical version of radar where very short pulses (8 nanoseconds) of high intensity laser light is pulsed into the air and the scatter /reflections from particles are measured.

There is no direct comparison available which relates aerosol concentrations accurately measured to other methods such as the ISO 9226 Salt Candle, flat deposition plates (vertical, inclined or horizontal), LIDAR or cascade methods. Some comparisons have been made and discussed in other publications [32].
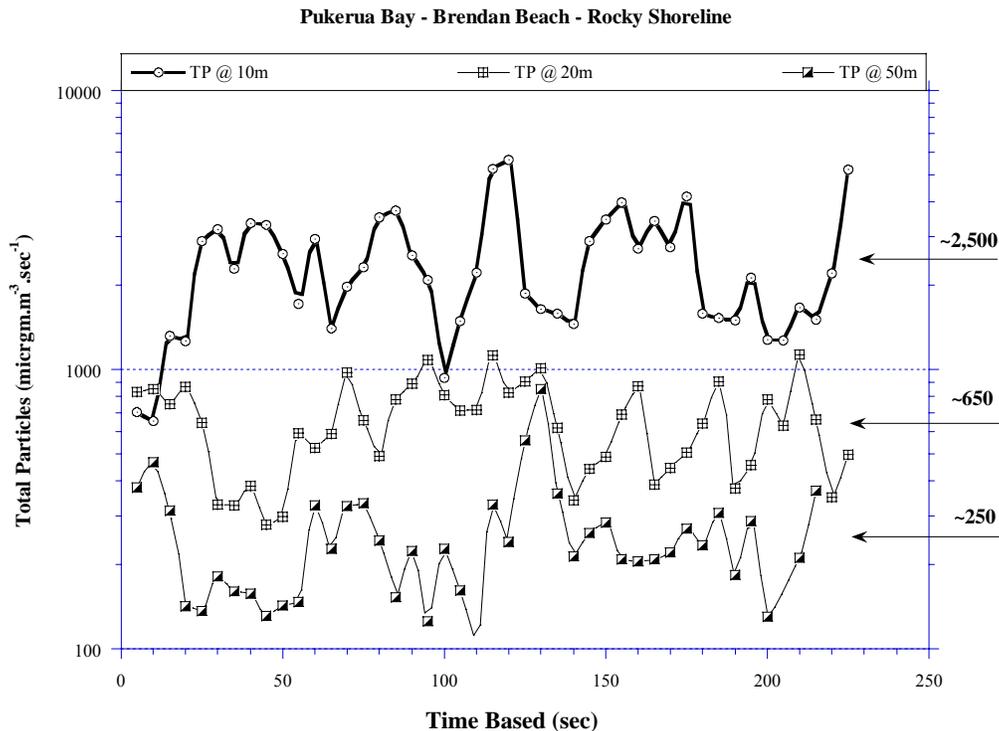

Pukerua Bay - Brendan Beach - Rocky Shoreline

Figure 5: A snap shot (200 sec) of total aerosol dispersion 10 m, 20 m and 50 m from a rocky beach

The test program was conducted at several sites in New Zealand using various methods and these sites conditions include: rocky coastline at Baring Head and Pukerua Bay (Wellington), and smooth coastline at Te Horo Beach – Sand Beach, Oteranga Bay – Pebble Beach (Wellington). The Te Horo test site was also the site where the inland transect from the beach to the hills (11 km) was conducted. Additional investigations into aerosol transport were conducted at the Koeberg nuclear power station near Cape Town, South Africa and the Hunter Valley, NSW, Australia, (Newcastle, Belmont and Cessnock) which will be reported separately. From this research, selected results are presented.
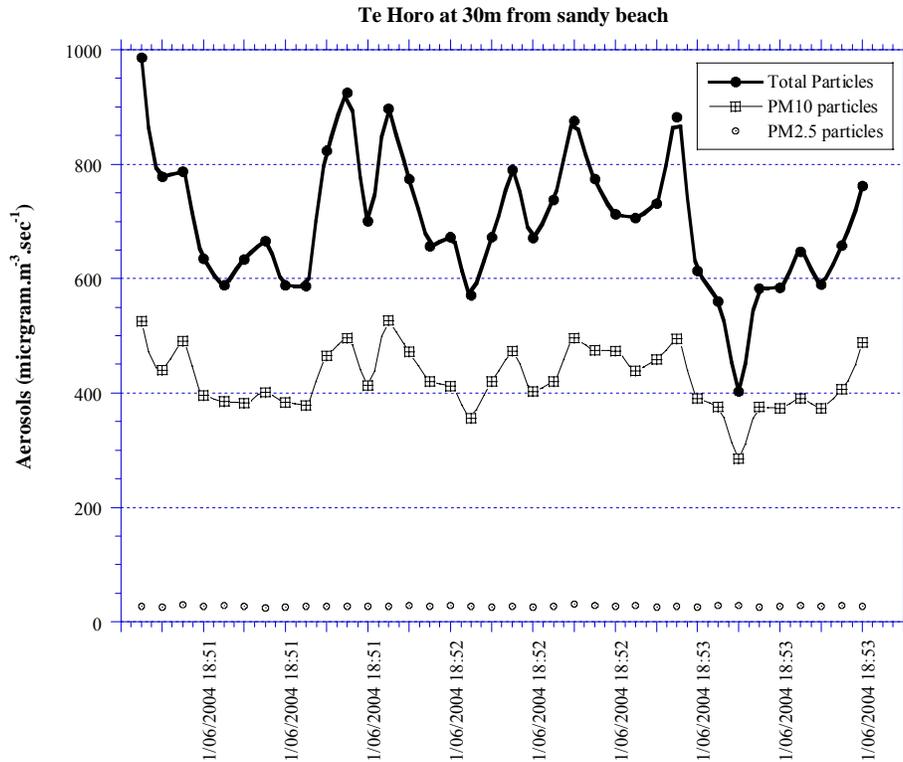

Te Horo at 30m from sandy beach

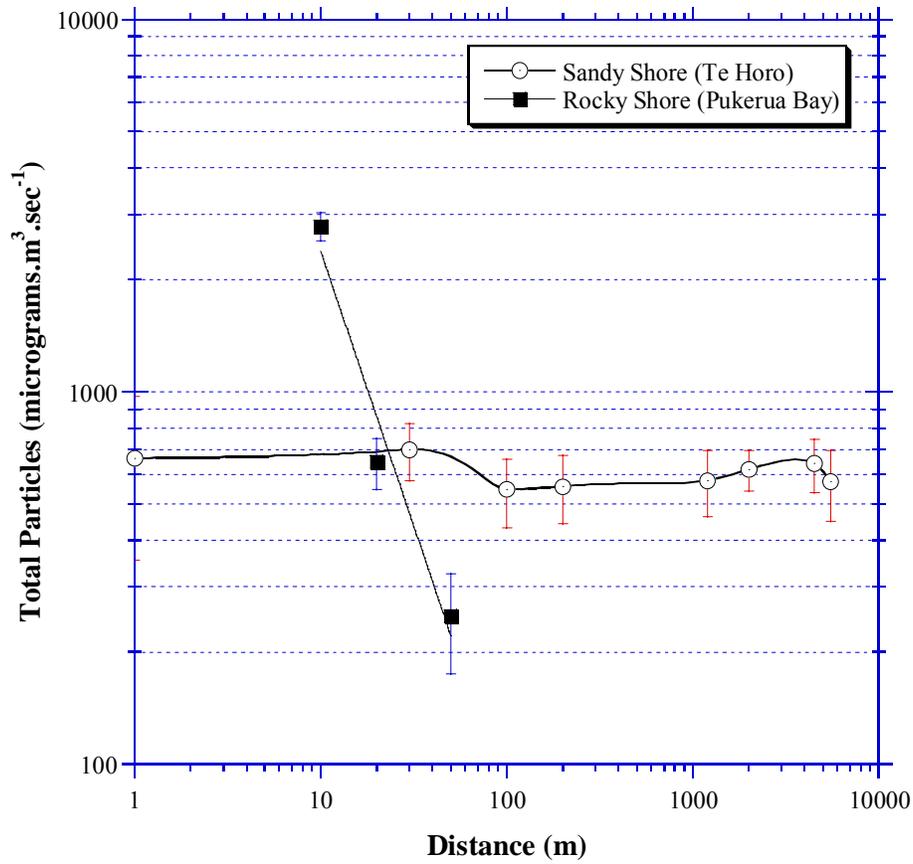**Figure 6: Typical aerosol distribution from Te Horo Sandy beach**

Figure 7: Plot showing different reduction in quantity of aerosols as a function of distance from different types of coastlines

SELECTED RESULTS

Pukerua Bay (Brendan Beach) – Type: rocky shoreline

The analysis conducted at Brendan Beach at Pukerua Bay is shown in Figure V as a function of distance from the rocky shoreline with mean wind speed around 10 m s^{-1}. The results indicate that at 10 m the concentration of aerosols is typically 2,500 µg m^{-3} sec^{-1}, at 20 m it is typically 650 µg m^{-3} sec^{-1}, and at 50 m it is typically 250 µg m^{-3} sec^{-1}. The PM10 content of the Total Particle count is typically more than 65%, with PM2.5 content being insignificant, the remainder being jumbo or greater than 10 µm aerosols.

Te Horo Beach – Type: smooth sandy beach

A transect study from 1 m to 5,500 m was conducted during a four hour period using the laser particle counter which has a limit of 6,000 µg m^{-3} sec^{-1}. The terrain varied from smooth beach to sand dunes (300 m) to the base of large hills.

The conditions were 16°C and mean onshore wind speed at ~8-10 m sec^{-1} (~35 km h^{-1}) and cloud level was approx 2,000 m. No rain had fallen for 24 hours and the wave height was average ~1.5-2 m. The following plot is typical of the measurements that were recorded. Because of the number of plots, the average results, including standard deviation from Pukerua Bay (Rock) and the Te Horo transect study, were plotted together.

DISCUSSION

This discussion paper is the start of a research program that looks at the issue of predicting environmental corrosivity in a broader and practical view that recognises the impact of the environment and the climatic conditions on the built environment.

On reviewing the literature, it was found that there is a physio-chemical limit on the amount of salt a steel surface can react with. It was also noted that increasing salt deposition rates from zero up to 100 mg Cl⁻ m⁻² d⁻¹ correlates very well with an increase in the corrosion rate. This means that in the short term, increasing the salt concentrations will result in a direct increase in the corrosion rate. The presence of water vapour, or the removal of moisture from a surface, will affect the corrosion rates as well. In fact, the corrosion rate on any metal is likely to be dynamic and dependent on the prevailing conditions.

The sum of the multitude of corrosion events a surface experiences provides a corrosion rate over a given period of time. Surfaces which are fully exposed to the environment move through levels of high and low moisture as solar drying or high humidity are present. The corrosion rate during this period also varies accordingly. Based on this principle then, periods of high corrosion would occur in locations where high chloride deposition has occurred and moisture is present. If the effective localised surface concentration of salt exceeds 100 mg Cl⁻ m⁻² d⁻¹, then very high and often unpredictable corrosion rates occur. During periods of low humidity, the corrosion rate is likely to be low.

It was proposed in this paper that the sum of the periods of low corrosion events may be the majority of time and, in effect, the exposure to occasional periods of high and very high corrosion events accounts for the annual environmental corrosion rate experienced at an exposed site. If this is the case, then measuring the periods of high corrosion rate could be a valid indicator of a location's environmental corrosivity rate.

Periods of high corrosion on building occur during periods of high humidity and deposition of surface contaminates. The most common contaminate in the pristine New Zealand environment is marine-sourced chloride, and the rapid transport of the aerosol from the surf zone to inland sites occurs easily during storms. Is it then possible to determine the environmental corrosivity of a site by determining the exposure to storm conditions over a 12 month period?

It would appear that this is very likely, but creating and transporting marine aerosols to a given site is strongly influenced by distance from coast, surface topography, wave height, wind speed, wind fetch, seabed profile, shoreline topography, weather fronts and the seasons. None of these factors are difficult to measure, or obtain measurement for, with reasonable accuracy. If this method is valid and robust, then the simplicity of this approach offers significant advantages compared to extensive instrumental analysis for determining expected corrosion rates of exposed external surfaces. In a pragmatic way, the measurement of environmental corrosivity at most proposed building sites is not required to be accurate to several significant figures, but often the order of magnitude is sufficient.

The physical testing in this work has been conducted to validate some of the assumptions about beach profiles, aerosols at elevation and understanding the transport of aerosols. The results from a study in New Zealand indicate that seabed profile does have a significant effect on the quantity and size of aerosols (Figure VII). This plot also indicates that aerosols from a beach at 10 m.s⁻¹ wind speed are transported over relatively flat land, and a reduction of only 20 to 30% occurred over a distance of 5.5 km, and this is significantly less than what happened in Sweden [23]. The islands of New Zealand have a high exposure to long wind fetch and high wind speeds from the 'Roaring 40s' winds. The role of fetch may go towards explaining the previous transect studies [28] which recorded significant salt concentrations more than 50 km inland.

The ratio of PM2.5, PM10 and jumbo PM+10 size aerosols (Figure VI) is surprising, in that effectively less than 0.05% of the aerosols are PM2.5. Of more significance is that approximately 20 to 50% of all aerosols are jumbo or PM+10 and are readily transported inland. The rocky shoreline delivers significantly more aerosols and significantly more jumbo aerosols than the beach, but after 50 m the quantity has be reduced by 95% at the site that was tested at 10 m.s^{-1} wind speed. Based on these single measurements, the baseline chloride deposition rate and corrosion rate would be higher near the beach than near the rocky shoreline, if the same number of storm days occurs.

Over the past two years, testing programs have been conducted in New Zealand, Canada, South Africa and in the Newcastle region (Cessnock and Newcastle suburbs). The testing program at various sites has included various methods of aerosol deposition measurements and also aerosol quantity and size measurement techniques. Further research is required into the relationship between aerosol transport rates (μg.m^{-3} sec^{-1}) and real surface deposition rates (mg Cl^{-} m^{-2} d^{-1}).

CONCLUSIONS

- The number of storms (specific environmental conditions) that a site experiences, combined with basic geographic and weather knowledge, may provide a simple but effective guide to environmental corrosivity.

- New Zealand is an island that is exposed to high winds and long wind fetch, which may be the reason behind the high transport of marine aerosol inland.

- Rocky coastlines deliver large quantities of jumbo and PM10 aerosols to the environment, but they quickly fall out within 50 m from the surf zone. Sandy beaches generate a large quantity of smaller aerosols which are readily transported inland.

- At distances greater than 20 m from the surf zone at low wind speeds (<10 m.s^{-1}), the baseline chloride deposition rate, and ultimately the corrosion rate, would be higher in the vicinity of an ocean beach than a rocky shoreline if the same number of storm days occurs (based on these single measurements). This boundary distance is dynamic and will change with wind speed, seabed profile and wind fetch.

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