UNIVERSITY OF NAIROBI

ATMOSPHERIC CORROSION ANALYSIS OF METALLIC COATED AND PREPAINTED STEEL ROOFING PRODUCTS IN SELECTED SITES IN KENYA

BY

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DECLARATION

I declare that this thesis is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other peoples or my work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi's requirements.

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ABSTRACT

Atmospheric corrosion of metallic materials is of concern due to structural failures and massive losses in infrastructure associated with corrosion. A study was conducted to assess the accelerated and outdoor corrosion rate of metallic coated and pre-painted roofing sheets. The metallic coated and pre-painted steel roofing sheets were obtained from the Mabati Rolling Mills (Manufacturer 1) and other selected manufacturers. The atmospheric corrosion study sites were based at Mariakani (industrial marine environment) and Mlolongo (industrial urban environment**)**. The accelerated tests which were performed in the laboratory showed that metallic coated sheets of Aluminium-Zinc (AZ) from manufacturer 1 had the lowest corrosion rate (0.345±0.004 mmpy) while Galvanized Iron (GI) sheets from manufacturer 5 had the highest corrosion rate (2.065±0.006 mmpy) at lower salt spray concentrations. The accelerated tests for the sheets pre-painted red and blue from manufacturer 2 gave the highest fade (4.98±0.02 and 4.41 ±0.03 Hunters units) respectively while gloss was-9.8±0.4 and–14.4±0.3 % respectively at lower concentrations. When the concentrations were increased to a mixture of 1.000% NaCl and 4.000% $(NH_4)_2SO_4$, the corrosion rate for AZ coated sheet from manufacturer 1 was still the lowest with a value of 0.408±0.003 mmpy while GI sheets from manufacturer 4 had the highest corrosion rate of 2.318±0.004 mmpy. The red, green and blue sheets from manufacturer 1 showed the lowest fade of 2.42±0.02, 2.14±0.01 and 0.95±0.01 Hunter units respectively while gloss was -4.7±0.1, -4.4±0.2 and -1.9±0.1 % respectively. The highest fade was given by pre-painted sheets from manufacturer 2 for red and blue and manufacturer 3 for green with values of 5.60±0.02, 6.24±0.02 and 5.31±0.01 Hunter units respectively while gloss was -22.0±0.4, -15.0±0.4 and -8.4±0.2 % respectively. The outdoor exposure tests at Mariakani for the metallic coated sheets showed that the AZ samples from manufacturer 1 had the lowest corrosion rate of, 0.019±0.001 mmpy while GI sheets from manufacturer 4 had the highest corrosion rate of 0.128±0.001 mmpy. For the prepainted sheets red, green and blue from manufacturer 1 showed the lowest fade of 0.92±0.02, 0.45±0.01 and 0.89±0.02 Hunter units while gloss was -0.8±0.1,-2.3±0.2 and-2.1±0.2 % respectively. The pre-painted sheets from manufacturer 4 showed highest fade values in Hunter units of: red (2.75±0.02) and blue (1.53±0.02) while fade for green sheets from manufacturer 2 was 11.21±0.03 and gloss values were -15.6±0.1, -5.0 ±0.1 and 1.8±0.1 % respectively. The outdoor exposure tests at Mlolongo showed that AZ sheets from manufacturer 1, had the lowest corrosion rate of, 0.029±0.001 mmpy while GI sheets from manufacturer 4 had the highest corrosion rate of, 0.178±0.001 mmpy. The pre-painted sheets from manufacturer 1 showed that red, green and blue had the lowest fade in Hunter units of 1.03±0.02 for red, 0.79±0.02 for green and 0.51±0.02 for blue while gloss values in % were; -0.8±0.2, -3.5±0.2 and -3.5±0.2 respectively. The red and blue sheets from manufacturer 2 and green from manufacturer 3 showed the highest fade values of 2.94±0.02, 2.44±0.03 and 3.91±0.02. The corresponding gloss values were:-7.3±0.2, -9.2±0.3 and -4.7±0.2 % respectively. The study showed that aluminium-zinc metallic coated and pre-painted roofing sheets from Manufacturer 1 had lower corrosion rates in both accelerated and outdoor tests indicating that the roofing sheets from manufacture 1 were of good quality. The findings of this study are of significance in improving the quality of the roofing sheets.

DEDICATION

I dedicate this work to my dear parents, wife, lovely son and my brothers and sisters for their love and support throughout the two years.

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LIST OF ABBREVIATIONS, SYMBOLS AND ACRONYMS

Al	Aluminum
ASTM	American Society of Testing and Materials
AZ	Aluminium-Zinc alloy
cm	Centimetre
C_r	Corrosion Rate
DFT	Dry film thickness
E	Emphindung (Color sensation)
G	Gloss
GI	Galvanized iron
gsm	Grams per square metre
mg	Milligram
Microns	Micrometre
mm	Millimetre
mpy	Mils per year
mmpy	Millimeters per year
MRM	Mabati Rolling Mills
OCP	Open circuit potential
ppm	Parts per million
QFOG	Quick Fog (Accelerated weathering test)
QUV	Quick Ultra Violet (accelerated weathering test)
μm	Micrometer
UV	Ultraviolet
V	Volt
Zn	Zinc

CHAPTER ONE

INTRODUCTION

1.1 Background of atmospheric corrosion

Steel roofing sheet as an alloy, consisting of iron and carbon, has been widely used as a roofing material for many years in Kenya and other parts of the world (Haddock and Dutton, 2011). This is because steel shows outstanding structural performance and also offers cost benefits compared to other alternative materials such as aluminium and copper (Obia *et al*., 2011). Like any other metallic material, when exposed to the atmosphere, steel experiences tremendous corrosion. Schmitt *et al*., (2009) estimated that in the world every second, five (5) tons of steel exposed to the atmosphere are destroyed as a result of corrosion. Figure 1.1 shows atmospheric corroded steel roofing rails on a roof at Mlolongo, in Kenya.

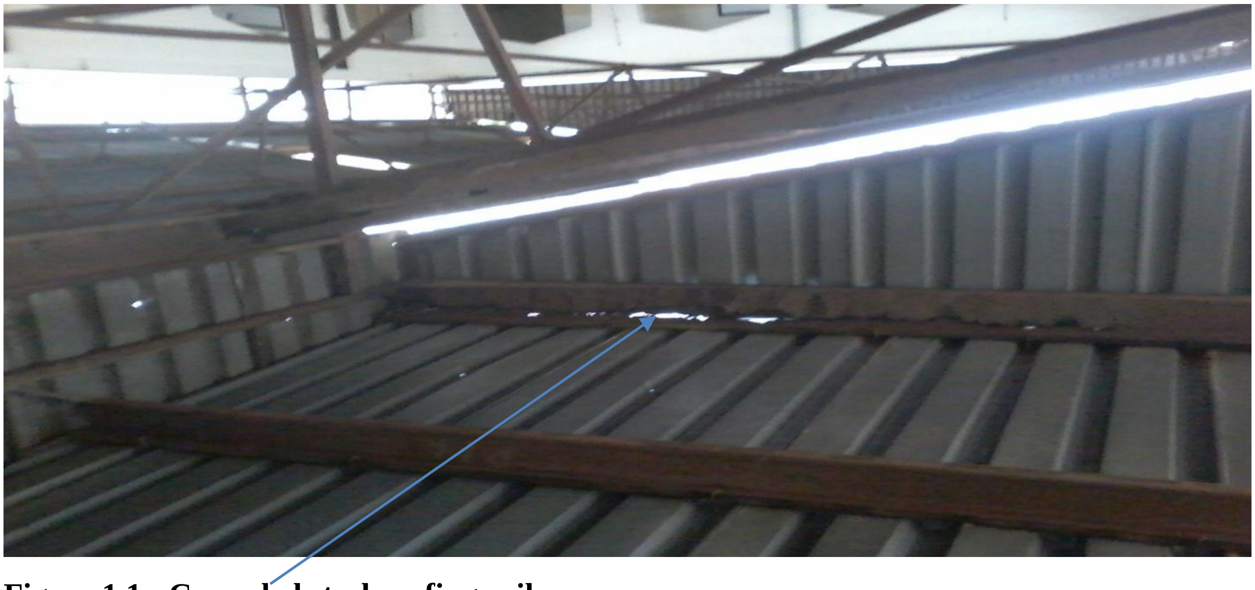


Figure 1.1: Corroded steel roofing rails

Due to concern on atmospheric corrosion, protection methods have been devised which include: Aluminium–Zinc coating (AZ), galvanizing and pre-painting using different coating systems. This study was initiated to determine the corrosion rate of metallic coated and pre-painted roofing sheets used in Kenya. Corrosion rates were determined from accelerated tests and outdoor exposure tests. It is envisaged that the information from this study would complement other studies in developing a corrosion map of Kenya and also to provide information to manufactures and the end users on the suitable steel roofing sheets in various parts of the country. The information could reduce maintenance cost and minimize losses due to corrosion.

1.2 Statement of the problem

Atmospheric corrosion is reported to constitute 50% of total corrosion loss (Roberge, 2010). This indicates that economic loss due to atmospheric corrosion is tremendous which further contributes to the loss of a huge portion of metal products (Almarshard and Syed, 2008). Further, Roberge (2008) reported that atmospheric corrosion accounts for a large number of damages in terms of cost and tonnage as compared to other corrosion types. In view of the economic losses originating from atmospheric corrosion, there is need to evaluate the effect of atmospheric corrosion on metallic coated and pre-painted steel roofing sheets in selected sites in Kenya. This will help improve the quality of roofing sheets.

1.3 Objectives

1.3.1 General objective

The general objective of this study was to assess the atmospheric corrosion of metallic coated and pre-painted steel roofing sheets in selected sites in Kenya.

1.3.2 Specific objectives

The specific objectives of this study were:

1. To determine the effect of atmospheric corrosion on some selected metallic coated roofing sheets under accelerated tests.
2. To determine the effect of atmospheric corrosion on some selected pre-painted roofing sheets under accelerated tests.
3. To evaluate the rate of corrosion of metallic coated roofing sheets at the marine industrial and urban industrial environments based on the recorded climatic data at these sites.
4. To evaluate the rate of corrosion of pre-painted roofing sheets at the marine industrial and urban industrial environments based on the recorded climatic data at these sites.

1.4 Justification and significance of the study

Assessment of atmospheric corrosion of metallic coated and pre-painted roofing sheets is important in the improvement of quality of the roofing products in Kenya. Furthermore there is need to have a national corrosion map for Kenya. The study is of significance because it will provide national reference information on atmospheric corrosion of metal coated and pre-painted steel roofing sheets found in Kenya.

CHAPTER TWO

LITERATURE REVIEW

2.1 Atmospheric corrosion

Atmospheric corrosion refers to electrochemical attack, direct chemical attack and oxidation on any material exposed to or that interacts with the atmosphere (Mohapatra, 2014). No material lasts forever, therefore all metallic structures exposed to atmosphere are susceptible to atmospheric corrosion. The large number of methods applied to reduce atmospheric corrosion, justifies that it is an important type of corrosion (Kaesche, 2003). To reduce atmospheric corrosion, steel sheets are metallic coated and/or laminated with thin organic film. The choice of which coating system that is to be applied depends on the end use, cost and the type of atmosphere in which the roofing sheet will be used (Morcillo *et al.*, 2015). Atmospheric corrosion on metallic coated and pre-painted steel roofing sheets occur due to changing climatic conditions and pollutant concentrations.

Atmospheric factors such as temperature changes, alternate wetting and drying, and the washing action of the elements of weather modify the rates of alloy, paint or film removal from the steel metal substrate (Ovri and Iroh, 2013).The corrosion rate (C_r) in rural atmospheres differ from industrial or marine-industrial atmospheres such that specialized tests and different considerations must be considered in selection of protective coatings and application methods (Dean *et al.,* 2010).

2.2 Reaction of metal surface with the atmosphere

Wang *et al*., (2015) reported that, during the initial level of atmospheric corrosion, moisture readily aggresses the metal surface. Further exposure of the metal to humid air, enhances adsorption of water on the surface leading to formation of single molecule layer or thin electrolyte layer (Nishimura and Rajendran, 2014). At the intermediate stage, components in the atmosphere, pollutant gases and airborne salt particles are deposited on the metal surface and get dissolved at varying degrees within the thin electrolyte layer. Qiu, (2011) found out that non-uniformly scattered droplets of water form native electrochemical corrosion cells that arise from apparently detachable anodes and cathodes. The dominant electrochemical reactions typical to all corrosion processes include; metal oxidation and oxygen reduction generally illustrated by Equations 2.1 and 2.2 respectively (Bala *et al*., 2009).

$M \rightarrow M^{n+} + ne^-$ Anodic reaction (2.1)

$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ Cathodic reaction. (2.2)

The aqueous metal ions combine with counter ions in the electrolyte layer, and consequently form a precipitate through a nucleation process of corrosion products. Nucleation happens at the super-saturation concentration levels of ion pairs in the electrolyte layer. At the final level of atmospheric corrosion, the amount and bulk of precipitated nuclei increase with continued exposure till eventually they entirely cover the metal surface forming a corrosion product layer. This final layer is composed of oxides and hydroxides (Syed, 2010). The determinants for atmospheric corrosion are illustrated in Figure 2.1.

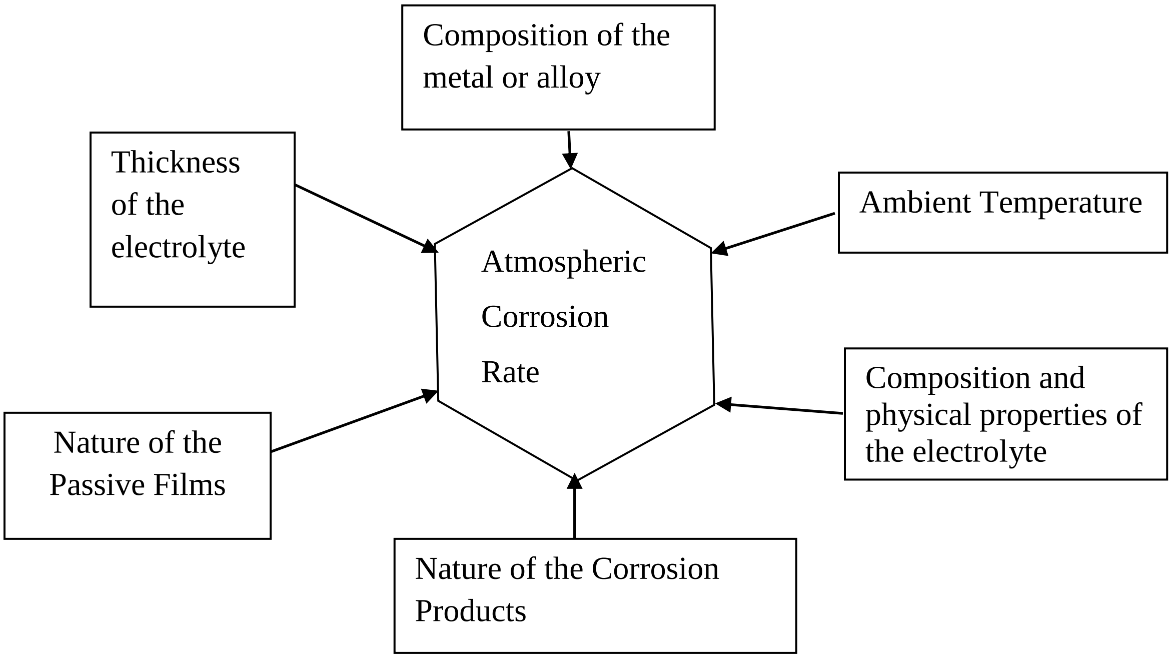


Figure 2.1: Determinants affecting atmospheric corrosion rates from elementary mechanistic scope (Ailor, 1978).

2.3 Classification of corrosive atmospheres

Corrosive atmospheres are broadly classified based on two key variables; weather changes and pollutant concentrations (Chetana and Bansal, 2013).Essentially, corrosion of roofing systems will be accelerated in:

(i) highly humid environments where the % relative humidity (RH) is greater than 70%, little rainfall and high temperature lag (Li *et al.*, 2013) and
(ii) greater wind speed that would convey pollutants (Meira *et al.*, 2006).

According to Corvo *et al.*, (2008) there is a correlation between atmospheric environment in which the roofing products are exposed and the resultant corrosion rate. The corrosive atmospheres differ significantly depending on: the moisture amount, time of wetness, temperature variation, and the amount of pollutants and other contaminants. According to ISO 9223(1999) and SANS 12944-2/ISO 12944-2, (2003) the corrosivity of atmospheric environments is classified into five categories presented in Table 2.1 (Castañeda *et al.*, 2013).

Table 2.1: Classification of atmosphere according to corrosivity of the environments (Castañeda *et al.*, 2013).

Category	**Description of corrosivity**
C1	very low
C2	low
C3	medium
C4	high
C5-I	very high (industrial)
C5-M	very high (marine)

The ISO 9223(1999) has classified the corrosive environment according to the corrosion rates of steel, zinc and aluminium under corrosivity categories as presented in Table 2.2.

Table 2.2: Corrosion rates (C_r) for selected sheets based on a one year exposure at different categories (ISO 9223, 1999).

Corrosivity category	**Corrosion rates (C_r) of metals**			
	units	**Carbon steel**	**zinc**	**aluminium**
C1	$g\ m^{-2}y^{-1}$	$C_r \leq 10$	$C_r \leq 0.7$	Negligible
C2	$g\ m^{-2}y^{-1}$	$10 < C_r \leq 200$	$0.7 < C_r \leq 5$	$C_r \leq 0.6$
C3	$g\ m^{-2}y^{-1}$	$200 < C_r \leq 400$	$5 < C_r \leq 15$	$0.6 < C_r \leq 2$
C4	$g\ m^{-2}y^{-1}$	$400 < C_r \leq 650$	$15 < C_r \leq 30$	$2 < C_r \leq 5$
C5	$g\ m^{-2}y^{-1}$	$650 < C_r \leq 1500$	$30 < C_r \leq 60$	$5 < C_r \leq 10$

The rate of atmospheric corrosion of metals depends upon the corrosive environment. The values of rates have led to classification of the environments as rural, urban, industrial, marine, or blends of these. The extent of damages caused by atmospheric corrosion on steel roofing sheets as observed in Kenya under rural, industrial-urban and industrial- marine environments are shown in Figures 2.2 (a), (b) and (c) respectively. The gradual corrosion of roofing sheets results in the development of white, black and red rust.

Figure 2.2(a) Rural environment

Figure 2.2 (b) Industrial urban environment

Figure 2.2 (c) Industrial-Marine environments

2.4 Corrosive environments

Corrosion of the roofing sheets can occur under the following environments.

2.4.1 Rural environments

Rural environment is the least corrosive and generally comprises of organic and inorganic particulates. However, it has no chemical pollutants. The major corrosion factors include; moisture, air (oxygen), traces of sulphur oxides (SO_X) and carbon dioxide. Ammonia (NH_3), occasionally from the decomposed farm manure and fertilizers may also be present (Syed, 2006). Arid or tropical environments found in Kenya represent special cases that may be categorized as the rural environment. The deposition rates of SO_2 and NaCl in the rural environments are less than 15 mg m^{-2} day^{-1}. Rusting of roofing sheets therefore, becomes noticeable when the relative humidity surpasses a critical value. In unpolluted air the critical value has been established to be about 70 percent (McCafferty, 2010; Aminu *et al*, 2015).

2.4.2 Urban environment

Urban environment is nearly the same as the rural environment in terms of pollution, however there are some industrial processes that occur. The primary corrodents are; sulphur oxide (SO_x) and nitrogen oxide (NO_x) emitted from motor vehicle and domestic fuel combustion processes (Obia, 2009).The emissions combined with dew or fog, results in a very corrosive wet acid film on exposed surfaces. Obia, (2009) found that in the urban environment, the deposition rate of $SO_2$is greater than 15 mg m^{-2} day^{-1}while that of NaCl is less than this value.

2.4.3 Industrial environment

Industrial atmosphere is characterized by intense industrial manufacturing activities that liberate huge volumes of sulphur dioxide, chlorides, phosphates, and nitrates (Kreysa and Schutze, 2004). Sulphur dioxide (SO_2) is a precursor in the formation of acid rain while nitrogen oxides (NO_X), are the principal precursors to smog formation in cities and towns. Sulphur dioxide emitted from combustion of coal or other fossil fuels is taken up by the moisture embedded on dust particles to form sulphurous acid. This acid is further catalytically oxidized on the dust particles resulting in sulphuric acid formation which deposits in microscopic droplets and condenses as acid rain on exposed surfaces. The pollutants in an industrial atmosphere dissolved in dew or fog, results in much more corrosive, wet acid film on galvanized iron surfaces (Obia, 2009). This condition leads to the formation of red brown rust on industrial structures as illustrated in Figure 2.3.

Figure 2.3: Metallic coated factory reservoirs with brown rust developed as patches

The chlorides (Cl^-) in various forms are extremely corrosive than acid sulfates. The activity of acid chlorides with most metals is greater than that of other pollutants such as phosphates and nitrates. In the presence of sulphur oxides and chlorides on the metal surface, the maximum relative humidity, above which metals begin to corrode, has been established to be approximately 60 percent (Yuri, *et al*., 2007).

2.4.4 Marine environment

According to Money (1987), marine environment is characterized by chloride salt particles deposited on surfaces. This salt carried by the ocean breeze, marine fog and wind-blown spray droplets that settle on steel roofing surfaces trigger severe corrosion. The deposition rate of sodium chloride (NaCl) in this environment is found to be greater than 15 mg m^{-2} day $^{-1}$. This greater contamination sets-off severe corrosion at relative humidity higher than 55%. Li and Hihara, (2014) found that in this environment there is extreme and severe corrosion of many structural materials, higher galvanic corrosion, and enhanced deterioration of protective coating systems. Corrosion rates of carbon steel in various atmospheres have been reported as in Table 2.3.

Table 2.3: The corrosion rate of steel in different atmospheres (Mong, 2012).

Type of corrosive atmosphere	Corrosion Rate (µm/year)
Rural	4 - 60
Urban	30 - 70
Industrial	40 - 160
Marine	60 - 170

2.5 Factors that affect the rate of atmospheric corrosion.

The following factors affect the rate of atmospheric corrosion of roofing sheets.

2.5.1 Moisture

Moisture in the form of rain, fog, dew, condensation or relative humidity is important in atmospheric corrosion. In an exclusively dry atmosphere, oxygen and carbon dioxide cause no corrosion (Roberge, 2012). Sulphate and chloride ions accelerate corrosion by forming electrolytes in industrial and marine atmospheres respectively. Rain may be considered beneficial since it washes off atmospheric pollutants deposited on exposed surfaces. This effect is typical in marine atmospheres. However, if rain water is accumulated within pockets or crevices created on a metal surface, it may speed up corrosion by continuously wetting such surface.

2.5.2 Relative humidity and time of wetness.

Humidity as a meteorological parameter refers to a measure of the quantity of water vapor existing in the atmosphere. Relative humidity (RH) is a parameter that is applied in corrosion studies (Vigdorovich and Ulianov, 2000). Owing to climatic differences, RH greatly varies during the day, and from day to day in open atmosphere. A combination of climatic factors in addition to temperature changes for the resultant electrolyte layer on a metal surface also changes relative humidity (Panayotova *et al.*, 2004). Electrolyte layer is important in triggering atmospheric corrosion because it offers a mode for electrochemical and chemical reactions and also becomes a solvent for atmospheric constituents.

The wetting of a metal surface by morning dew or from settled fog or mist, promotes corrosion (Katayama *et al.*, 2001). The dew point, the relative humidity of the atmosphere, and the hygroscopic (moisture absorption) nature of dust deposits are significant in the corrosion process. Most important is the length of time when the metal surface is covered with thin layer of electrolyte referred to as the 'time of wetness' (TOW). TOW regulates the duration of the electrochemical corrosion process and is considered as a major environmental factor affecting the atmospheric corrosion (Badea *et al.*, 2011). Katayama *et al.*, (2001) found that there is a relationship between a rise in corrosion rate of carbon steel, during night hours and rainy day than during the daytime and sunny days. This essentially explains the effect of TOW. TOW greatly influences the useful life of a metal or a protective coating and depends on the macroclimatic zone.

2.5.3 Carbon dioxide

Carbon dioxide is naturally one of the constituents in the atmosphere that is released from anthropogenic activities especially combustion of fossil fuels. On average the amount of carbon dioxide in the atmosphere ranges between 350-400 ppm (Syed, 2006). Carbon dioxide is generally not reactive in ambient air, though it partially dissolves in rain water to form carbonic acid (bicarbonate (HCO_3^-) and carbonate ions (CO_3^{2-}) which have a noticeable effect on the corrosion process of various metals (Suzuki and Robertson, 2011).

2.5.4 Sulphur dioxide

Sulphur dioxide (SO_2) gas, predominantly emitted from combustion of coal, oil and gasoline is a major environmental pollutant in the atmosphere and is highly corrosive to various metals (Obia, 2009). Sulphur dioxide (SO_2) exists in urban and industrial atmospheres and is easily dissolved in water in which it forms various sulphur species including; hydrogen sulphite (HSO_3^-) and sulphate (SO_4^{2-}) both in airborne water droplets and in the electrolyte surface film on the metal surface. This film usually has a low pH (below 4.5) which can lower the oxide's stability and raises the corrosion rate of certain metals.

During an electrochemical attack, sulphur dioxide (SO_2) is usually adsorbed on metal surfaces (Merajul, *et al.*, 2014). The sulphate ions (SO_4^{2-}) are in the surface moisture layer, through the oxidation of sulphur dioxide as in Equation 2.3.

$$SO_2 + O_2 + 2e^- \quad \rightarrow \quad SO_4^{2-} \qquad (2.3)$$

The required electrons in Equation 2.3 come from the anodic (metal) dissolution reaction and, for iron; they originate from the oxidation of iron to ferrous ions. In case of iron, the formation of sulphate ions is the principal corrosion accelerating process. The existence of sulphate ions results in the formation of iron sulphate ($FeSO_4$). Iron sulphate is a corrosion product in industrial atmospheres and is mainly found in form of layers at the metal surface. The iron sulphate formed hydrolyzes according to Equation 2.4.

$$FeSO_4 + 2H_2O \rightarrow FeOOH + SO_4^{2-} + 3H^+ + e- \qquad (2.4)$$

The sulphate ions that trigger corrosion are regenerated as in Equation 2.4. This leads to an auto-catalyzed reaction on iron.

2.5.5 Chlorides

Aerosols rich in chloride ions (from hygroscopic salts; NaCl and $MgCl_2$) are the dominant pollutants in the marine environments that speeds up the corrosion of metals/alloys by several degrees (Suzuki and Robertson, 2011).The aerosols appear as heterogeneous mixture of small liquid or solid particles originating from salt spray and fog from the adjacent seashore (Cole *et al.*, 2003). Deposition of aerosols results in the formation of corrosive aqueous surface layer of increased conductivity in which the chloride ions attack the surface to initiate corrosion, *e.g.* pitting. Chlorides may damage natural outer metal/alloy oxides and hydroxides of various passive properties of certain metals. Apart from increased surface electrolyte composition by hygroscopic salts, there also occurs direct attack of chloride ions in the electrochemical corrosion reactions (Badea *et al*., 2011).

2.5.6 Solid matter

According to Chen *et al*., (2016) the deposition of solid particles from the atmosphere to the steel surface could have a critical effect on atmospheric corrosion rates, particularly in the primary stages. Such deposition can speed up atmospheric attack by: lowering the critical humidity levels of hygroscopic action, supplying anions that improve metal dissolution and micro-galvanic effects caused due to deposition of more noble metals with respect to corroding metal for instance carbonaceous deposits.

2.5.7 Air temperature

Temperature is among the major important factors that influence atmospheric corrosion (Veleva and Alpuche-Aviles, 2002). Temperature impacts become evident at sudden temperature variations. A rise in temperature tends to accelerate corrosive attack by increasing the rate of electrochemical reactions and diffusion processes. For a constant humidity, a rise in temperature causes a higher corrosion rate. In most cases increase in temperature, causes a fall in relative humidity and an increased evaporation rate of surface electrolyte. However, in situations with shortened time of wetness, decrease in corrosion rates have been reported.

2.5.8 Ultraviolet radiation

Harmful ultraviolet (UV) radiation from the sun at the wavelength below 295 nm cause tremendous damage to roofing sheets especially pre-painted ones (McGreer, 2001; Hongxiang, 2012). The paints applied as a coat are complex mixtures consisting of hydrocarbon molecules. These hydrocarbon molecules absorb UV radiation from sunlight and finally break down, resulting in cracking, buckling, and overall deterioration of the physical properties of the paints (color coat). The resistance of the metals to ultraviolet (UV) rays is beneficial to the roofing sheets against atmospheric corrosion.

2.6 Atmospheric corrosion kinetics and corrosion electrochemistry

2.6.1 Corrosion kinetics

The kinetics of anodic and cathodic reactions relies upon the electrolyte film thickness and not by the time of wetness (Stratmann and Streckel, 1990). The diffusion of oxygen through the metal surface is influenced by fine surface layer of electrolyte, compared to the bulk electrolyte. This effect is increased by reducing the electrolyte layer thickness. The enhanced oxygen movement ends up in two dominant effects: stimulation of the cathodic reduction of oxygen and initiation of the anodic passivation. In the marine atmosphere, presence of chloride and hygroscopic salts inhibits passivation and anodic concentration polarization. Marine salts that dissolve in electrolyte film formed on the metal surface ensure that there is sufficiently high conductivity. This condition reduces the possibility of ohmic control (Panayatova *et al*., 2004).

2.6.2 Corrosion electrochemistry

The thermodynamically steady states of nearly all metallic elements are the cations, instead of the metal itself under normal environmental conditions. This explains why a significant amount of energy must be used during the abstraction of a metal from its ore. However, once the metal is abstracted and put into use, it immediately turns back to its steady state which is a more stable form. To become more stable, the metal must release electrons. This process demands an electron acceptor or oxidizing agent. Oxygen is found to be the predominant oxidizing agent in such cases. In most corrosion processes, oxidation and reduction processes take place at isolated locations on the metal. This is due to the inherent conductive property of metals, and therefore the electrons drift through the metal from the anodic to the cathodic sites. Such a system is similar to an electrochemical cell within which the anodic process occurs as follows :(Equations 2.5- 2.6).

$$\mathrm{Fe} \rightarrow Fe^{2+} + 2e^{-} \tag{2.5}$$

and the cathodic process can be;

$$O_2 + 2H_2\mathrm{O} + 4e^{-} \rightarrow 4OH^{-} \tag{2.6}$$

Atmospheric corrosion of steel is a crucial structural problem which results in the red rust formation on the steel surface. In Equation 2.5, iron oxidizes and forms divalent cation Fe^{2+} thereby releasing two electrons while in cathodic reaction oxygen is reduced as in Equation 2.6. The divalent cation Fe^{2+} which is formed in Equation 2.5 will combine with the hydroxide ions to form the complex iron hydroxide as in Equation 2.7.

$$\mathrm{Fe}^{2+} + 2\mathrm{OH}^{-} \rightarrow \mathrm{Fe\,(OH)_2} \tag{2.7}$$

In the atmosphere excess oxygen is present and readily dissolves in water. Consequently, a further reaction occurs resulting in the formation of red rust as outlined in Equation 2.8.

$$4\mathrm{Fe\,(OH)_2} + \mathrm{O_2} + 2\mathrm{H_2O} \rightarrow 2\mathrm{Fe_2O_3}\cdot\mathrm{H_2O} + 4\mathrm{H_2O} \tag{2.8}$$

2.7 Metallic coating of steel

Coating is referred to as a coverage that is applied over the surface of any metal substrate (Maria *et al*., 2013). The essence of applying coatings is to enhance surface characteristics of a whole material ordinarily referred to as a substrate. Coating improves the surface properties that include; appearances, adhesion, wettability, corrosion resistance, wear resistance, scratch resistance, etc. Metallic coating of steel is achieved by four industrial processes namely ;(i) Hot dip galvanizing (HDG) (ii) Cold rolling (iii) Electro-galvanizing and (iv)Passivation using chromium.

2.7.1 Hot-dip galvanizing

In hot dip galvanizing (HDG) process fabricated steel is bathed into a vat containing molten zinc at a temperature range of 445-450°C. The HDG process is simple and gives a unique benefit over other corrosion protection techniques (Robinson, 2013). While steel is in the vat, iron within steel metallurgically bond with molten zinc to produce a tightly-bonded alloy coating that shows superior corrosion protection to steel.

2.7.2 Cold rolling

Cold rolling process involves rolling pickled coils to a desired shape and special thicknesses between rollers. During the cold rolling process cold rolled steel sheets and coils develop enlarged crystal grains in the rolling direction that results in the hardened and brittle texture (Mimura, 2012).Cold rolling has benefits over other metal coating processes, since it has more pristine surface finish, greater strength , lighter and enhanced formability.

2.7.3 Electro-galvanizing (Electroplating)

Electrogalvanizing is an electrolytic process in which carbon steel is made to form a thin deposit of zinc coat by means of passing an electric current between an anode (zinc) and the carbon steel (cathode) (Rendley *et al.*, 2011). Electrogalvanizing similarly acts as a reversed galvanic cell.

2.8 Electrochemical protection of steel by aluminium

Aluminium and its alloys readily form chemically protective oxide (passive) layer that inhibit corrosion attack. Nevertheless, corrosion reaction may take place when conditions within which the passive layer exists are unsteady (Abdulkarim, *et al.*, 2009). In aqueous media corrosion of aluminium takes place according to equations 2.9, 2.10 and 2.11 (Asoh and Nishio, 2010).

$$Al \rightarrow Al^{3+} + 3e^{-} \qquad \text{Anodic reaction} \qquad (2.9)$$

To balance the system, competing cathodic reactions occur simultaneously as in Equations 2.10 and 2.11.

$3H^+ + 3e^- \rightarrow \frac{3}{2}H_2$ Cathodic reaction (2.10)

$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ Cathodic reaction (2.11)

The combination of anodic and cathodic reactions results in the general reaction which is represented by equations 2.12 and 2.13 for corrosion attack on aluminium in aqueous neutral and acidic media respectively.

$$Al + 3H^+ \rightarrow Al^{3+} + \frac{3}{2}H_2 \qquad (2.12)$$

$$Al + 3H_2O \rightarrow Al\,(OH)_3 + \frac{3}{2}H_2 \qquad (2.13)$$

Corrosion of aluminium therefore may cause formation of aluminium hydroxide, $Al\,(OH)_3$, according to Equation 2.13, which does not dissolve in water and hence precipitate out as a white jell covering the metal surface. Because of ease in passivation, aluminium metal spontaneously develops an oxide layer that behaves as a protective barrier layer. This layer reduces the substrate corrosion. Equation 2.14 shows the reaction between aluminium and oxygen which occurs to form aluminium oxide.

$$2Al + \frac{3}{2}O_2 \rightarrow Al_2O_3 \qquad (2.14)$$

2.9 Protection of steel by zinc

Zinc offers a hard; metallurgically bonded covering that stretches on the steel surface entirely and blocks steel substrate from the corrosive attack from the environment. Zinc additionally offers sacrificial protection to steel (Bajat *et al*., 2012) especially due to a scratch, breakage or a small discontinuity in the coating (Kartsonakis *et al*., 2012). Furthermore, the natural corrosion of zinc coating results in the development of a protective zinc patina (layer) that protects the surface (subsection 2.9.3). These three protective mechanisms of zinc are discussed in sub-sections 2.9.1 to 2.9.3.

2.9.1 Barrier protection of zinc

Barrier protection was the first and still the most commonly applied technique for protection of corrosion. It operates by sealing off steel from the surrounding environment. The hot dip galvanized (HDG) coating offers barrier protection to steel, similar to paints. Provided that the barrier is in place, steel is protected and as a result corrosion will not progress.

To resist corrosion, zinc (a barrier) must remain intact. Therefore it must show adhesion property to steel (base metal) and be resistant to abrasion. The stronger metallic bond that zinc forms on steel and its impervious character make galvanizing a very good barrier coating. Depending on the environment it has been shown that, zinc corrodes approximately 2.5 to10 % the rate of steel (Rodríguez *et al.*, 2003). This explains the reason why corrosion rate of a fine zinc coating is almost equal to a much thicker piece of steel (Jörg, 2010).

2.9.2 Cathodic protection of zinc

Cathodic protection is the most effective and excellent method of corrosion resistance. It entails electrically connecting a high corrosion (more reactive) element and steel. In this system, steel (base metal) turns to be the cathodic element of the circuit. In galvanized roofing materials, hot dip galvanizing protect steel cathodically. This method works with the same mechanism as that of the sacrificial anode protection. In reality an anodic metal (zinc) with respect to the base metal (steel) is introduced in the circuit to corrode, preference to the base metal.

2.9.3 Zinc patina in corrosion protection

When natural zinc gets into contact with air (oxygen and carbon dioxide) and water over time it forms own protective layer, called a patina(Langill, 2006). The zinc patina protects zinc coating and protects steel from corrosion. Similar to other metals, zinc starts to corrode on exposure to the atmosphere. Therefore, naturally freshly galvanized steel continuously undergoes a corrosion process on exposure to the wet and dry cycles in the environment. When the galvanized coatings interact with free flowing air, zinc patina commences to develop with the formation of thin zinc oxide layer (Goidanich *et al*, 2011). However, when the piece is left exposed to moisture (rainfall, dew and humidity), zinc oxide particles are attacked by moisture resulting in the formation of a porous, jelly-like zinc hydroxide. Carbon dioxide combines with the zinc hydroxide during the dry cycles, eventually forming a thin compact and firmly sticky layer of zinc carbonate. The rate of the patina formation varies and relies on the environmental conditions, but it takes approximately 6-12 months to perfectly develop (Chen *et al*, 2008).

The completely developed patina is passive and steady. This passive film sticks to the zinc surface and is not soluble in water (Goidanich *et al*, 2011). Therefore it is not washed off by rain. Zinc patina therefore slowly corrodes and protects the galvanized coating beneath. Owing to this property the corrosion rate is reduced to approximately 3.33% the rate of steel in the same environment (Knotkova and Kreislova, 2007). The zinc patina formation is a critical process in terms of durability of hot- dip galvanized steels. Since the formation of patina depends on prevailing wet and dry cycles of the surrounding environment, the results of salt spray tests, which rely on fixed wet exposure, may inaccurately predict the life of galvanized coatings in the real situations (Zielnik and Scott, 2015).

2.10 Aluminium-zinc (AZ) alloy coatings

The extensive use of aluminium-zinc (AZ) alloy coatings in industrial environments instead of galvanized steels is because zinc exhibits a high dissolution rate in these environments (Mokaddem *et al*, 2010). In some cases, hot dip aluminized coating has also found use commercially. Aluminium exhibits major advantage over galvanized coating by offering excellent barrier protection to the substrate (steel). However, aluminium is found to unsatisfactorily offer cathodic protection (CP) to the steel, since the oxide layer developed on the steel surface is highly insulating (Ahmed, 2011).

2.11 Significance of use of hot-dip aluminium-zinc (AZ) coated steel.

Hot-dip aluminium-zinc (AZ) coated steel is gaining significant use in most atmospheric environments. This is because it is inexpensive and considered efficient coating system. However in cases where the material is left bare to the atmosphere and other aggressive environments, it is important to densely coat (using aluminium-zinc alloy) the steel to prevent corrosion.

The common aluminium-zinc (AZ) coatings consist mostly of aluminium, zinc, silicon, iron and chromium alloys that are crystalline in appearance. The thinnest outer coating is a layer of chromium that passivates the immediate layer beneath comprising of aluminium (53-57%), silicon (1.2-1.5%), zinc (43-45%) and iron (< 0.5 %) (Van Rooyen *et al*, 2011). The AZ alloy layers contribute to the thickness of the final metallic coated product. The thickness of the alloy layer is affected by numerous interconnected factors such as steel (substrate) thickness, steel chemistry, temperature of the galvanizing bath, duration of immersion of steel in the fused aluminium-zinc bath and alloy additions in the bath.

2.12 Pre-painting (color coating) of steels.

Pre-painting or color coating refers to the laying of a decorative (Gary, 2014) and/or protective organic cover to steel substrate existing as a coil before shipment (Kohei, *et al.*, 2003). Color or paint coatings are special products, which are applied to give steel a durable protection under wide range of corrosive environments, spanning from atmospheric exposure to complete immersion in extremely corrosive solutions (Kartsonakis *et al*., 2012). Color coating offer little strength to the substrate steel, however it protects steel in order to maintain strength, integrity and decorative.

2.13 Paint and its composition

Paint refers to an inorganic or organic coating that majorly protects equipment and constructions from atmospheric attack and at the same time offer an aesthetic surface. Paint fundamentally consists of liquid which changes to a fine coherent and adherent layer when spread on a surface. According to Lambourne, (1999) there are four principal components of paint which are; the binder, pigment, solvent and additive. Binder is the chief component of a paint system and as such forms a basis of classifying the paint system.

2.13.1 Binders

Binder is an important component that provides uniformity and consistency to the paint system. It joins up the pigments especially when a dry film is finally formed, and provides adhesion to the substrate material. The type of binder always relates to the durability of the final product. The ability of a binder to form a thick and sticky film directly correlates to its molecular weight and complexity. Binders of high molecular weight normally tend to form fine film by evaporation, while low molecular weight binders form films by a reaction in situ. A way of classifying a binder is through its chemical reactions (Streeitberer and Dossel, 2008). Table 2.4 lists some of the important binders according to their functional groups and chemical reactions.

Table 2.4: Classification of binders according to their functional groups and chemical reactions (Streeitberer and Dossel, 2008).

Classification	Examples	Chemical reactions
Oxygen reactive binders	Alkyds	The binder molecules react with oxygen and a cross-linking of the resin molecules takes place
	Epoxy esters	
	Urethane alkyds	
Lacquers	Polyvinyl chloride polymers	Drying mechanism by solvent evaporation. The long chain resins entangle with each other but no cross-linking exist
	Chlorinated rubbers	
	acrylics	
Heat conversion binders	Hot melts	Curing takes place upon heating as the components melt. Both cross-linked coatings are possible
	Organisols and plastisols	
	Powder coatings	
Co-reactive binders	Epoxies	The film is formed by a polymerization between the resin and curing agent. A three-dimensional network is formed.
	Polyurethanes	
Inorganic binders	Post-cured silicates	The binders are usually used in zinc-dust pigmented primers where a reaction between zinc and binder takes place forming a very hard film.
	Self-curing water silicates	
	Self-curing solvent based silicates	
Coalescent binders	Latex	Film formation by coalescence of binder particles dispersed in water.

2.13.2 Pigments

Pigments include various dry powder products which are mixable with the paint so as to offer functionality and appearance to the paint system. The pigments are insoluble in the paint system and consist of naturally occurring and synthetic organic materials. Pigments give color and opacity however they are also useful additives for corrosion resistance, film strength, coverage and adhesion (Gilleo, 2006). For anti-corrosive paint systems, pigments primarily offer protection by one or a series of the following mechanisms; 1) Inhibition of corrosion; 2)

Passivation of substrate metal; 3) Barrier against water permeability and 4) Cathodic protection. The common pigments, their classification and functionality are described in Table 2.5.

Table 2.5: Classification of pigments according to their functionality (Gilleo, 2006).

Classification	Examples	Functionality
Color pigments	Titanium dioxide, iron oxides, organic azo pigments	Provide color to the paint. Titanium dioxide is the most popular white pigment because of its high refractive index
Inhibitive pigments	Zinc phosphate, aluminium phosphate, zinc molybdate	Provide active corrosion inhibition to the metal substrate. The pigments are slightly water soluble. Dissolved ion species thus react with the metal to form passivating reaction products.
Barrier pigments	Aluminium flake, micaceous iron oxide.	Increase the permeation path length to the substrate for incoming moisture.
Sacrificial pigments	High purity zinc dust.	Function as sacrificial anodes which provide cathodic protection of the substrate metal.
Hiding pigments	Rutile titanium dioxide, zinc oxide	Pigments with a high light refractive index to provide good hiding.
Extender pigments	Carbonates, silicates, sulfates, barites and mica.	Acts as reinforcement and flow control pigments. They are relatively inexpensive.

2.13.3 Solvents

Solvents are volatile liquid materials that solvate solid paint components to reduce the viscosity and perfects paint fluid application (Talbert, 2007). At the end of application, the solvent evaporates to facilitate curing of the coating and develop hardness. If solvent possesses low volatility it can develop runs and sags during the drying process of a coating layer. Solvents must moderately volatilize to avoid defects such as; solvent pops, loss of gloss, dry spray, poor surface wetting and penetration, poor film flow and prevent cure. Solvents are categorized according to their chemical composition. Table 2.6 provides a list of common groups of solvents, their advantages and disadvantages.

Table 2.6: Classification of solvents and their descriptions (Talbert, 2007).

Classification	Examples	Solvent description
Aliphatic hydrocarbons	Naphtha, mineral spirits, hexane, heptane	Used with asphalt, oil and vinyl based coatings. Poor to moderate solvency and wide range of evaporating rates. Least expensive of all solvents.
Aromatic hydrocarbons	Toluene , xylene	Used with chlorinated rubbers, coal tars and certain alkyds. Greater solvent power than the aliphatics.
Ketones	Acetone, methyl ethyl ketone, methyl isobutyl ketone.	Effectively used with vinyls and some epoxies. Exhibits varying evaporation rates and relatively strong solubility parameters. Strong hydrogen bonding and high polarity
Esters	Ethyl acetate, isobutyl acetate, ethylene glycol.	Used as latent solvents with epoxy and polyurethane. Solvency power between aromatic hydrocarbons and ketones. Strong hydrogen bonding and a relatively high polarity.
Alcohols	Ethanol, isopropanol, n-butanol	Good solvents for highly polar binders such as phenolics. Alcohols are highly polar with a strong affinity for water.
Ether and alcohol ethers	Ethyl ether.	Excellent solvents for some of the natural resins, oils and fats
Water	Water	Used in latex paint

2.13.4 Additives

Additives usually contain less than 1% of the entire paint formulation. They are included as stabilizers of the paint fluid and improve numerous physical and chemical properties such as; viscosity, surface and interfacial tensions, gloss and drying time (Gardner, 2011). Addition of additives only applies when necessary since non-desirable effects on the paint properties may occur. The common additives are described in Table 2.7 with an account of their functionality.

Table 2.7: Classification of additives according to their functionality (Gardner, 2011)

Classification	Examples	Functionality
Antifoam additives	Mineral oils, silicone oil ,wax dispersions	Hinders the formation of foam e.g. by coalescence of small bubbles to large bubbles which increases the buoyancy of the bubbles.
Thickeners	Bentonite, cellulose derivatives, polyacrylates.	Raises the viscosity of the paint by creating a network between hydrophobic and hydrophilic parts of the paint.
Dispersion additives	Tensides	Raises the wettability of pigments to the binder phase by formation of micelles.
Siccatives	Metal salts of organic acids	Used in oxygen containing paints with reactive binders. Enhances the curing process.
Cold stabilizers	Ethylene glycol, propylene glycol	Used in water based paint to increase the stability to freezing

2.14 Paint resin systems

For pre-painted roofing sheets, there are three main paint resin systems; Polyester resins, Silicon polyester resins and Polyvinylidene fluoride (PVDF) resins.

2.14.1 Polyester resins.

Polyester resins have a variety of color spectrum and thus applicable to a wide variety of substrates. They provide a hard, scratch-resistant finish and a broader range of gloss (5 – 80 degree), however they are prone to chalking especially on exposure to UV light (Haddock, 2013). Polyesters include a wider class of chemical compounds and have elaborate characteristics and can be modified to fit desired end uses. They can be improved with better weathering properties. In their final form they are scratch resistant and inexpensive.

2.14.2 Silicon polyester resins.

The silicon polyester resins exist in two forms that include; silicon modified polyester (SMP) and super polyester resins. Both are discussed in sub-sections 2.14.2.1 and 2.14.2.2 respectively.

2.14.2.1 Silicon modified polyester

Silicon modified polyester (SMP) consist of polyester and silicon intermediates (Wilson and Magnus, 2012). SMPs provide an expanded range of color, improved color and gloss retention, together with superior corrosion resistance to chalking and fading. Silicon in the paint enhances gloss retention and also increases weather resistance (Witucki, 2003). The greater the silicon contents the better the performance of these paints.

2.14.2.2 Super polyester resins

Super polyester resins (SPR) are new technology resins with warranties of 40 years (Haddock, 2013).

2.14.3 Polyvinylidene fluoride resins

Polyvinylidene fluorides (PVDF) or polyvinyl di-fluoride (PVF_2) are the most recent state of the art coatings (Drobny, 2008). Water-based PVDF Fluoropolymer roof coatings include Polyvinylidene Fluoride (PVDF) resin technology which provides a variety of increased benefits as compared to typical acrylic roof coatings. PVDF coatings have a much harder finish, providing many benefits as compared to typical acrylic/ elastomeric roof coatings (Wang *et al.*, 2015). Figure 2.4 shows molecular structure of fluoropolymer.

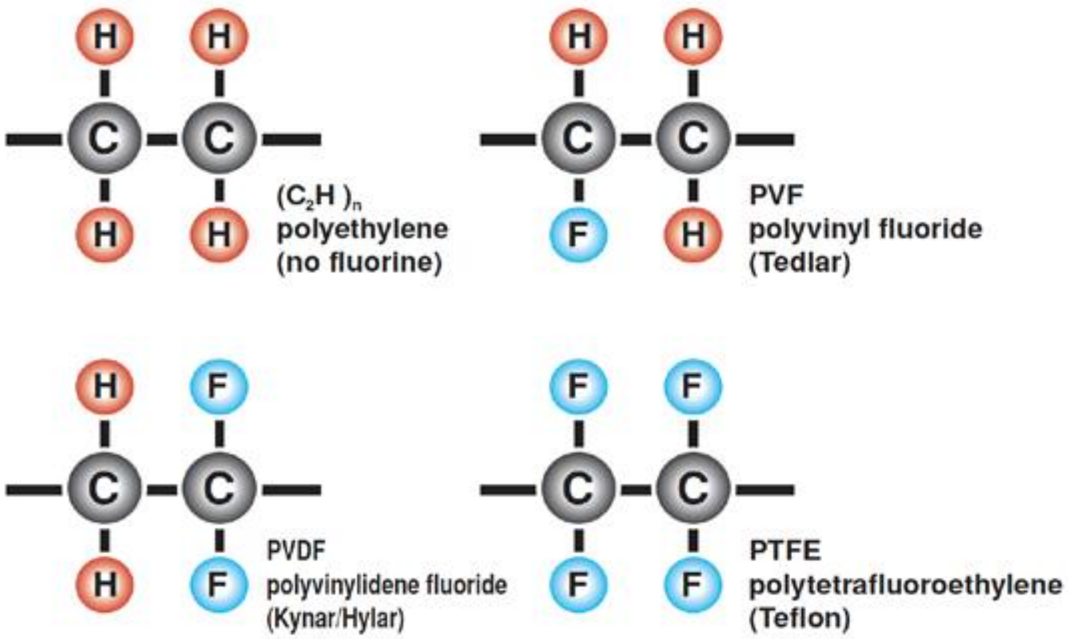


Figure 2.4: Structural formula of fluoropolymer coatings (Hongxiang, 2012).

The covalent bond between carbon and fluorine is one of the strongest chemical bonds. PVDF provides a slippery surface that makes most environmental pollutants to be washed off by rain. PVDF paints usually have a medium- or low-gloss finish with very good weathering and color stability properties. (Haddock, 2013).

2.15 Mechanisms of paint degradation

There are three main types of paint degradation mechanisms that may act on pre-painted (organic) coatings: chemical, mechanical or physical (Ellison, 2001). These mechanisms act in a synergistic manner and it is unusual that degradation of organic coatings is due to just one single cause. Figure 2.5 shows different degradation mechanisms related to organic coat deterioration.

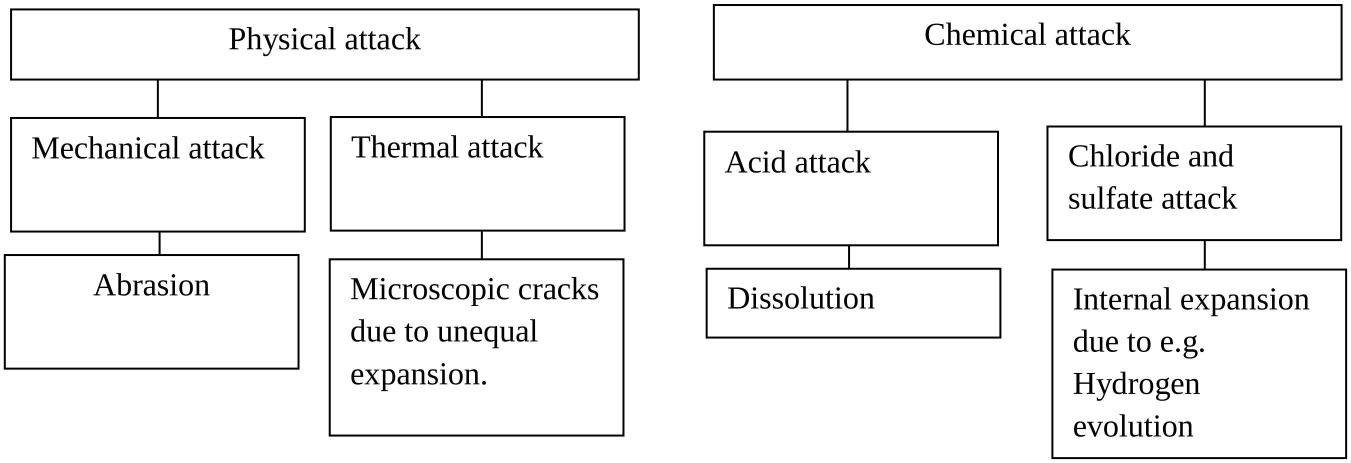


Figure 2.5: Degradation processes in an organic coating (Mohseni *et al.*, 2011)

Organic coating systems contain pigments as bulk reinforcement. The pigment is exposed to degradation mechanisms, such as chalking. Chalking of a paint system is often induced by temperature fluctuation, photolysis of the bonds and chloride ingress. Degradation of paints includes two partial processes; 1) the initiation phase and 2) the propagation phase. The time during which the temperature changes affect the non-uniform expansion of the paint and the metal substrate to cause microscopic 'cracks' is considered as the initiation phase. At the beginning of the propagation phase the degradation is established and advances until the corrosive chemical (pollutant) conditions stop. If the propagation phase continues, it might result in severe damages to the metal substrate underneath and a decreased strength of the roofing structure.

2.16 Blistering

Blisters refer to severe defects that occur in the paint coating particularly when water and other corrodents pass through the paint film during time of wetness (Tator, 2015). Presence of corrosive substances will trigger corrosion reaction just underneath the coating and cause the paint film to bulge. As the blister grows, it combines with several blisters and the paint will eventually peel off as flakes. There are three classes of blisters that may form; Osmotic blister, Anodic blister and cathodic blister (Hare, 1998). Osmotic blisters are dominant and always form near contaminants on the metal surface. They develop when water passes through the paint and begin to dissolve soluble constituents within the paint. This creates a dense fluid beneath the paint film which absorbs water outside the paint by osmosis. The blister consequently develops to counterbalance the density between the two fluids.

2.17 Fade (Color change)

Fade (color change) refers to visual total color difference that comprises of lightness, chroma and hue of a color coating. It is usually a single metric number that infers a pass or a fail decision hence shows quality of a pre-painted roofing sheet. The term Delta E or ∆E is used to describe fade (color change) in the Commission Internationale de l'Eclairage Laboratory (CIE Lab) color space (Billmeyer and Saltzman, 1981).

2.18 Gloss and surface roughness

Gloss refers to an optical property of a surface and it is defined as the ability of a surface to reflect light without scattering (Kumar and Choudhury, 2014). It is proportional to the reflectance of the surface. Spectroguide as a gloss meter reads gloss at 85^0,$65^0$and 20^0 after shining a known amount of incident light and measuring the reflectance. The extent of glossiness of a surface mainly depends on the surface texture. Gloss and surface roughness are linearly related, in such a way that, the higher the gloss, the lower the surface roughness (Farrier, 2007). For a paint or coating, pigmentation is always considered to change the surface roughness in order to control the gloss. The protrusion of paint pigment particles makes the reflected light scatter ending up in a reduced gloss. Gloss variation is affected by several factors such as size of pigment particles, shape, and concentration.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study sites

The atmospheric corrosion study sites were located at Mabati Rolling Mills in Mariakani and Mlolongo (Figures 3.1 and 3.2). Mariakani (Figure 3.1) is located at longitude 39^{0}27’E and latitude 03°52’S in the Kilifi County, Kenya. It lies on a dry low land zone 36 km North West of port city of Mombasa. Mabati Rolling Mills (MRM) is one of the industries in Mariakani that manufactures steel roofing sheets. The other industries in Mariakani include: Corrugated Steel Mills, Kaluworks, Nyumba Steel Mills and Steel Rolling Mills. All these industries could be possible corrosive pollutant sources (chloride from nearby ocean and sulphate ions from factory flue gases) in the area.

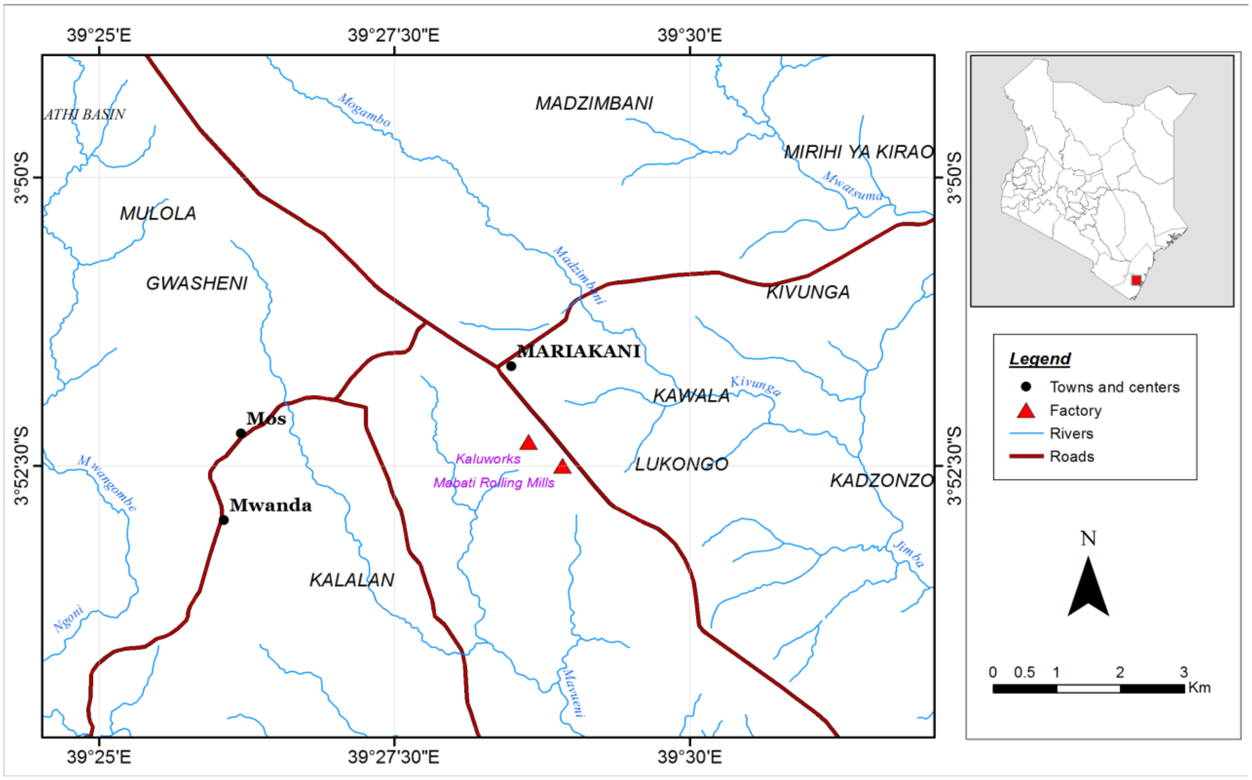


Figure 3.1: Mabati Rolling Mills atmospheric corrosion study site at Mariakani (Onyatta *et al.*, 2016)

Mabati Rolling Mills at Mariakani lies at an altitude of 203m above sea level and within the humid tropics that experiences low rainfall and average monthly temperature of between 23.7 and 27.9°C. A typical climatic data for Mariakani site in Kenya is presented in Table 3.1.

Table 3.1: Mariakani annual climatic data (www. climatemps.com, 23-01-2016)

Month	Temperature(°C)	Precipitation (mm)	Relative humidity (%)
January	27.1	32.4	69.0
February	27.6	18.6	66.9
March	27.9	62.1	68.5
April	27.1	148.1	73.6
May	25.7	217.1	76.2
June	24.4	81.1	73.1
July	23.7	65.6	74.0
August	24.3	57.2	73.1
September	25.4	61.5	71.3
October	25.4	81.1	71.0
November	26.5	100.8	72.5
December	26.9	71.6	72.2
Average	26.0	83.1	65.9

Mlolongo corrosion study site (Figure 3.2) is located in Machakos County, Kenya. It is located at longitude $36^0$55'E and latitude 01°22'S. It is located to the east of Nairobi, the capital city of Kenya. Apart from being situated between busy Nairobi-Mombasa highway and the Standard Gauge Railway line, this project site is surrounded by two other industries namely; Kapa oil and Signode industries.

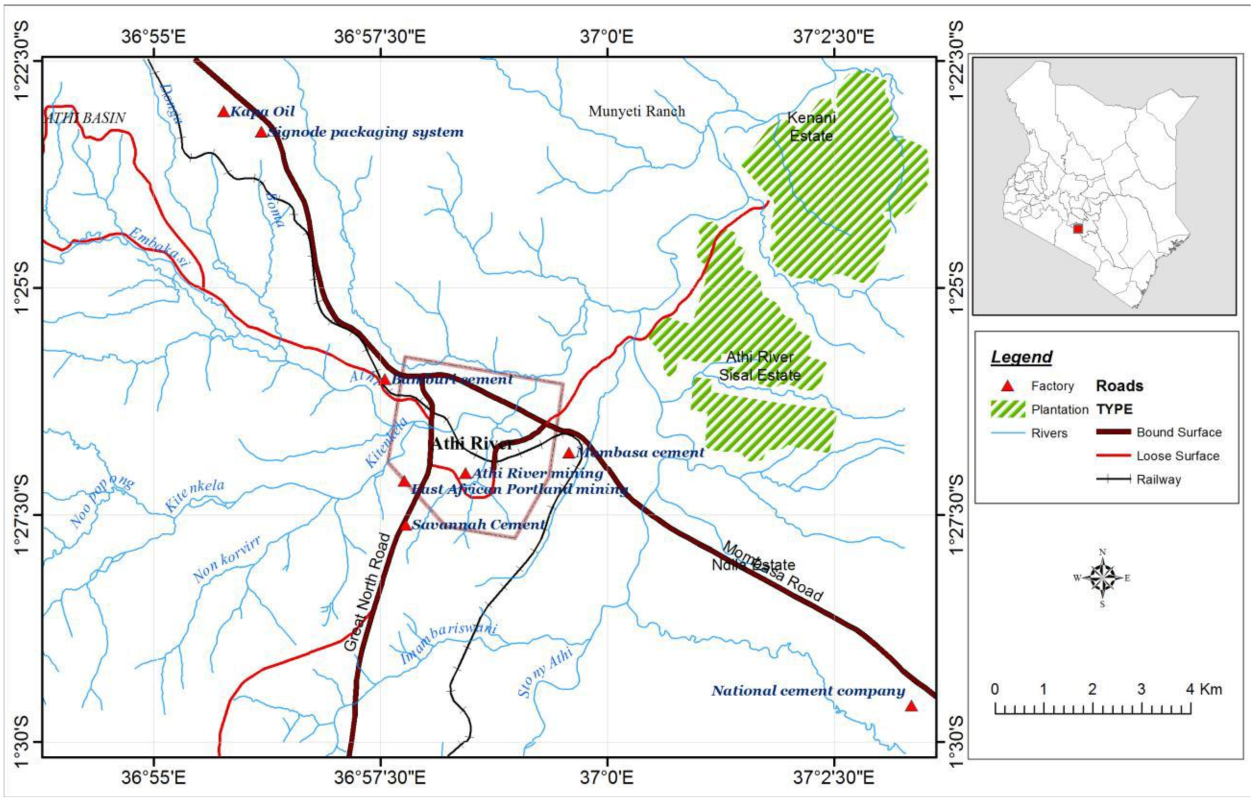


Figure 3.2: Mabati Rolling Mills atmospheric corrosion study site at Mlolongo

Mlolongo is at an altitude of 1,606 meters above sea level. It receives a mean annual rainfall of 69.2 mm with temperature ranging between 17.0 to 20.7°C. A typical climatic data for Mlolongo sites in Kenya is presented in Table 3.2.

Table 3.2: Mlolongo annual climatic data (www. climatemps.com, 23-01-2016)

Month	Temperature(°C)	Precipitation (mm)	Relative humidity (%)
January	19.5	47.0	59.9
February	20.3	49.0	58.2
March	20.7	107.0	61.5
April	20.0	179.0	69.4
May	19.0	69.0	71.3
June	17.4	9.0	69.3
July	16.5	5.0	69.5
August	17.0	4.0	67.7
September	18.5	8.0	61.3
October	20.1	53.0	59.1
November	19.4	191.0	67.2
December	19.2	109.0	65.6
Average	19.0	69.2	65.0

3.2 Experimental procedures

Accelerated and outdoor exposure tests were conducted at the two sites.

3.2.1 Sampling procedures and description of samples

Metallic coated and pre-painted roofing sheets for accelerated test were cut into150 mm x 75 mm sizes while the ones for outdoor exposure were 190 mm × 130 mm sizes as shown in Figure 3.3.

Red Green Blue

Figure 3.3: Pre-painted samples used during the accelerated and outdoor exposure tests

The samples in triplicate were packed into clean and dry polythene bags for subsequent use (Chotimongkol *et al*, 1999). Before setting up the tests, the roofing sheets were wiped with dry piece of cloth to remove grease and dirt particles and other debris then wiped with soft cotton wool soaked in acetone.

3.2.2 Procedure for accelerated tests for metallic coated sheets.

The initial coating mass of cleaned metallic coated sheets measuring 150mm x 75 mm was determined using XRD-7000 (Japan, Model EDX-7000 ROHS ASSY) instrument and recorded before exposure(Abdel *et al*., 2016).The sheets were then set in a chamber at an angle of 60^0 (Figure3.4) and salt fog from a mixture of0.073% sodium chloride and 0.289% ammonium sulfate in the reservoir was sprayed on the sheets for 12 hours at 25^0 C. Immediately a purge of dry air at 35^0 C was blown on the sheets for two hours to simulate the natural exposure environment after a rainfall. This was done for 4 hours then the sheets were left to dry at ambient temperature of 25^0C. The 12 hour cycle of fog and dry-off was done for 672 hours (28 days).

After exposure; rust was removed mechanically by scrubbing carefully with a dry cloth and thereafter with 5% nitric acid solution (Xia *et al*., 2012). After wiping the samples with soft cloth soaked in distilled water, the samples were dried at ambient laboratory temperature and the final coating mass after 28 days exposure was again measured using XRD-7000 instrument. The process was repeated using a solution mixture of 1.000% sodium chloride and 4.000% ammonium sulphate.

Figure 3.4: Arrangements of samples during salt spray (Fog) process (Onyatta *et al*., 2016)

3.2.3 Procedure for accelerated tests for pre-painted sheets

The initial fade and gloss of cleaned pre-painted sheets measuring 150mm x 75 mm in size were measured using Spectroguide (BYK Gardner 82638, GmbH) instrument and recorded before exposure. The sheets were then placed in a Quick Ultra violet (QUV) chamber where they were exposed on a series of 4 hour cycle of alternating condensation (at 50^0C) and UV radiation (60^0C). The QUV test proceeded for 168 hours (7days) after which the sheets were placed in a salt spray chamber at an angle of 60^0 (Figure3.4) and salt fog from a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate in the reservoir was sprayed on the sheets for 12 hours at 25^0 C. Immediately a purge of dry air at 35^0 C was blown on the sheets for 6 hours to simulate the natural drying of the samples after rainfall. The sheets were then left to dry at ambient temperature of 25^0C for 6 hours. Fog and dry-off cycles were repeated for 168 hours. The exposed sheets were left to dry for 2 hours at 25^0 C wiped dry with soft clean pieces of cloth before final fade and gloss were measured and recorded. Immediately the same sheets were placed back in the QUV chamber to start the next cycle. After each exposure cycle of 336 hours, fade and gloss were measured and recorded. The 168 hour QUV test and 168 hours of fog and dry-off were done for total of 1344 hours (56 days). The process was repeated using a solution mixture of 1.000% sodium chloride and 4.000% ammonium sulphate.

3.2.4 Procedure for outdoor exposure tests for the metallic coated sheets.

The initial coating masses of cleaned metallic coated roofing sheets measuring 190 mm by 130mm in size were measured using XRD-7000 (Japan, Model EDX-7000 ROHS ASSY) and recorded .The sheets were then fastened using removable winged nuts on exposure racks that were set up facing south at an angle of 30^0 to the horizontal(Figure 3.5). This orientation was to ensure that maximum ultraviolet light from the sun illuminates the sheets while the angle simulates most elevation of roofing systems in Kenya. The samples were allowed to stand for 180 days after which the sheets were unfastened, kept in a dark polythene bag and transported to the laboratory. The samples were wiped using dry piece of cloth just before final coating masses were measured using XRD-7000 and recorded. The coating mass loss was calculated from the difference between initial and final coating mass.

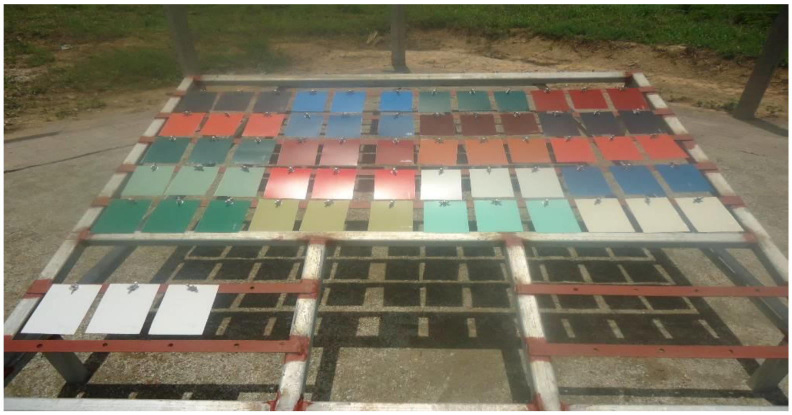


Figure 3.5: The outdoor exposure rack at Mariakani site showing pre-painted roofing sheets (Onyatta *et al.*, 2016).

3.2.5 Procedure for calculation of corrosion rates of metallic coated sheets

To determine corrosion rate (C_r) for both accelerated and outdoor exposure tests , the difference between initial and the final coating mass was calculated for each metallic coated sample to obtain the coating mass loss using Equation 3.1;

$$m_l = m_i - m_f \tag{3.1}$$

Where;

m_l = coating mass loss (grams per square metre, gsm)

m_i = Initial coating mass (grams per square metre , gsm)

m_f = Final coating mass (grams per square metre ,gsm)

The coating mass losses of the metallic coated sheets from manufacturers 1, 2, 3, 4 and 5 were tabulated in Tables 4.1 and 4.2 (accelerated tests) as well as Tables 4.15 and 4.16 (outdoor exposure tests). The calculated coating mass losses were then used to calculate corrosion rates, C_r (millimetres per year, mmpy) using Equation 3.2 (Hongwei *et al.*, 2015).

$$C_r = \frac{Km_l}{ADT} \tag{3.2}$$

Where;

C_r = Corrosion rate (millimetres per year, mmpy),

m_l = Coating mass loss (grams per square metres, gsm)

K= Constant (K =8.76×10^4 (accelerated tests) and K =3,650(outdoor exposure tests))

A= Area of sheet (square metres (accelerated tests)) or

A= Area of sheet (square centimetre (outdoor exposure tests))

D= Density of coat (=3.75 gram per cubic centimetre)

T= Time (Hours (accelerated tests) and days (outdoor exposure tests))

3.2.6 Procedure for outdoor exposure tests for the pre-painted sheets

Fade (color loss, ΔE) and gloss variation (ΔG) were measured using the Spectroguide (BYK Gardner 82638, GmbH). The Spectroguide was placed on to the surface of unexposed and exposed samples to determine fade (color loss) in Hunters units (Glander, 2013). Gloss variation (ΔG) was measured in percentage (%). The initial fade and gloss of cleaned pre-painted roofing sheets measuring 190 mm by 130mm were measured and recorded. The sheets were fastened on the racks and allowed to stand for 180 days (Figure 3.5). The sheets were then unfastened, kept in a dark polythene bag and transported to the laboratory. The samples were wiped using dry piece of cloth just before final fade and gloss were measured using spectroguide and recorded. The fade and gloss variation were calculated from the difference between initial and final fade and gloss measurements.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Accelerated tests

4.1.1 The effect of salt spray on corrosion of metallic coated roofing sheets

The intensity of corrosion of metallic coated roofing sheets from selected manufacturers after a salt spray using a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate is represented in Figure 4.1.

(1) (2) (3)

Figure 4.1: Intensity of rusting of AZ samples from manufactures 1, 2 and 3 after 28 days (672 hours) exposure in 0.073% sodium chloride and 0.289% ammonium sulphate solution mixture.

The differences in the intensities of corrosion of the samples are attributed to the coating mass of aluminium-zinc coat and amount of chromium applied during the manufacturing process. The results showed the ability of the sample to resist corrosion when sprayed with a corrosive agent such as a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate. Therefore the sample marked 1 in Figure 4.1 which was an aluminium–zinc (AZ) coated obtained from manufacturer 1 was able to resist corrosion more than samples marked 2 and 3 indicating that sample 1is of better quality. The intensity of rusting of galvanized (GI) samples marked 4 and 5 from manufactures 4 and 5, after 28 days in a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate solution is shown in Figure 4.2

(4) (5)

Figure 4.2: Intensity of rusting of GI samples from manufactures 4 and 5 respectively, after 28 days (672 hours) exposure in 0.073% sodium chloride and 0.289% ammonium sulphate solution.

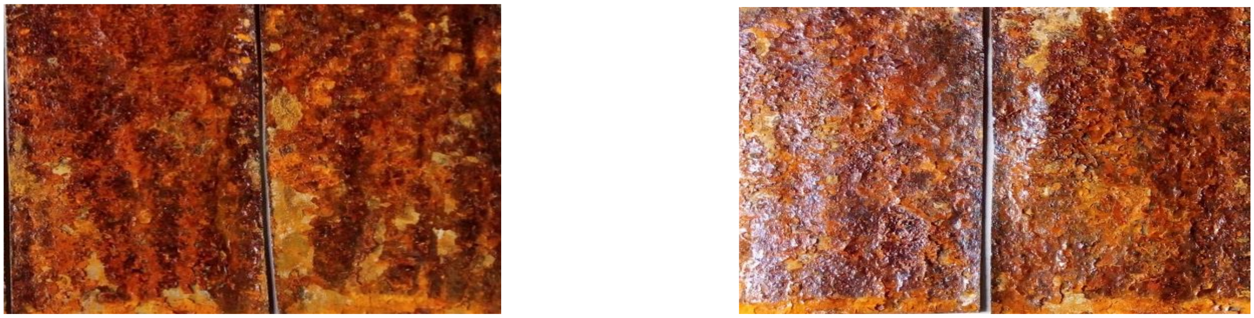
It was observed that sample in Figure 4.2 the sample labeled 4was highly corroded based on the intensity of the red brown rust on the surface. The differences in the intensities of corrosion of the samples are attributed to the coating mass of zinc coat. The observed results showed that, GI samples from manufactures 4 and 5 least resisted corrosion compared to AZ samples. The results for the GI samples labeled 4 and 5 in Figure 4.2 showed that sample labeled 4 corroded the most (based on the appearance of completely brown-black rust) indicating that it was of poor.

When the concentration mixture was increased (1.000% sodium chloride and 4.000% ammonium sulphate), the intensity of corrosion varied with the nature of the roofing sheets. The results for the AZ sheets labeled 1, 2 and 3 from manufactures 1, 2 and 3 are shown in Figure 4.3.

(1) (2) (3)

Figure 4.3: Intensities of corrosion on metallic coated samples from different manufacturers (1, 2 and 3) exposed for 672 hours (28 days) after salt spray.

Sample labeled 2 in Figure 4.3 was moderately corroded (appearance of black rust) while the sample labeled 3 corroded more (appearance of red-brown rust) based on the observed effect on the surface. The differences in the intensities of corrosion of the samples are attributed to the coating mass of aluminium-zinc coat and amount of chromium that was applied by the manufacturer. The results therefore showed that sample labeled 1 in Figure 4.3 which was an aluminium–zinc (AZ) obtained from manufacturer 1 was still resisted corrosion, indicating that it is of better quality than samples from manufacturers 2 and 3. Figure 4.4 shows intensity of rusting of galvanized (GI) samples from manufactures 4 and 5 after 28 days (labeled 4 and 5) in a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate solution.



(4) (5)

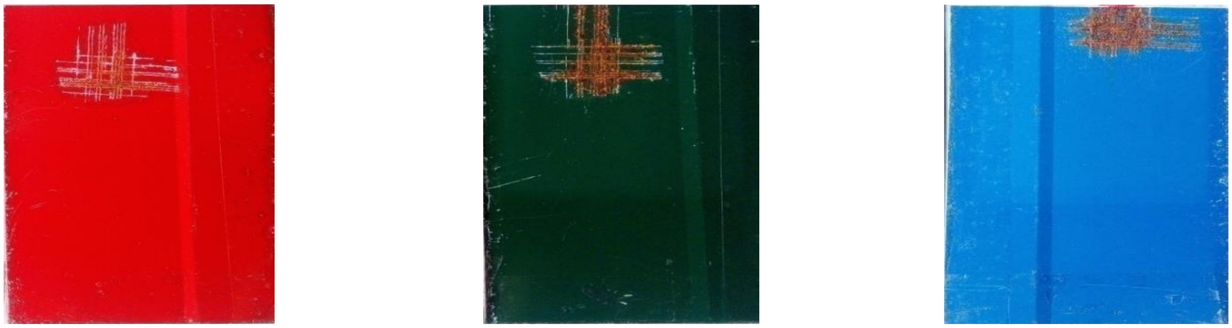
Figure 4.4: Intensity of rusting of GI samples from manufactures 4 and 5 respectively, after 28 days (672 hours) exposure in 1.000% sodium chloride and 4.000% ammonium sulphate solution.

It was observed that sample labeled 4 in Figure 4.4 was highly corroded based on the intensity of the red brown rust on the surface. The differences in the intensities of corrosion of the samples are attributed to the nature of the steel sheet and coating mass of zinc coat. The observed results showed that GI samples resisted corrosion the least (based on appearance of intense red-brown-black rust). Sampled labeled 4 was of poor quality in terms of their corrosivity. GI samples contain zinc as the major component of the coating mass on the surface of the samples which corroded highly in salt solutions compared to aluminium-zinc (AZ) coated samples.

When pre-painted roofing sheets from selected manufacturers were exposed for 28 days (672 hours) after a salt spray using a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate, observations in Figure 4.5 and 4.6 were obtained.

Red Green Blue

Figure 4.5: Intensities of fade of pre-painted samples from manufacturer 1 exposed for 672 hours (28 days) after salt spray.



Red Green Blue

Figure 4.6: Intensities of fade of pre-painted samples from manufacturer 2 exposed for 672 hours (28 days) after salt spray.

The red, green and blue samples from manufacturer 2 faded most compared to corresponding samples from manufacturer 1 at higher salt solution concentration. This could be due to thin color coat, application of unstable pigments, improper paint formulation, absence or use of weak primer and poor paint curing in the oven. The higher the concentration of the salt spray, the more effect it had on corrosion.

4.1.2 Corrosion rate of the metallic coated roofing sheets

The coating mass losses and corresponding corrosion rates from the accelerated tests for the metallic coated roofing sheets from manufactures 1, 2, 3, 4 and 5 in a mixture of 0.073% chloride and 0.289% sulphate were calculated (Appendix 1) and recorded in Table 4.1.

Table 4.1: Corrosion rate, Cr (mmpy) for metallic coated sheets from accelerated test in a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate for 28 days (672 hours).

Coating mass(gsm)	Manufacturer 1(AZ sample)	Manufacturer 2(AZ sample)	Manufacturer 3(AZ sample)	Manufacturer 4(GI sample)	Manufacturer 5(GI sample)
Initial mass, m_i (gsm)	41.945±1.141	8.270±0.701	21.079±1.472	47.922±4.178	50.075±5.274
Final mass, m_f (gsm)	40.828±1.129	7.081±0.690	19.770±1.458	41.904±4.158	43.392±5.256
Mass loss, m_l (gsm)	1.117±0.012	1.189±0.011	1.309±0.014	6.018±0.020	6.683±0.018
Corrosion rate,C_r (mmpy)	0.345±0.004	0.367±0.004	0.405±0.004	1.860±0.006	2.065±0.006

The trend of corrosion rate from lowest to highest was manufacturer 1, 2, 3, 4 and 5 and the order of corrosion rate in millimetres per year (mmpy) was therefore 0.345, 0.367, 0.405, 1.860 and 2.065 as shown in Table 4.1. The sample from manufacturer 1 was of a better quality for roofing applications. This could be due to a higher ratio of aluminium to zinc in the coating, chromium added and better coating process on AZ sheet from manufacturer 1 which resist chloride and sulphate attack more than sheets from manufacturers 2, 3, 4 and 5.

The corrosion rate for the metallic coated roofing materials in a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate were as recorded in Table 4.2.

Table 4.2: Corrosion rate, Cr (mmpy) for metallic coated sheets from accelerated test in a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate for 28 days (672 hours)

Coating mass(gsm)	Manufacturer 1(AZ sample)	Manufacturer 2(AZ sample)	Manufacturer 3(AZ sample)	Manufacturer 4(GI sample)	Manufacturer 5(GI sample)
Initial mass, m_i (gsm)	43.050±0.101	7.508±0.072	21.144±0.403	53.298±1.210	51.251±0.147
Final mass, m_f (gsm)	41.730±0.090	6.062±0.063	19.035±0.393	45.796±1.197	43.983±0.137
Mass loss, m_l (gsm)	1.320±0.011	1.446±0.009	2.109±0.010	7.502±0.013	7.268±0.010
Corrosion rate, C_r (mmpy)	0.408±0.003	0.447±0.003	0.652±0.003	2.318±0.004	2.246±0.003

In Table 4.2 the trend of corrosion rate from lowest to highest was manufacturer 1, 2, 3, 5 and 4 and the order of corrosion rate in millimetres per year (mmpy) was therefore manufacturer one (0.408), two (0.447), three (0.652), five (2.25) and four (2.32). Sample from manufacturer 1 was more resistant to corrosion followed by two, three, five and four. In both spray concentrations AZ samples had lower corrosion rates compared to GI samples. This revealed that aluminium-zinc (AZ) coated sheets are superior products than galvanized (GI) roofing sheets for roofing applications. From the results the increase in concentration of salt spray mixture increased the rate of corrosion.

4.2 Fade for the pre-painted roofing sheets for accelerated tests.

Fade for pre-painted sheets were measured and tabulated in Tables 4.3-4.8.

Table 4.3: Fade for pre-painted red sheets in a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate for 56 days (1344 hours).

	Fade (Hunter units)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
336	0.59±0.02	1.88±0.02	1.38±0.02	1.41±0.02
672	0.69±0.02	2.04±0.02	1.86±0.02	1.88±0.02
1008	0.80±0.02	4.17±0.02	2.39±0.02	2.08±0.01
1344	1.40±0.01	4.98±0.02	2.91±0.01	3.66±0.01

In Table 4.3 the order of performance of red color was manufacturer one (1) having the best property followed by three (3), four (4) and two (2). This revealed that red sheet from manufacturer 1 had the lowest fade as compared to sheets from other manufacturers. However, increased spray concentrations and time of exposure, increased fade for all the four red samples. This could be attributed to increased chloride and sulphate attack on red paint components applied on the sheets.

Table 4.4: Fade for pre-painted red sheets in a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate for 56 days (1344 hours).

	Fade (Hunter units)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
336	1.95±0.01	2.18±0.02	3.61±0.01	2.27±0.01
672	2.36±0.02	2.34±0.01	4.09±0.01	2.75±0.02
1008	2.39±0.01	4.95±0.01	4.62±0.02	2.94±0.02
1344	2.42±0.02	5.60±0.02	4.63±0.01	4.52±0.02

In Table 4.4 the order of performance of red sheets at 1008 and 1344 hours from the lowest to the highest was 1, 4, 3 and 2. At any given period of exposure time for Tables 4.3 and 4.4, fade was higher at an increased concentration of spray mixture. This revealed that red coated sheet from manufacturer 1 was a superior product as compared to the other manufacturers. This could be due to better fade resistance property of red sheet (paint) components in terms of pigment, binder, additive and solvent, pre-treatment process and oven baking conditions during manufacturing process.

Table 4.5: Fade for pre-painted green sheets in a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate for 56 days (1344 hours).

	Fade (Hunter units)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	No sample was available
336	0.66±0.02	1.81±0.02	2.21±0.02	
672	1.51±0.02	2.80±0.02	4.94±0.01	
1008	1.72±0.02	3.80±0.01	6.38±0.02	
1344	1.81±0.01	3.82±0.03	8.21±0.01	

The results in Table 4.5 revealed that performance of green sheets from the manufacturers followed the order; 1, 2 and 3. This revealed that green coated sheet from manufacturer 1 had the lowest fade as compared to the other manufacturers. Therefore green sheet from manufacturer 1 is a better material for roofing applications.

Table 4.6: Fade for pre-painted green sheets in a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate for 56 days (1344 hours).

	Fade (Hunter units)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	No sample was available
336	0.64±0.01	1.74±0.02	2.12±0.02	
672	0.88±0.01	2.52±0.01	3.02±0.01	
1008	1.44±0.02	3.41±0.01	4.17±0.02	
1344	2.14±0.01	3.47±0.02	5.31±0.01	

In Table 4.6 the order of performance of manufacturers of green color from best to the worst was 1, 2 and 3. This revealed that green coated sheet from manufacturer 1 had the lowest fade hence the best product for roofing applications. However, increased salt mixture concentrations reduced fade on sheets from manufacturer 2 and 3 but increased fade for sheets from manufacturer 1. This could be attributed to the application of green paints of varying types, composition and proportions of components (e.g. binder, pigment, solvents and additives).

Table 4.7: Fade for pre-painted blue sheets in a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate for 56 days (1344 hours).

	Fade (Hunter units)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
336	0.46±0.02	1.98±0.01	0.52±0.02	0.67±0.01
672	0.52±0.02	2.51±0.02	2.21±0.03	1.51±0.02
1008	0.60±0.02	4.40±0.02	2.23±0.02	1.56±0.03
1344	0.69±0.01	4.41±0.03	2.48±0.01	1.56±0.02

In Table 4.7 the order in performance of manufacturers of blue color (1008, 1344 hours) from best to worst was 1, 4, 3 and 2. This revealed that blue coated sheet from manufacturer 1 had the lowest fade as compared to the other manufacturers, therefore a better product for roofing applications.

Table 4.8: Fade for pre-painted blue sheets in a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate for 56 days (1344 hours).

	Fade (Hunter units)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
336	0.65±0.01	2.33±0.02	0.88±0.02	0.49±0.01
672	0.81±0.01	3.58±0.01	0.91±0.02	0.82±0.02
1008	0.84±0.02	5.22±0.01	1.77±0.01	1.43±0.02
1344	0.95±0.01	6.24±0.02	2.14±0.01	1.50±0.01

In Table 4.8 the order of performance of manufacturers of blue color (1008, 1344 hours) from best to worst was 1, 4, 3 and 2. This showed that blue coated sheet from manufacturer 1 had the least fade as compared to sheets from other manufacturers. Thus, a blue sheet from manufacturer 1 was a better product for roofing applications. Increased salt mixture concentration increased fade on blue sheets from manufacturer 1 and 2 but decreased fade on sheets from manufacturer 3 and 4. This was attributed to the use of different types, composition and proportion of blue paints in terms of pigment, binder, additive and solvent, pre-treatment process and oven baking conditions during manufacturing process.

4.3 Gloss for the pre-painted roofing sheets under accelerated tests.

Gloss provided the degree of how much a pre-painted surface reflected or absorbed incident light. Positive gloss meant increased reflection and reduced absorption of light a quality desired by modern roofing applications. Negative gloss indicated decreased reflection and increased absorption of sunlight. Gloss variations for pre-painted sheets were measured and recorded in Tables 4.9- 4.14.

Table 4.9: Gloss for pre-painted red sheets in a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate for 56 days (1344 hours).

	Gloss (%)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
336	0.2±0.1	-6.1±0.3	2. 2±0.1	-3.1±0.2
672	-6.8±0.3	-10.7±0.2	4.5±0.2	-12.8±0.2
1008	0.0±0.0	-0.1±0.1	4.5±0.2	0.0±0.0
1344	-6.1±0.3	-9.8±0.4	-5.7±0.1	-3.1±0.2

After 1344 hours the trend in gloss loss of red sheets from the lowest to highest was manufacturers 4, 3, 1 and 2. This revealed that red coated sheet from manufacturer 4 was superior product for roofing applications as shown in Table 4.9. Gloss for sheet from manufacturer 1 showed a better stability with a less fluctuation between 0.2±0.1 and -6.8±0.3%, therefore in 0.073% sodium chloride and 0.289% ammonium sulphate spray its texture appeared consistent hence another good roofing product.

Table 4.10: Gloss for pre-painted red sheets in a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate for 56 days (1344 hours).

	Gloss (%)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
336	-1.1±0.2	-3.8±0.1	-0.4±0.1	2.8±0.2
672	-1.5±0.1	-1.4±0.2	0.0±0.0	-4.0±0.2
1008	-4.9±0.2	-15.2±0.3	-5.3±0.2	-8.3±0.3
1344	-4.7±0.1	-22.0±0.4	-9.3±0.2	-14.1±0.3

After 1344 hours the trend in gloss loss of red sheets from lowest to highest was manufacturer 1, 3, 4 and 2. This revealed that red coated sheet from manufacturer 1 was superior product as shown in Table 4.10. Red sheets from manufacturer 1 showed reduced gloss loss with increased salt spray concentration while increased gloss loss was noticed on sheets from manufacturer 2, 3 and 4. This could be due to red paint components on sheets from manufacturer 1 resisting chloride and sulphate attack as concentration of the spray increases.

Table 4.11: Gloss for pre-painted green sheets from accelerated test in a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate for 56 days (1344 hours).

	Gloss (%)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	No sample was available
336	-1.1±0.1	3.1±0.2	-4.1±0.3	
672	-3.3±0.2	-3.0±0.1	-2.8±0.2	
1008	0.3±0.1	-4.4±0.3	0.0±0.0	
1344	-6.9±0.1	3.5±0.2	-4.1±0.4	

After 1344 hours the gloss of green sheets from best to worst at was 2, 3 and 1 as in Table 4.11. This showed that green coated sheet from manufacturer 2 was superior product for roofing applications.

Table 4.12: Gloss for pre-painted green sheets in a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate for 56 days (1344 hours).

	Gloss (%)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	No sample was available
336	-2.8±0.2	-9.7±0.3	-4.5±0.2	
672	-2.3±0.1	-6.6±0.2	-4.5±0.3	
1008	0.3±0.2	-6.4±0.2	-5.4±0.1	
1344	-4.4±0.2	-5.8±0.2	-8.4±0.3	

After 1344 hours the gloss of green sheets from best to worst at was 1, 3 and 2 as shown in Table 4.12. This confirmed that green coated sheet from manufacturer 1 was superior product for roofing applications. Increased spray concentration led to further gloss loss resulting from increased reaction of paint components and spray (chloride and sulphate solution).

Table 4.13: Gloss for pre-painted blue sheets under accelerated test in a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate for 56 days (1344 hours).

	Gloss (%)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
336	-2.2±0.2	-6.9±0.3	6. 6±0.1	-3.3±0.2
672	-1.5±0.3	-15.0±0.2	5.4±0.2	-8.6±0.2
1008	0.1±0.1	-0.1±0.1	10.0±0.2	0.2±0.1
1344	-0.2±0.1	-14.4±0.3	9.9±0.2	-3.1±0.2

After 1344 hours the gloss of blue sheets from best to worst was 3, 4, 1 and 2 as shown in Table 4.13. This revealed that blue coated sheet from manufacturer 3 was a better product for roofing applications.

Table 4.14: Gloss for pre-painted blue sheets in a mixture of 1.000% sodium chloride and 4.000% ammonium sulphate for 56 days (1344 hours).

	Gloss (%)			
Time (Hours)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
336	1.3±0.1	-3.7±0.3	-2.3±0.2	-1.3±0.1
672	-1.0±0.1	-0.7±0.1	0.9±0.1	-5.4±0.2
1008	-3.5±0.2	-13.6±0.3	-4.2±0.2	-18.3±0.3
1344	-1.9±0.1	-15.0±0.4	-6.4±0.2	-24.5±0.3

After 1344 hours the gloss of blue sheets from best to worst at was 1, 3, 2 and 4. This confirmed that blue sheet from manufacturer 1 was a better roofing product. However, increased spray concentrations significantly, increased gloss loss hence increased loss of quality of blue sheets as roofing materials. This could be due to increased spray (chloride and sulphate) attack on blue paint components.

4.4 Outdoor exposure tests

4.4.1 Corrosion rate of metallic coated sheets in Mariakani and Mlolongo test site.

The coating mass losses and the corresponding corrosion rates from outdoor tests for the metallic coated roofing sheets from manufactures 1, 2, 3, 4 and 5 at Mariakani were calculated (Appendix 2) and recorded in Table 4.15.

Table 4.15: Corrosion rate, Cr (mmpy) for metallic coated sheets at Mariakani site for 180 days exposure.

Coating mass(gsm)	Manufacturer 1(AZ sample)	Manufacturer 2(AZ sample)	Manufacturer 3(AZ sample)	Manufacturer 4(GI sample)	Manufacturer 5(GI sample)
Initial mass, m_i (gsm)	46.692±0.160	5.218±0.139	18.190±0.897	53.054±0.352	49.698±0.755
Final mass, m_f (gsm)	45.812±0.149	4.287±0.129	16.663±0.887	47.201±0.341	44.063±0.741
Mass loss, m_l (gsm)	0.880±0.011	0.931±0.010	1.527±0.010	5.853±0.011	5.635±0.014
Corrosion rate, C_r (mmpy)	0.019±0.001	0.020±0.001	0.033±0.001	0.128±0.001	0.123±0.002

In Table 4.15 the order of corrosion rate in millimetres per year (mmpy) from the lowest to the highest was manufacturer one (0.019) nearly same as two (0.020), three (0.033), five (0.123) and four (0.128). The sample from manufacturer 1 was of a better quality for roofing applications Mariakani. This could be ascribed to a higher corrosion resistance of AZ coating, chromium added and better coating process on AZ sheet from manufacturer 1.

Table 4.16: Corrosion rate, Cr (mmpy) for metallic coated sheets at Mlolongo site for 180 days exposure.

Coating mass(gsm)	Manufacturer 1(AZ sample)	Manufacturer 2(AZ sample)	Manufacturer 3(AZ sample)	Manufacturer 4(GI sample)	Manufacturer 5(GI sample)
Initial mass, m_i (gsm)	46.46±0.008	5.965±0.078	19.929±0.012	54.538±0.038	55.791±0.011
Final mass, m_f (gsm)	45.120±0.001	4.070±0.066	16.897±0.080	46.410±0.028	47.884±0.004
Mass loss, m_l (gsm)	1.340±0.007	1.895±0.012	3.032±0.004	8.128±0.010	7.907±0.007
Corrosion rate, C_r (mmpy)	0.029±0.001	0.041±0.001	0.066±0.001	0.178±0.001	0.173±0.001

In Table 4.16 the order of corrosion rate in mmpy from the lowest to the highest was manufacturer one (0.029), two (0.041), three (0.066), five (0.173) and four (0.178). In both sites the AZ samples had lower corrosion rate as compared to GI samples. Manufacturer 1 gave the best product followed by 2, 3, 5 and 4 in that order. Mlolongo corrosion rate was higher than Mariakani. This could have been attributed to higher pollution caused by high concentration of sulphate ion from industries into the atmosphere above the test site, lower precipitation (69.2 mm) and relative humidity (65.0 %). This revealed that aluminium-zinc (AZ) coated sheet is superior product than galvanized (GI) roofing sheets for roofing applications.

4.4.2 Fade for pre-painted sheets in Mariakani and Mlolongo test site.

Fade for selected pre-painted sheets for 180 days were tabulated in Tables 4.17-4.22.

Table 4.17: Fade for pre-painted red sheets at Mariakani test site for 180 days exposure

	Fade (Hunter units)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
90	0.69±0.01	1.45±0.01	1.63±0.02	1.48±0.02
180	0.92±0.02	2.39±0.02	1.97±0.01	2.75±0.02

After 180 days the order of performance of manufacturers of red sheets from best to worst at Mariakani was 1, 3, 2 and 4. This revealed that red coated sheet from manufacturer 1 was a better product for roofing application. This could be attributed to higher quality of paint and primer applied, extensive pre-treatment and better paint baking conditions during manufacturing process.

The results for the Mlolongo site for the metallic coated and the pre-painted samples are given in Tables 4.18.

Table 4.18: Fade for pre-painted red sheets at Mlolongo test site for 180 days exposure

	Fade (Hunter units)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
90	0.91±0.01	2.38±0.01	1.61±0.02	0.85±0.01
180	1.03±0.02	2.94±0.02	1.96±0.02	2.08±0.02

After 180 days the order of performance of red sheets from best to worst at Mlolongo was 1, 3, 4 and 2. This revealed that red coated sheet from manufacturer 1 was still the superior product for roofing applications. However, fade increased for red sheets from manufacturer 1 and 2 in Mlolongo than in Mariakani. This could be attributed to effect of higher sulphate pollution around Mlolongo from surrounding industries rather than climatic effects. Fade decreased on red sheets from manufacturer 3 and 4 attributable to effect of higher temperature (26.0^0C), precipitation (83.1 mm) and relative humidity (65.9%) at Mariakani than Mlolongo.

Table 4.19: Fade for pre-painted green sheets at Mariakani test site for 180 days exposure

	Fade (Hunter units)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	No sample was available
90	0.32±0.01	9.76±0.01	7.10±0.02	
180	0.45±0.01	11.21±0.03	8.34±0.02	

After 180 days the order of performance of green color from best to worst at Mariakani was 1, 3 and 2. This revealed that green coated sheet from manufacturer 1 was a much better product for roofing as shown in Table 4.19. Extremely higher fade values of green sheets for manufacturer 3 and 2 could be attributed to inhomogeneity of paint components (pigment, solvent and additives) and primer applied, poor pre-treatment and paint baking conditions during manufacturing process.

Table 4.20: Fade for pre-painted green sheets at Mlolongo test site for 180 days exposure.

	Fade (Hunter units)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	No sample was available
90	0.67±0.01	1.42±0.02	3.66±0.01	
180	0.79±0.02	2.71±0.02	3.91±0.02	

After 180 days the order of performance of green sheets from best to worst at Mlolongo was 1, 2 and 3. This revealed that green sheet from manufacturer 1 was again the best roofing product. However, sheets from manufacture 2 and 3 did not show a wide difference in fade as was the case at Mariakani. Fade for green sheet from manufacturer 1 was higher at Mlolongo than at Mariakani. This could be due to effect of sulphate pollution from industries and burnt fuel from vehicles passing along highway near the site. However, fade on sheets from manufacturer 2 and 3 were much lowered at Mlolongo than Mariakani. This could be attributed to effect of low temperature (19.0ºC), precipitation (69.2 mm) and relative humidity (65.0 %).

Table 4.21: Fade for pre-painted blue sheets at Mariakani test site for 180 days exposure

	Fade (Hunter units)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
90	0.75±0.01	0.35±0.02	0.72±0.01	0.71±0.02
180	0.89±0.02	1.15±0.02	1.09±0.02	1.53±0.02

After 180 days the order of performance of blue sheets from best to worst at Mariakani was 1, 3, 2 and 4 as shown in Table 4.21. Therefore blue sheet from manufacturer 1 was still superior product for roofing applications. Higher fade values of blue sheets for manufacturer 3, 2 and 4 could be attributed to the type of bulk paint components (pigment, solvent and additives) , primer which was applied, chemicals (and their concentrations) used for pre-treatment and optimum paint baking conditions in the oven during manufacturing process.

Table 4.22: Fade for pre-painted blue sheets at Mlolongo test site for 180 days exposure.

	Fade (Hunter units)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
90	0.49±0.01	1.06±0.02	1.47±0.01	0.74±0.01
180	0.51±0.02	2.44±0.03	1.92±0.02	1.69±0.01

After 180 days the order of performance of blue sheets from best to worst at Mlolongo was 1, 4, 3 and 2. Blue sheet from manufacturer 1 was still the best roofing material as seen in Table 4.22. At Mlolongo, blue sheet showed low fade than at Mariakani, attributable to low values of climatic factors (temperature (19.0^{0}C), precipitation (69.2mm) and relative humidity (65.0%)) at Mlolongo. However, fade increased on sheets from manufacturer 4, 3 and 2 at Mariakani than Mlolongo. This could be due to effect of climatic factors (higher temperature (26.0^{0}C), precipitation (83.1mm) and relative humidity (65.9%)) but noticeable effect on sulphate pollution from industries surrounding Mlolongo site.

4.5 Gloss for pre-painted samples in Mariakani and Mlolongo test site.

The gloss values for pre-painted sheets after 180 days are given in Tables 4.23-4.28. The higher the difference from zero gloss (%) the lower the quality of a pre-painted sheet.

Table 4.23: Gloss for pre-painted red sheets at Mariakani test site for 180 days exposure.

	Gloss (%)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
90	-3.0±0.1	-9.0±0.1	-6.2±0.2	-0.3±0.1
180	-0.8±0.1	-12.3±0.1	-2.1±0.0	-15.6±0.1

After 180 days the order of performance of red sheets from best to worst at Mariakani was 1, 3, 2 and 4. This confirmed that red coated sheet from manufacturer 1 was a superior product in Mariakani (industrial marine environment). However, red sheet from manufacturer 4 lost most gloss thus became most rough and not suitable for roofing applications in industrial marine environment. This could be attributed to chloride attack from nearby ocean, higher temperature (26.0^{0}C), precipitation (83.1 mm) and relative humidity (65.9%).

Table 4.24: Gloss for pre-painted red sheets at Mlolongo test site for 180 days exposure

	Gloss (%)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
90	-0.2±0.1	-4.1±0.2	-0.2±0.1	-4.1±0.2
180	-0.8±0.2	-7.3±0.2	-1.7±0.2	-6.5±0.3

After 180 days the order of performance of red sheets from best to worst at Mlolongo was 1, 3, 4 and 2. Gloss for red sheet from manufacturer 1 was again revealed as superior roofing product as shown in Table 4.24. However, gloss loss for red sheets at Mlolongo were lower this could be due to lower temperature (19.0^{o}C), precipitation (69.2mm) and relative humidity (65.0%)) at Mlolongo and surface attack by sulphate pollution at the site. Therefore, red sheets, performed better at Mlolongo (industrial urban environment) than at Mariakani (industrial marine environment).

Table 4.25: Gloss for pre-painted green sheets at Mariakani test site for 180 days exposure.

	Gloss (%)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	No sample was available
90	-2.2±0.1	-3.8±0.1	-5.4±0.2	
180	-2.3±0.2	1.8±0.1	2.2±0.1	

After 180 days the order of performance of green sheets from best to worst at Mariakani was 2, 3 and 1 as shown in Table 4.25. Therefore, green sheet from manufacturer 2 was a better roofing product. However, overall gloss variation (-2.3±0.2 %) revealed that green sheet from manufacturer 1 best withstood higher climatic effects (temperature(26.0ºC), precipitation (83.1mm) and relative humidity (65.9 %)) and chloride spray from Indian ocean than those from manufacturer 2 and 3.

Table 4.26: Gloss for pre-painted green sheets at Mlolongo test site for 180 days exposure.

	Gloss (%)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	No sample was available
90	-3.8±0.3	-5.8±0.3	-3.5±0.1	
180	-3.5±0.2	-5.9±0.1	-4.7±0.2	

After 180 days the order of performance of green sheets from best to worst at Mlolongo was 1, 3 and 2. Green sheet from manufacturer 1 proved to be a superior roofing product. However, all green sheets showed higher gloss loss at Mlolongo than Mariakani. This could be attributed to increased attack of the sulphate to the green pigment at Mlolongo rather than climatic effect contributions.

Table 4.27: Gloss for pre-painted blue sheets at Mariakani test site for 180 days exposure.

	Gloss (%)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
90	-2.3±0.1	-8.5±0.1	-5.8±0.2	0.0±0.0
180	-2.1±0.2	-4.7±0.1	-2.1±0.3	-5.0±0.1

After 180 days the order of performance of blue sheets from best to worst at Mariakani was 1 and 3, 2 and 4 as seen in Table 4.27. This showed that blue sheet from manufacturer 1 was of better quality in roofing applications at Mariakani. As time increased gloss decreased then increased for sheets from manufacturer 1, 2 and 3. However, gloss for sheets from manufacturer 4 decreased with increase in time. These general variations could be attributed to difference in properties of components of the blue paints used, oven conditions and the effects of higher values of climatic factors (temperature (26.0ºC), precipitation (83.1mm) and relative humidity (65.9%)) at Mariakani.

Table 4.28: Gloss for pre-painted blue sheets at Mlolongo test site for 180 days exposure.

	Gloss (%)			
Time (Days)	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
0	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
90	-0.2±0.1	-4.1±0.2	-0.2±0.1	-4.1±0.2
180	-0.8±0.2	-7.3±0.2	-1.7±0.2	-6.5±0.3

After 180 days the order of performances of blue sheets from the best to worst at Mlolongo was 1, 3, 4 and 2 as shown in Table 4.28. Blue coated sheet from manufacturer 1 was therefore confirmed a superior sheet for roofing applications. At Mlolongo however, gloss loss was increased as compared to Mariakani for all blue sheets from manufacturers 1, 2, 3 and 4. This could be attributed to higher sulphate pollution from industrial flue gases (sulphur oxides majorly) and exhaust gases (sulphur oxides and nitrogen oxides) from vehicles passing along a busy highway adjacent to Mlolongo.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The corrosion rates for metallic coated sheets under accelerated tests for 28 days were in the range of 0.345-2.065 mmpy in 0.073% sodium chloride and 0.289% ammonium sulphate mixture. The higher concentration spray (1.000 % sodium chloride and 4.000 % ammonium sulphate mixture) gave 0.408-2.246 mmpy. Increase in concentration of the salt spray increased the corrosion rates of the sheets. Manufacturer 1 had the lowest corrosion rate in both concentrations of salt spray mixtures. The performance of metallic coated sheets decreased in the order of manufacturers 1, 2, 3, 4 and 5.

Fade of the red pre-painted sheets after 56 days in 0.073% sodium chloride and 0.289% ammonium sulphate mixture decreased in the order of manufacturers 1, 3, 4 and 2, while in 1.000 % sodium chloride and 4.000 % ammonium sulphate mixture, fade of red coated sheets decreased in the order of manufacturers 1, 4, 3 and 2. Manufacturer 1 made the best red painted roofing sheet. The study showed that red pre-painted sheets from manufacturer 1 was the best roofing sheet.

Fade of the green pre-painted sheets after 56 days decreased in the order of manufacturers was 1, 2 and 3 for both spray concentrations. Green pre-painted roofing sheet from manufacturer 1 was the best. Fade for the blue pre-painted sheets after 56 days decreased in the order of manufacturers 1, 4, 3 and 2 in both the spray concentrations. This shows that blue sheets from manufacturer 1 were the best roofing sheet.

Gloss for red pre-painted sheets after 56 days exposure decreased in the order of manufacturers' 3, 1, 4 and 2 in 0.073% sodium chloride and 0.289% ammonium sulphate mixture. Higher spray concentration (1.000 % sodium chloride and 4.000 % ammonium sulphate mixture) gave the order of manufacturers 1, 3, 2 and 4. The gloss for green pre-painted sheets after 56 days exposure in terms of performance decreased in the order of manufacturers 2, 3 and 1 in 0.073% sodium chloride and 0.289% ammonium sulphate mixture. In 1.000 % sodium chloride and 4.000 % ammonium sulphate mixture the decreasing order was 1, 3 and 2. The gloss for blue pre-painted sheets after 56 days exposure gave the decreasing order of manufacturers 3, 4, 1 and 2 at low spray concentration. Higher spray concentration gave 1, 3, 2 and 4.

Corrosion rate for metallic coated sheets at Mariakani after 180 days exposure was in the range of 0.019-0.128 mmpy while for Mlolongo was 0.029-0.178 mmpy. At both sites the performance decreased in the order of manufacturers 1,2,3,5 and 4. AZ sheets had lower corrosion rates than GI ones. Higher sulphate pollution from surrounding industries and lower values of climatic factors such as temperature (19.0ºC), precipitation (69.2 mm) and relative humidity (65.0%) could have increased corrosion rate of metallic coated sheets at Mlolongo than at Mariakani.

Fade after 180 days outdoor exposure for red pre-painted sheets from both Mariakani and Mlolongo showed that manufacturer 1 was the best (lowest fade) followed by 3, 2 and 4. Fade for green (at Mariakani) had manufacturer 1 as the best (lowest fade) followed by 3 and 2. At Mlolongo, green sheet from manufacturer 1 was the best (lowest fade) followed by 2 and 3. Fade for blue sheet (at Mariakani) had manufacturer 1 as the best (lowest fade) followed by 3, 2 and 4. At Mlolongo the blue had manufacturer 1 as the best (lowest fade) followed by 4, 3 and 2. In general manufacturer 1 prepared the best red, blue and green pre-painted sheets.

Gloss for red pre-painted sheets after 180 days outdoor exposure showed that sheets from manufacturer 1 was the best (lowest gloss change) followed by 3, 4 and 2 at Mariakani while Mlolongo’s order was 1, 3, 4 and 2. Gloss for green sheets at Mariakani and Mlolongo was in the order of 2, 3, 1 and 1, 3, 2 respectively. Gloss for blue pre-painted sheets for manufacturer 1 was the best (lowest gloss change) followed by 3, 4 and 2 for Mariakani while for Mlolongo the order was 1, 3, 4 and 2.

5.2 RECOMMENDATIONS

1. Atmospheric corrosion study on the metal coated and pre-painted steel roofing sheets be conducted in severe marine e.g. Mombasa and rural environments.
2. Atmospheric corrosion experiments be set up for at least two years to get better results.
3. Information from this study could be used to create awareness on the effects of atmospheric corrosion and to help manufacturers improve the quality of roofing sheets

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APPENDICES

APPENDIX 1: Calculation of corrosion rates for accelerated tests

According to Hongwei *et al.*, (2015) the following expressions were used in the calculation of corrosion rates

(i) $m_l = m_i - m_f$

Where;

m_l = Coating mass loss (grams per square metre, gsm)

m_i = Initial coating mass (grams per square metre, gsm)

m_f = Final coating mass (grams per square metre, gsm)

(ii) $C_r = \frac{Km_l}{ADT}$

Where;

C_r = Corrosion rate (millimetres per year, mmpy),

m_l = Coating mass loss (grams per square metre, gsm)

K= Constant (=8.76×10^4)

A= Area of sheet (square metre)

D= Density of coat (=3.75gram per cubic centimetre)

T= Time (hours)

Example:

Calculation of corrosion rate (mmpy), for AZ sample from manufacturer 1 in a mixture of 0.073% sodium chloride and 0.289% ammonium sulphate for 28 days (672 hours) under accelerated test (mass loss is given in Table 4.1)

$$C_r = \frac{8.76\times\ 10^4 \times 1.117}{150\times 75\times 10^6 \times 3.75\times 672}$$

$C_r = 0.345$ mmpy

APPENDIX 2: Calculation of corrosion rates for outdoor exposure tests

According to Hongwei *et al*., (2015) the following expressions were used in the calculation of corrosion rates of metallic coated samples under outdoor exposure tests;

(i) $m_l = m_i - m_f$

Where;

m_l = coating mass loss (grams per square metre, gsm)

m_i = Initial coating mass (grams per square metre, gsm)

m_f = Final coating mass (grams per square metre, gsm)

(ii) $C_r = \frac{Km_l}{ADT}$

Where;

C_r = Corrosion rate (millimetres per year, mmpy),

m_l = Coating mass loss (grams per square metres, gsm)

K= Constant (=3,650)

A= Area of sheet (square centimetre)

D= Density of coat (=3.75 gram per cubic centimetre)

T= Time (days)

Example:

Calculation of corrosion rate (mmpy), for AZ sample from manufacturer 1 at Mariakani for 180 days under outdoor exposure tests (mass loss is given in Table 4.15)

$$C_r = \frac{3,650 \times 0.880}{190 \times 130 \times 10^2 \times 3.75 \times 180}$$

$C_r = 0.019$ mmpy