



Corrosion Resistance of Hot Dip Galvanized Coatings

The life of a hot dip galvanized coating is more or less proportional to its thickness in a given environment. (Table 2).

Hot dip galvanized coatings on steel protect against corrosion in two ways:

- 1 - Barrier protection is provided by a virtually non-porous film which isolates the steel substrate from corrosion inducing substances in the surrounding environment.
- 2 - Cathodic or sacrificial protection is provided at small uncoated surfaces while corrosion creep under the surrounding coating cannot occur.

The corrosion rate of zinc is low in most environments. This is due to the natural formation of a stable protective film of zinc conversion products which develops on the surface of the coating.

12.1 THE CORROSION TEST

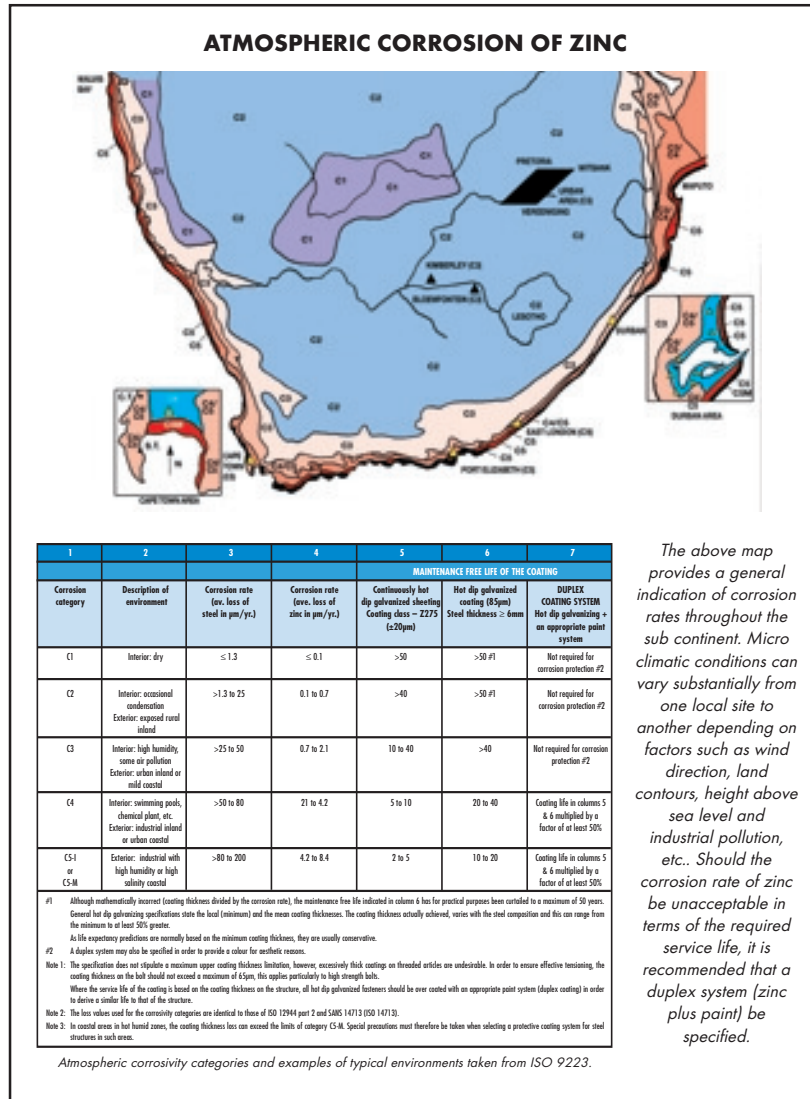
Summary

The selection of coatings for corrosion resistance is a process which normally combines practical experience and scientific knowhow. One aid in the process is the corrosion test.

Testing the corrosion resistance of materials is necessary in order to identify materials, coatings, and designs that will help prevent corrosion damage. However, these tests can be confusing and even misleading if they are not



Figure 85. Exposed surface of a hot dip galvanized coating with outer layer of pure zinc. The shiny surface disappears to be replaced by grey corrosion products (sometimes called zinc patina).



The above map provides a general indication of corrosion rates throughout the sub continent. Micro climatic conditions can vary substantially from one local site to another depending on factors such as wind direction, land contours, height above sea level and industrial pollution, etc.. Should the corrosion rate of zinc be unacceptable in terms of the required service life, it is recommended that a duplex system (zinc plus paint) be specified.

Figure 86. Map showing atmospheric corrosion rate of mild steel and pure zinc coatings in South Africa. CSIR Data. Areas C1 to C5 are more or less in terms of SABS ISO 14713.

understood and conducted properly.

Standardised Tests

Many types of corrosion tests have been developed. Some are standardised tests spelled out by associations such as ASTM or the National Association of Corrosion Engineers (NACE). Others are in-house tests designed to simulate actual field conditions.

Standardised tests have the advantages of reproducibility and general acceptance. These tests have usually been evaluated in a number of locations

(round-robin testing) to verify that results are not affected by local conditions.

So many factors affect corrosion, however, that these standardised tests may not adequately simulate field conditions. For example, one of the most commonly used tests for corrosion resistance is the ASTM-B117 salt spray test. Results of this test are still frequently quoted in automotive product specifications, although the test has virtually been dismissed by auto manufacturers, primarily because it shows that zinc coated steel does not perform as well in an automotive environment as plain



Figure 87. Discoloured surface on lighting column. Coating consists mainly of an iron/zinc alloy that grows out to the surface. Iron is freed during corrosion, which leads to rust formation. It is only surface rust and is of aesthetic significance only. The bracket for the traffic sign has a coating of pure zinc as an outer layer.

cold-rolled steel. Field experience has proven the opposite to be true.

Electrochemical tests are appealing because of their precision. By immersing electrodes made of the materials being evaluated in the electrolyte that the materials will be exposed to in service, a galvanic cell is created similar to that in a battery. Because corrosion is an electrochemical process, the measured potential and current flow between electrodes can be correlated with corrosion rates. However, these tests do not necessarily reflect actual service conditions, such as when the materials are alternately wetted and dried. Without valid parameters, results from electrochemical tests can be misleading as any other corrosion test.

Another common mistake in corrosion testing is to try to extrapolate long-term data from short-term tests, or to rely on data from a single sample. If the corrosion process does not reach steady state during the test, then results can be misleading. Use of several specimens is also recommended to get a good statistical sampling.

12.2 CORROSION RESISTANCE IN THE ATMOSPHERE

When a hot dip galvanized article is withdrawn from the molten zinc, the coating surface immediately reacts with oxygen and moisture to form combinations of both zinc oxide and zinc hydroxide.

Carbon dioxide in the atmosphere rapidly converts these surface conversion products into a stable, tightly adhering, basic zinc carbonate film with very low solubility. This ensures that further attack of the underlying zinc is prevented. The initial shiny surface with a metallic lustre disappears to be replaced by a matt, light grey appearance (figure 85).

The atmosphere contains greater or lesser corrosive substances such as chlorides, in marine environments and sulphur dioxide associated with industrial pollution. Humidity levels, rain patterns and condensation all influence the degree of corrosion. The different factors can occur in favourable or unfavourable sequences, one after another, alternately, or in combination with each other.

It is normal to differentiate between corrosion rates in:

1. rural environments
2. marine (coastal) environments
3. urban environments
4. industrial environments

(See figure 86 for atmospheric corrosion of zinc).

The atmosphere in cities and industrial areas contains various pollutants. These are able to attack the stable zinc carbonate film producing more soluble products which can be washed away. Consequently the corrosion rate of galvanized steel will accelerate. Modern environmental controls are resulting in lower pollution levels and hot dip galvanizing offers good protection in locations where previously limited coating life was experienced.

In marine environments the corrosion of zinc is influenced by the salt content of the air. However, marine air contains small quantities of magnesium salts, with good passivating influences. Corrosion is therefore not as great as

may be expected. The salt content of the air usually diminishes rapidly away from the coastline i.e. by 80% over the first 800m from the high water mark.

The colour of zinc corrosion products varies according to the environment in which they are formed. Marine environments give somewhat whiter corrosion products compared with rural and urban environments. Corrosion products are usually darkest in urban environments.

The corrosion of zinc is influenced by many factors. This means that a generally applicable formula for corrosion rates can not be given.

The ubiquitous nature of hot dip galvanizing means that there is always a product such as a lamp post or fence near a proposed future site that can be used to predict future performance.

The Hot Dip Galvanizers Association have frequently been involved in the assessment of the corrosive conditions prevailing at a particular site, prior to the selection of the final coating specifications. Knowledge about the corrosion of zinc, and corrosion rates in different environments, is therefore extensive.

Reddish-Brown Discolouration

Some hot dip galvanized steel can adopt a reddish-brown colour after a period of exposure. After prolonged exposure, particularly in sulphur-rich atmospheres, this discolouration can gradually turn black. The discolouration occurs mainly on coatings consisting largely of iron/zinc alloys on silicon-killed steels.

The source of discolouration is the corrosion of Fe/Zn alloy to form rust in the presence of humid air or rain water. Rust has a great ability to stain, and even small amounts can cause considerable discolouration.

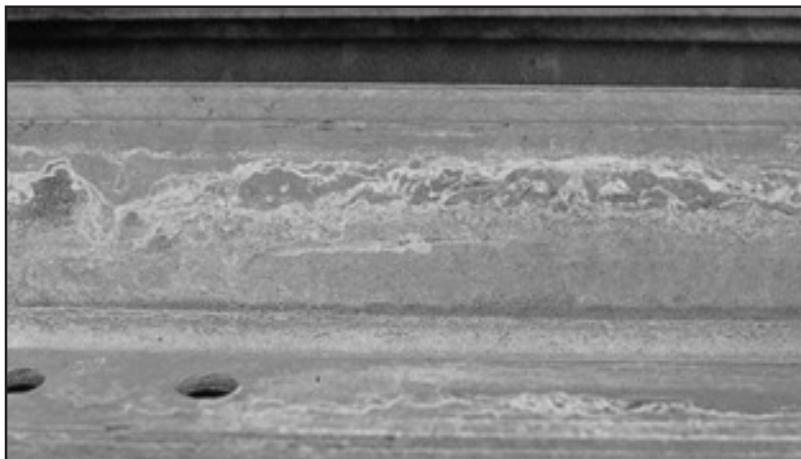


Figure 88. Wet storage stain that has formed between tightly packed angles.

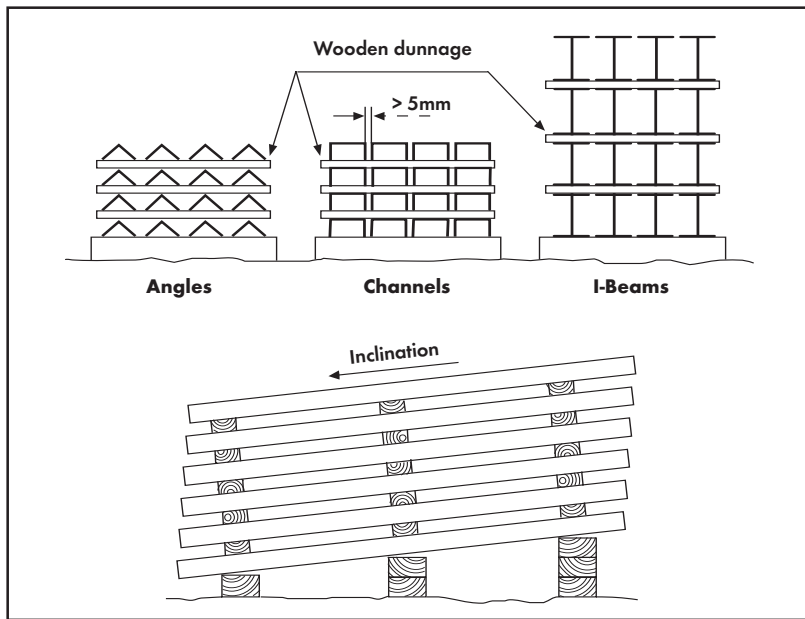


Figure 89. In order to avoid the formation of wet storage stain on newly galvanized surfaces, profiled steel, beams and structures should be packed at an angle and turned to prevent the accumulation of water. Spacers are placed so as to avoid narrow crevices between the zinc surfaces.

Electro-positive end - more noble metals	↑	Gold
		Silver
		Stainless steel (304)
		Nickel
		Monel
		Aluminium bronze (95% Cu, 5% Al)
		Copper
		Brass
		Tin
		Lead
Electro-negative end - more reactive metals	↓	CAST IRON, unalloyed
		CARBON STEEL
		Cadmium
		Aluminium
		ZINC
		Magnesium

Table 24. Electrochemical potential scale in sea water at +25°C.



Figure 90. Galvanized bolt in contact with 3CR12 plate after 10 cycle SO₂ test. Note the cathodic protection provided by the galvanized bolt head to the surrounding steel.

shiny surfaces and particularly between closely packed sheets, angles and similar products. A pre-requisite is that the material is exposed to condensate or rain water in conditions where the moisture cannot evaporate quickly. Zinc surfaces that have already formed a normal protective layer of conversion products are seldom attacked.

When freshly galvanized surfaces are exposed to the atmosphere, soluble zinc oxide and zinc hydroxide are formed. Under the influence of carbon dioxide in the air basic zinc carbonate is formed. If air access to the zinc surface is restricted, as in narrow crevices, then the area receives insufficient carbon dioxide to enable the normal layer of zinc carbonate to form.

The wet storage stain deposit is voluminous and porous, and attached only loosely to the zinc surface. As a result, protection against continued attack does not exist. Corrosion can therefore continue as long as moisture remains on the surfaces. When wet storage stain has occurred the object should be re-stacked to enable the surfaces to dry quickly. This will stop the attack and, with free access to air, the normal protective layer will be formed. The wet storage stain is gradually washed away and the coating acquires an appearance that is normal for exposed, hot dip galvanized steel.

Since the product of wet storage stain is very bulky (about 4.5 times the solid volume of zinc from which it is formed), an attack can appear to be serious.

Sometimes when discolouration is severe it is natural to conclude that rust protection has been greatly reduced, or completely destroyed. However, this is seldom the case. The iron/zinc alloys give better protection (in most environments up to 30-40% greater) to the underlying steel than pure zinc.

If appearance is important, discoloured surfaces can be painted (figures 30, 31 and 87).

12.3 WET STORAGE STAIN

Sometimes a white, flourey and voluminous deposit called wet storage stain, or white rust, appears on galvanized surfaces (figure 88).

The deposit forms on freshly galvanized,

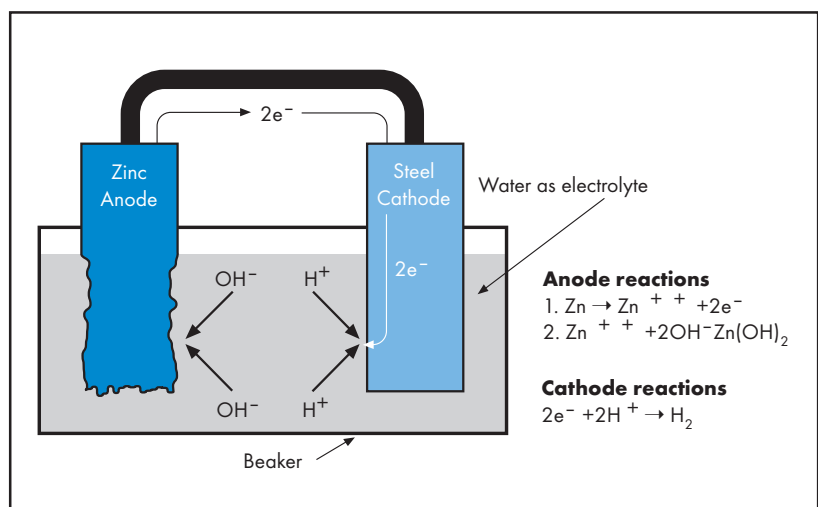


Figure 91. Galvanic corrosion of zinc in contact with steel in water.



Figure 92. After 20 years of marine exposure, this site cut unrepaired hot dip galvanized steel grating still offers cathodic protection at the cut ends.

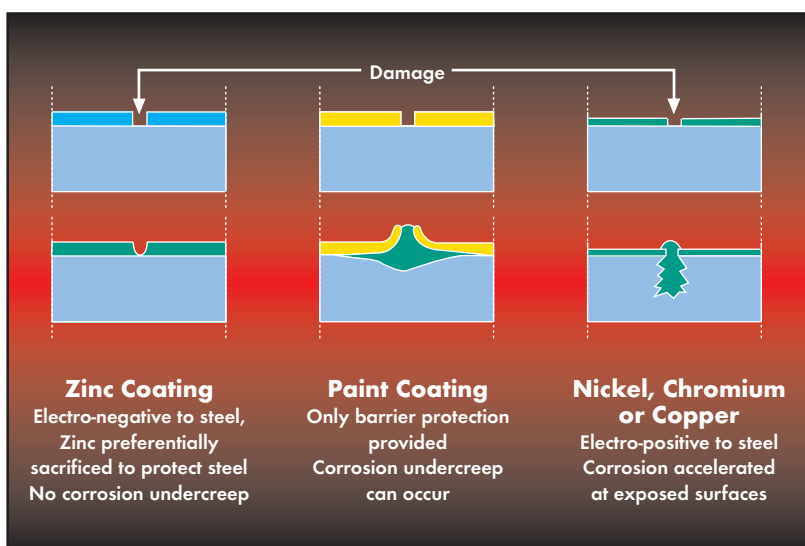


Figure 93. Schematic diagram to illustrate the consequences of damage to different types of coatings offering corrosion protection.

However, wet storage stain often has little or no significant impact on the service life of the coating but in the case of very thin coatings a severe attack of wet storage stain can be significant.

Wet storage stain is best avoided by preventing closely packed galvanized surfaces from coming into contact with rain or condensate. Freshly galvanized material which is exposed to the elements should be stacked in a manner that ensures free air circulation (figure 89). Temporary protection against wet-storage stain is obtained through chromating or phosphating.

Wet storage stain which has already formed can be removed completely or partially by moderate mechanical or

chemical treatment. See "Removal of Wet Storage Stain" page 17.

12.4 GALVANIC OR BIMETALLIC CORROSION

Corrosion can be defined as an electrochemical process. Galvanic or bimetallic corrosion occurs when two different metals or alloys in the presence of an electrolyte, are in direct electrical contact with each other. Basic corrosion theory states that for corrosion to take place, there are four essential requirements, i.e. an anode, a cathode, an electrolyte and an electrical circuit. If one of these is absent, corrosion ceases. Different metals possess different electrochemical potentials as shown in Table 24. The electronegative and more reactive met-



Figure 94. Stainless steel fasteners attached to hot dip galvanized plate in immersed conditions, note the sacrificial attack of the zinc coating surrounding uninsulated fasteners compared with the insulated fastener where no attack of the surrounding zinc has taken place.

als will corrode in preference to a more electropositive metal when the two are in direct electrical contact, i.e. the anode is attacked whereas the cathode is protected. The electrical potential scale of some metals may vary, depending on the electrolyte but the information contained in table 24 which relates to sea water is typical for most liquids.

If steel is in direct contact with copper or brass, it constitutes the anode and it will be preferentially attacked. On the other hand, if steel is coupled to cadmium, aluminium, zinc or magnesium, it will constitute the cathode and be protected, while the anodic material is consumed.

A hot dip galvanized coating primarily provides barrier protection since in most environments it corrodes at a substantially slower rate than steel. The second line of defense is however the cathodic or sacrificial protection at small uncoated surfaces which is provided by the electronegative potential of zinc in relation to carbon steel.

The impact of bimetallic corrosion can be prevented by the provision of a paint

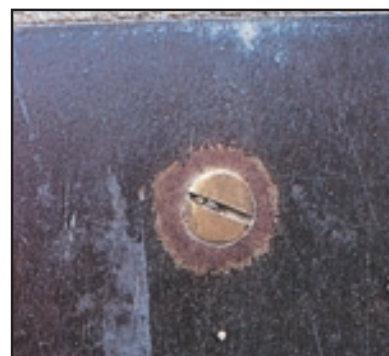


Figure 95. Brass bolt in hot dip galvanized steel on a parking deck.

or other insulating material between the dissimilar metals.

The concept of sacrificial protection is harnessed to provide cathodic protection to structures subjected to severe corrosive conditions such as immersion in aggressive water or corrosive soils. Zinc or magnesium anodes are attached to steel components to provide protection to the steel. These sacrificial anodes are replaced once they have been consumed.

Crevice corrosion can occur in conditions of high humidity at overlapping hot dip galvanized surfaces. This can be prevented by the application of an inhibitive jointing compound in accordance with SANS 1305. Alternatively a suitable paint may be used. Hot dip galvanized surfaces in contact with other materials also require insulation.

Hot dip galvanized components in contact with aluminium conductors may require the use of an electrical conducting compound at joint faces to repel moisture and inhibit corrosion.

12.5 CORROSION RESISTANCE OF HOT DIP GALVANIZED COATINGS IN AQUEOUS CONDITIONS

General

Zinc carbonate, the protective film formed over a hot dip galvanized coating, is relatively insoluble in water. However, this stability is restricted to an acid/alkali pH range of 6 to 12.5. Zinc is amphoteric in nature; that is, it forms soluble salts at low and high pH values. This is clearly shown in figure 96.

Notwithstanding the above, water contains numerous dissolved salts as well as

carbon dioxide and oxygen in solution. Organic matter can be picked up by water as it passes over vegetation. This can also be a major contributor to corrosion in some instances. The effects of water quality on the corrosion rate are summarized in figure 97.

In soft waters, zinc corrosion is accelerated. Also, the tolerance for chloride salts is reduced. A reserve alkalinity level is required to stabilize the zinc carbonate film. This is generally assumed to be of the order of 50 - 75mg/l (as CaCO₃). In hard waters, high chloride levels (>2000mg/l) can be tolerated. Sulphates, nitrates and phosphates are generally considered to be protective towards hot dip galvanizing. However, when combined with ammonia compounds (such as with fertilizers) soluble zinc compounds may be formed and acid conditions can arise causing attack of hot dip galvanized steel. Organic compounds such as tannins will arrest the corrosion of hot dip galvanized steel but the settling of solids can create conditions for crevice corrosion. Similarly, slime build-up should be avoided as microbially induced corrosion (MIC) can occur, leading to rapid attack.

Flow rates should be maintained at sufficiently high levels to ensure that all debris is held in suspension rather than allowed to settle. It should be considered "good practice" to flush systems on a regular basis. This should be carried out on all fire protection systems although, as the water entering these systems is generally of good quality, corrosion rates tend to be low provided that MIC does not occur. In all instances, the corrosion performance of galvanized piping in fire protection systems

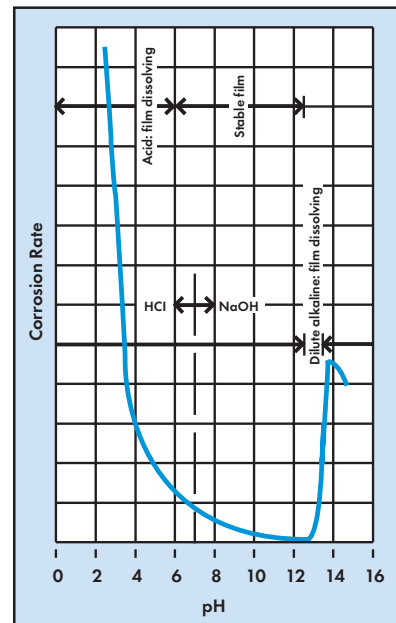


Figure 96. The influence of pH on the corrosion rate of zinc in aerated (CO₂ free) solutions. (Dilute HCl and NaOH at 30°C).

Note: The curve only applies for continuous exposure under the specific conditions. For other conditions it can be used as a guide. In hard/scale forming waters protective layers are formed which greatly alter the curve.

is far superior to that of bare steel. Crevice or under deposit corrosion is likely to occur where sediment becomes dense and compacted. This may result in the provision of anaerobic sites suitable for the start of MIC.

Under normal circumstances the amount of dissolved oxygen in a water would be sufficient to ensure that no deleterious effects occur. However, anaerobic or septic conditions can affect hot dip galvanized piping adversely as is the case with other metals. For drinking water purposes some form of chlorination is generally applied. Therefore, in normal distribution systems anaerobic conditions giving rise to MIC, should not occur. It is important when testing water lines that clean water be used **and the system drained if it is to be left unused for some time.** Chlorination has no effect upon the protective properties of galvanizing. High oxygen levels accelerate the corrosion rate of zinc. Similarly, high carbon dioxide levels tend to produce acid conditions, which can accelerate corrosion in flowing systems.

Effect of water temperature

Hot dip galvanized piping has been used for hot water supplies with no deleterious effects in many applications. However, when used above 65°C the zinc is no longer protective to exposed steel. It is therefore recom-

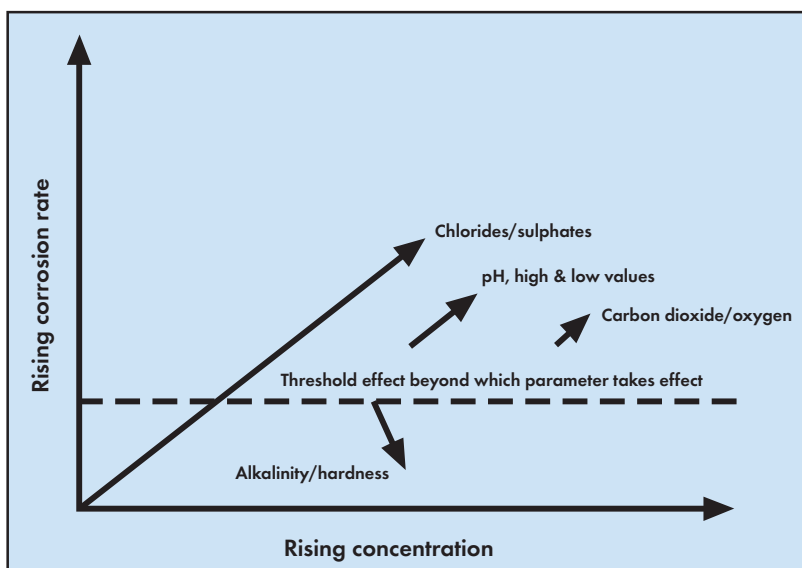


Figure 97. Effects of water quality on the corrosion rate of a hot dip galvanized coating.

No.	Aggressiveness	Soil Condition	Resistivity in ohm	Method of protection
1	low	dry	>100	Hot dip galvanizing > 200µm
2	low	moist	>450	Hot dip galvanizing > 200µm
3	moderate	dry	<100	Hot dip galvanizing > 200µm plus a rust allowance on the basis material of 0.5mm on each side.
4	moderate	moist	150-450	Same as for 3
5	high	moist	50-150	Hot dip galvanizing > 200µm and rust allowance of 1 mm on each side.
6	very high	moist (In certain cases H ₂ SO ₄ can form)	<50-100	Same as for 5 but rust allowance of 1.5mm on each side

Table 25. Soil aggressiveness at different resistivity levels with hot dip galvanized coatings.

mended that hot dip galvanized systems not be used above 65°C.

The electricity supply commission (Eskom), advise that with proper pipe insulation, the maximum temperature for hot water cylinders be 60°C. For practical purposes therefore, hot dip galvanized piping is acceptable for use in both hot and cold water systems.

In domestic systems copper should only be used downstream of hot dip galvanized piping. This will avoid the possibility of pitting corrosion.

Effect of sea water

Hot dip galvanized coatings perform relatively well in submerged seawater conditions which are severely corrosive to most protective systems. Dissolved salts present in seawater react with zinc to form a protective layer minimizing corrosive action. The pH of seawater tends to be constant worldwide as a result of the buffering action of the hydrogen-carbonate salts present. The presence of pollutants is equally not detrimental provided that levels are within internationally acceptable norms.

A simple nomogram (table 27) has been produced to allow the specifier to determine the suitability of hot dip galvanizing for the protection of steel piping in water. This provides guidance based upon the water quality and general operating conditions likely to be encountered. More detailed information is contained in **ARP 060: Guidance on the use and application of hot dip galvanized steel piping for the transportation of potable water in South Africa.**

12.6 CORROSION RESISTANCE OF HOT DIP GALVANIZED COATINGS IN SOIL CONDITIONS

Soil can contain weathered products, free or bound salts, acids and alkalis,

mixtures of organic substances, oxidizing or reducing fungi, micro-organisms, etc.. Depending on its structure, soil has different degrees of permeability to air and moisture. Normally, the oxygen content is less than in the air, while the carbon dioxide content is higher. The corrosion conditions in soil are therefore very complicated and variations can be great between different locations, even those in close proximity to each other.

Southern African soils vary from highly corrosive in some regions to moderately corrosive in others.

One method of determining the corrosivity of a soil is to measure its resistivity. Recommendations are given in table 25.

If the resistivity of the soil cannot be determined, the rule-of-thumb method listed in table 26 can give a measure of guidance. Where the exposure of metals to soil is concerned, it is advisable to seek expert advice from suitably qualified sources.

See also "Guidelines for Buried Hot Dip Galvanized Conveyance Piping" – available from the Association.

12.7 HOT DIP GALVANIZED STEEL IN CONTACT WITH BUILDING MATERIALS

Mortar, Plaster and Wood

Damp mortar and plaster attack zinc. The attack ceases when the material dries out. Dry or moderately damp wood, both impregnated and unimpregnated, can be nailed with hot dip galvanized nails to good effect. However, in the case of nails or threaded unions that are constantly exposed to water an acid-resistant material is preferred. Other dry building materials, such as mineral wool, do not attack zinc.

Wood with acidic properties should not come into contact with galvanized steel.

Soil type	Aggressiveness
Lime, calcareous marl, moraine, sand marl	Low
Sand, gravel	Moderate
Clay, peat, bog, humus-rich soils	High

Table 26. Corrosivity of different soil types.

VALUE	PARAMETER	UNIT	RATING
CONDITION OF WATER			
A	Flowing		2
	Standing		1
	Anaerobic		-5
CORROSION INDEX *			
B	<1		0
	≥1, <2		-1
	≥2, <5		-2
	≥5		-4
TOTAL ALKALINITY			
C	<50	ppm as (CaCo3)	-1
	≥50, <200		1
	≥200, ≤300		0
	>300		-1
CALCIUM HARDNESS			
D	<50	ppm as (CaCo3)	-1
	≥50, <200		2
	≥200		3
pH			
E	<5.5		-6
	≥5.5, <6.5		-4
	≥6.5, ≤7		-1
	>7		1
CALCIUM CARBONATE PRECIPITATION INDEX			
F	<-2		-2
	≥-2, <0		-1
	0		0
	>0, ≤6		1
	>6		0
Probability = Sum (A to F)			
Result	Performance		
Greater than 1	Satisfactory (+25 years)		
1 to -1	Fair		
-3 to -5	Unsatisfactory		
* Corrosivity index (B) can be calculated by - (C1 x 0,03) + (SO ₄ x 0,04)			

Table 27. Probability of performance.

Concrete

Unprotected reinforcement can corrode in certain environments when moisture penetrates the concrete through cracks and pores. Since rust has a greater volume than the steel from which it was formed, the covering layer over the reinforcement can crack and spall (figure 99).

Steel components such as bolts and edge guards that have been partly grouted in are often poorly protected against rust. Apart from crack formation and scaling, a problem occurs with unsightly rust staining on the concrete surfaces below.



Figure 98. Hot dip galvanized reinforcing bars prior to casting concrete, marine conditions.

This kind of damage can be avoided if the reinforcing steel is hot dip galvanized (figure 98). Hot dip galvanized reinforcing steel or mesh can therefore be used in grouted facade sections. One of the advantages of this is that there is no risk of rust runs discolouring the facade.

According to the Building Research Establishment in the UK, the average adhesion for smooth reinforcement steel in concrete is as follows:

hot dip galvanized steel	3.3-3.6 MPa
black steel	1.3-4.8 MPa

The large range for black steel stems from different degrees of rust and compositions of oxide scale.

According to work done in Finland, the stress for 0,1 mm of slip in reinforcement bars in concrete is approximately as follows:

black steel	150 MPa
hot dip galvanized steel	160 MPa
hot dip galvanized and chromated steel	190 MPa

When concrete is cast its pH value is around 13. At this high pH, fresh zinc is attacked and hydrogen is produced, which could give rise to poor adhesion. However, the attack ceases as soon as the concrete has hardened and any residual pores are not harmful.

In order to avoid fresh zinc surfaces coming into direct contact with wet concrete it is advisable to allow the galvanized steel to age for several weeks. The cover layer of basic carbonates which then appears will minimize both attack and the production of gas, and will also promote adhesion. Another common way of

preventing attack from fresh concrete is to chromate the galvanized steel. A further alternative is to add about 40 ppm (by mass) of chromates, to the water when concrete is mixed.

12.8 ABRASION RESISTANCE OF HOT DIP GALVANIZED COATINGS

Pure zinc is a soft metal, even though it is harder than most organic coating materials. The iron/zinc alloys produced in hot dip galvanized coatings are, however, very hard. In fact, they are harder than ordinary structural steel (figure 100).

The alloys are therefore more resistant to abrasion than pure zinc and experiments have shown that the alloy layer has a resistance to abrasion 4-5 times that of pure zinc.

Hot dip galvanized articles are often used when the surface is to be subjected to abrasion. Examples of this include

stairs, floor hatches, hand railings, grid flooring and walkways (figure 5).

12.9 HOT DIP GALVANIZED COATINGS EXPOSED TO ELEVATED TEMPERATURES

Conventional zinc coatings can be exposed continuously to temperatures up to about 200°C and non-continuously to temperatures of up to 350°C.

At sustained temperatures in excess of 200°C a diffusion reaction begins inside the coating and causes the outer layer to split-off from the underlying iron/zinc layer. However, the iron/zinc layer has a very good resistance to corrosion and can, depending on its thickness, protect the steel from rust for a very long time.

Aluminium-alloyed zinc layers on thin sheet can resist even higher temperatures. Aluzinc and galvalume for instance, can withstand sustained temperatures up to 315°C.



Figure 99. Spalling of the concrete layer on reinforcing steel in a concrete bridge balustrade.

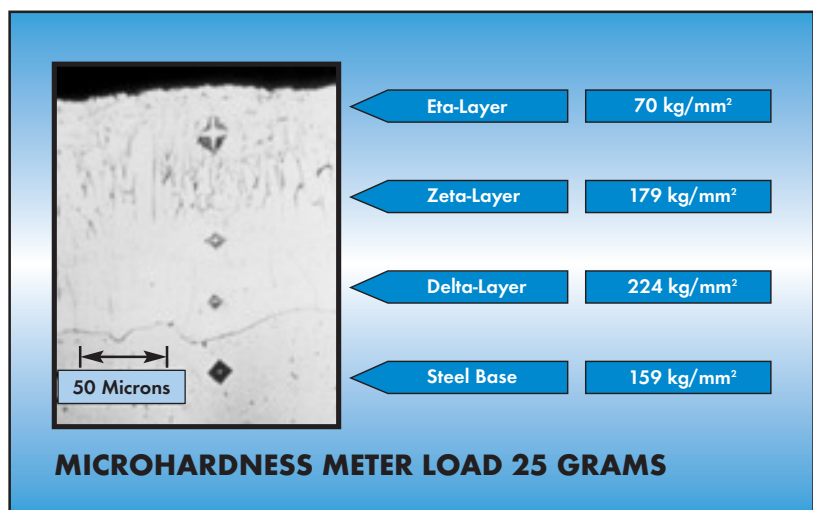


Figure 100. Microsection of a hot dip galvanized coating showing variations in hardness through the coating.