

**CONSTRUCTION OF PILES IN AGGRESSIVE ENVIRONMENTS**

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**ABSTRACT**

The importance of chemical and mechanical investigations of soil and water in laboratory as well as at site for establishing durable foundation work by way of identifying deleterious factors is inevitable for any durable concrete structure. These factors clearly identify the type of the mix design applicable to cope with the aggressive environments under which the piles subjected to be established. An inherent durability problem can be tackled by taking into account the identified deleterious constituents present in the environment in which the piles are to be placed. The paper focuses on the types of possible damages to occur and its remedial measures thereof.

**INTRODUCTION**

Aspects on environments those are indicative about damage causing parameters either of mechanical or chemically aggressive in nature are to be well established for designing a durable pile foundation. The major deleterious environments encountered are chemicals in soil/water, industrial effluents contamination, biological damage and acidic conditions from peaty soils. Both ordinary and reinforced concrete piles are normally subjected to such aggressive environments. The cause, the effect and remedial practices available are briefly discussed in this Paper.



**AGGRESSIVE ENVIRONMENTS**

**Acidic conditions**

Natural ground waters and soils which may be aggressive to concrete due to organic and mineral acids content and dissolved carbon dioxide in pure/very soft mountainous natural waters as they generate acidic conditions. Peaty deposits in marshes, run-off-river schemes in contact with coal deposits and natural waters mixed with manmade contaminants are few examples where acidic environment exists. Such waters leach lime from cement paste and cause durability problems. Low permeability and application of blended cements other than OPC may partially impart resistance against acidic conditions.

**Industrial contaminants**

The major parameters which influence soil contamination are tipping of chemical waste, spillage from mining or acid mine drainage effluents, and other contaminants from processing and manufacturing industries. Mineral

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and organic acids, salts, certain coal tar distillates are few examples which are potentially hazardous to concrete piles durability and are found harmful to piles foundations.

### Biological damage

Principle damage arises from the direct attack by living organisms or from a change in the chemical environment brought about by their metabolic activities. Another form of damage to steel or concrete piles arises from biological origins. There are number of anaerobic and aerobic Bactria which is capable of modifying the chemical environment to give rise to corrosive conditions. For example, sulphate reducing bacteria which remove oxygen from sulphur compounds to produce aggressive ground conditions.

### STANDARD CODES & PRACTICES

The most widely used National and International Standards for assessing the aggressive environments for pile foundations with respect to soil and water and necessary precautionary measures are given blow (Table 1).

*Table 1 : National and International Standards*

SI No.	Country	Standard
1.	American	Concrete Manual (Bureau of Reclamation – 1992)
2.	British	B.R.E. Digest No. 174 (1992) also C.P.110 Part 1 (1972) C.P. 2004 (1972)
3.	West German	DIN 1045 (2008); DIN 1048 (1991) and DIN 4030 (2008)
4.	Indian	IS : 456 - 2000

### STEEL PILES



Coutsy : corrocell.co.uk

Romanoff and his co-workers observed that soil that was otherwise corrosive to iron or steel in excavated trenches did not affect steel piles driven into undisturbed ground. This is due to the low oxygen content in the ground at depth below the surface. Thus corrosion of embedded steel piles is a function of a permeability of the soil, being greatest in the porous material such as sand where in necessary free or dissolved oxygen may be available. The use of steel piles in the marine structures raises the addition issue of the corrosion of the free-standing pile lengths above the soil line. Studies indicate corrosion at the rate of 0.75 mm per year in the temperate waters to something over double this in tropical environments. The corrosive attack on piles in temperate conditions is found to extend from below the soil line to the uppermost limit of the splash zone. In warmer climates the encouragement of the marine growth below the water level may somewhat inhibit the corrosion. Protective measures for steel piling in marine conditions depend on accessibility above tide levels. Concrete encasement may be formed throughout the length of the piles by driving within a tubular casing. Concrete encasement above the tide levels may be carried out by conventional formwork techniques. The use of

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protective coatings for steel piles has to take account of probable damage to them during handling and driving. The addition of small copper content (0.25-0.35%) to steel can be effective protective measures preferably in the atmospheric conditions.

Cathodic protection of steel piles utilizes the principle of depressing the potential of the steel surface to make it cathodic to the surrounding soil and water. This is achieved by introducing artificial metal anodes buried in the ground or immersed in the water in the case of jetty.

### SULPHATES

Sulphates in solution attack concrete and cause expansion, deterioration and eventual disintegration. In early stages of attack, there is a little visual evidence of any change in the concrete, though there may be some reduction in strength as the chemical reaction proceeds. This is accompanied by slight expansion, which may be apparent in the concrete itself, but may cause trouble at points of restraints. The rate of attack depends on a number of factors.

The higher the concentration of sulphates in solution, the attack increases. The severity of attack is increased as the sulphate bearing water brings a continuous supply of the salts in contact with concrete. If the pH value of the water and soil is below 6.0, i.e. acidic, the rate of attack is likely to be increased. Temperature plays an important role too as the rate of attack increases as the temperature increases. Moderately impermeable concrete is only attacked on surface; therefore, the deterioration is slow. However, in the permeable concrete particularly when one side is in contact with moist soil containing sulphates while the other side is open to air so that the evaporation occurs, or if subjected to a one sided water pressure, the concrete pile is attacked throughout its thickness resulting in an overall expansion and complete disintegration.

There are apparently two chemical reactions involved in sulphate attack on concrete (i) combination of sulphate with free calcium hydroxide (hydrated lime) liberated during the hydration of cement, to form calcium sulphate (gypsum) and (ii) combination of gypsum and hydrated calcium aluminate to form calcium sulphoaluminate (ettringite)  $(3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot3\text{CaSO}_4\cdot32\text{H}_2\text{O})$  mineral which imbibes water and expands. Both of these reactions result in increase in solid volume. The later is generally predominates for most of the expansion and disruption of concrete caused by sulphate solutions. The USBR has recommended a separate classification for sulphate aggression levels. The same is reproduced in Table 2.

*Table 2 : USBR Classification of Sulphate Aggressivity*

Relative degree of sulphate attack	Percent water soluble sulphate (as $\text{SO}_3$ ) in soil sample	Mg/l sulphate (as $\text{SO}_4$ ) in water sample
Negligible	0.00-0.10	0 to 150
Positive (1)	0.10 – 0.20	150 to 1500
Severe (2)	0.20 – 2.00	1500 to 10000
Very severe (3)	2.00 or more	10000 or more

1. Use Type II cement (containing maximum of 8%  $\text{C}_3\text{A}$ )
2. Use Type V cement (containing maximum of 5%  $\text{C}_3\text{A}$ ) or approved combination of Portland cement and pozolana which has been shown by tests to provide comparable sulphate resistance when used in concrete.
3. Use Type V cement plus approved pozolana which has been determined by tests to improve sulphate resistance when used in concrete with Type V cement.

Indian Standard 456 – 2000 (4<sup>th</sup> revision) mentions different requirements for concrete under various sulphate concentrations (Table 3). This code can not be directly used for assessing aggressiveness since it applies to a concrete made with 20mm maximum size aggregate complying with the requirements of IS : 383 – 1970 placed in ground water of pH 6 to 9 containing naturally occurring sulphates but not contaminants such as ammonium salts. For 40 mm maximum size aggregate, the value has to be reduced by about 15% and for 12.5 mm maximum size aggregate, the value has to be increased by about 25%. Concrete prepared from OPC would not be recommended in acidic conditions (pH 6 or less).

*Table 3 : Classification of soil & ground water according to a sulphate content*

Sl No	Class	Concentration of Sulphates, Expressed as SO <sub>3</sub>			Type of cement	Dense, fully Compacted Concrete made with 20 mm Nominal Maximum Size Aggregates Complying with IS 383	
		In Soil		In Ground Water		Minimum cement content kg/m <sup>3</sup>	Maximum Face Water-Cement ratio
		Total SO <sub>3</sub> Percent	SO <sub>3</sub> in 2:1 Water: Soil Extract g/l	In Ground Water g/l			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
i)	1	Traces (<0.2)	Less than 1.0	Less than 0.3	Ordinary Portland cement or Portland slag cement or Portland Pozzolana cement	280	0.55
ii)	2	0.2 to 0.5	1.0 to 1.9	0.3 to 1.2	Ordinary Portland cement or Portland slag cement or Portland Pozzolana cement	330	0.50
					Supersulphated cement or sulphate resisting Portland cement	310	0.50
iii)	3	0.5 to 1.0	1.9 to 3.1	1.2 to 2.5	Supersulphated cement or sulphate resisting Portland cement	330	0.50
					Portland Pozzolana cement or Portland slag cement	350	0.45

**Notes**

1. Cement content given in this table is irrespective of grades of cement
2. Use of supersulphated cement is generally restricted where the prevailing temperature is above 40°C
3. Supersulphated cement gives an acceptable life provided that the concrete is dense and prepared with water-cement ratio of 0.4 or less, in mineral acids, down pH 3.5
4. The cement content given in col 6 of this table are the minimum recommended. For SO<sub>3</sub> contents near the upper limit of any class, cement contents above these minimums are advised.
5. For severe conditions, such as thin sections under hydrostatic pressure on one side only and sections partly immersed, considerations should be given to a further reduction of water-cement ratio.
6. Portland slag cement conforming to IS 455 with slag content more than 50 percent exhibits better sulphate resisting properties.

Where chloride is encountered along with sulphates in soil or ground water, ordinary Portland cement with C<sub>3</sub>A content from 5 to 8 percent shall be desirable to be used in concrete instead of sulphate resisting cement. Alternatively, Portland slag cement conforming to IS 455 having more than 50 percent slag or blend of ordinary Portland cement and slag may be used provided sufficient information is available on performance of such blended cements in these conditions.

Protection against the sulphate attack is obtained by using a dense, high quality concrete with low water-cement ratio. Air entrainment is of benefit insofar it reduces the water-cement ratio. There is fairly good correlation between the sulphate resistance of cement and its tricalcium aluminate (C<sub>3</sub>A) content. Accordingly ASTM C150

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includes a Type V (Sulphate resisting cement) with a maximum limit of 5% C<sub>3</sub>A, and Type II (moderately sulphate resisting) cement which limits the C<sub>3</sub>A to 8%.

Studies have shown that some pozzolans used either in blended cement or added separately to the mixture, in the amount of approximately 15 to 25% of the Portland cement, increase the concrete life in the sulphate exposure considerably.

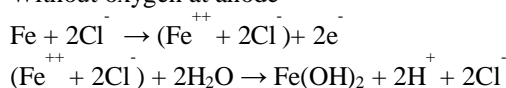
### CHLORIDES

Under the moist conditions, Portland cement concrete provides adequate protection of embedded materials against corrosion (i.e. rusting, oxidation etc.). The protection value of the concrete is attributable to its high alkalinity and relatively high electrical resistivity in atmospheric exposure. The degree to which concrete will provide satisfactory protection is in most instances a function of the quality of the concrete, the depth of concrete cover and degree to which good practices are followed throughout the entire construction operation. The chief cause of damage by chloride is the corrosion of steel in the reinforced concrete leading to cracking and spalling of the concrete cover.

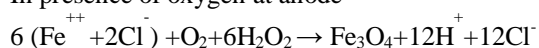
### Corrosion of Reinforcement

The mechanism of corrosion of reinforcement is essentially due to either in stand alone or in combination of factors such as carbonation of concrete, chloride attack and sulphates diffusing into the body of concrete and subsequently coming into contact with reinforcing steel. Chloride attack on reinforcing steel in concrete has been well documented. Chloride ion in mixing and curing water or water soluble chlorides from the atmosphere or ground water or from concrete ingredients, reaches the reinforcing steel. As the water permeability of concrete varies in a given section, there will always be different ionic concentration at the interface of concrete and the embedded steel. This sets in corrosion cells with anode and cathodes at the higher and relatively lowers chloride ion concentration regions respectively. Formation of corrosion cell results in pitting corrosion. As chloride attack is an electro- chemical process, it changes the chemistry of steel affecting the ductility properties of the bars too.

Without oxygen at anode



In presence of oxygen at anode



Chloride acts as catalyst in corrosion of steel and becomes free to take part in corrosion reaction again. Chloride ions break the passivating oxide film formed on steel. External penetration causes differential concentration and setup micro-cells. Presence of salt increases its electrical conductivity. Permissible limit of chloride in OPC 33 and 43 grades used in prestressed concrete structures is 0.05% and overall limit of 0.15% by wt. of cement for plain and reinforced concrete as per IS : 456-2000. While ACI: 318-83 document prescribes different limits of chloride content under different environments (Table 4).

*Table 4 : Chloride limit in ACI document*

Maximum water-soluble chloride ion at an age of 28 days contributed from the ingredients including water, aggregate, cementitious materials and admixture	LIMITS (% by wt. of cement)
Prestressed concrete	0.06
Reinforced concrete exposed to chloride in service	0.15
Reinforced concrete that will be dry or protected from moisture in service	1.00
Other reinforced concrete construction	0.30



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The permeability of concrete is a major factor affecting the process of corrosion of embedded materials. It is also a major factor affecting the service life of the concrete itself. Low water-cement ratio produces less permeable concrete and thus provides greater assurance against corrosion. Good workmanship and adequate curing are the most important factors in securing uniform concrete of low permeability. Other factors include the use of low slump concrete, low w/c ratio, adequate cement content, precaution against aggression, through vibration to ensure good consolidation and good finishing practice. Table 5 gives a general guidelines in respect of cement content and W/C ratio to be adopted for different piles.

**Table 5 : Range of cement contents and water cement ratios in general use for concrete mixes**

Pile type	Normal conditions	Moderately aggressive conditions	High aggressive conditions
Pre-cast	450-475 Kg/M <sup>3</sup> W:C ratio 0.4-0.5	450-475Kg/M <sup>3</sup> W:C ratio 0.4	450-475Kg/M <sup>3</sup> W:C ratio 0.4
Driven cast-in-situ*	280-370 Kg/M <sup>3</sup> W:C ratio 0.25 – 0.6	330-450 Kg/M <sup>3</sup> W:C ratio 0.3 – 0.55	370-500 Kg/M <sup>3</sup> W:C ratio 0.3 – 0.45
Bored or Augured	300-450 Kg/M <sup>3</sup> W:C ratio 0.5 – 0.55	350-450 Kg/M <sup>3</sup> W:C ratio 0.475 – 0.5	380-500 Kg/M <sup>3</sup> W:C ratio 0.43 – 0.5
Tremid under bentonite	350-475 Kg/M <sup>3</sup> W:C ratio 0.5 – 0.6	350-450 Kg/M <sup>3</sup> W:C ratio 0.475 – 0.5	400-500 Kg/M <sup>3</sup> W:C ratio 0.43 – 0.45
• (Includes both standard and vibrated shaft Franki piles)			

### Marine Environment

Concrete in seawater may be deteriorated by freezing and thawing, by corrosion of reinforcement and by chemical influences. Other possible causes of deterioration in sea water include corrosion and wave action and crystallization of salts due to their concentration being increased by capillary action and evaporation particularly in and above the tidal zones. The marine environment can be divided into three zones:

- Atmospheric zone which is above high tidal level (Splash zone), where build up of salt spray, wetting-drying and freeze-thaw cycles can occur.
- Tidal zone also known as inter-tidal zone or splash zone, where the concrete is in a mainly wet state, but intermittently exposed to the air.
- Submerged zone, where oxygen availability for steel corrosion is limited, but where hydrostatic pressure increases with depth resulting in rapid penetration of sea water in concrete.

The extent of deterioration is different in three exposure zones. The embedded zone i.e. zone below the sea bed is sometimes termed as fourth zone. The deterioration phenomena occurring in each zone is shown in Figure 1 and 2.

### PROTECTIVE MEASURES

The coarse aggregates need to be evaluated for durability characteristics by conducting petrographic examination, shrinkage test, alternate wetting and drying test, soundness test etc. apart from carrying out routine investigations. The fine aggregates need to be petrographic examination apart from conducting soundness and other routine physical and chemical tests. The petrographic examination of coarse aggregates will identify the mineral composition of the parent rock. Some basalt rocks when tested using electron microscope under similar environment (Chloride/Sulphate) have been found to be deteriorated within a few days, thus raising doubts on the durability of the basalt rocks under marine environment.

IS : 456 – 2000 (fourth Revision) recommends the following:

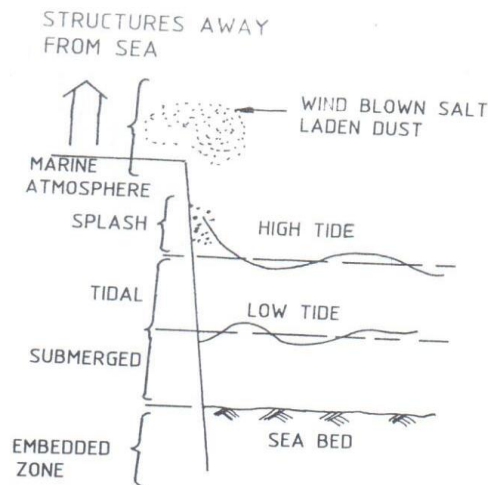


FIG.1 MARINE EXPOSURE ZONES

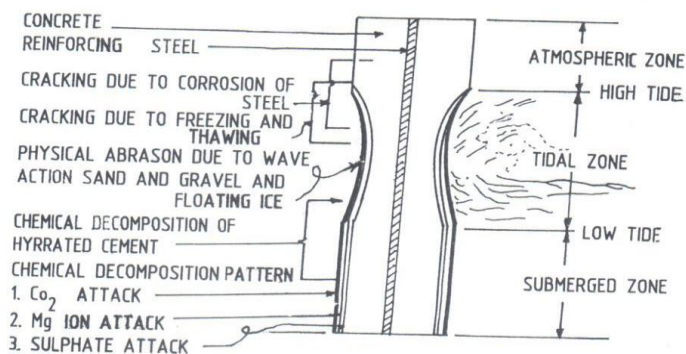


FIG.2 DETERIORATION OF CONCRETE STRUCTURE IN SEA WATER

“Concrete in sea water or exposed directly along the sea-coast shall be of at least M-15 grade in the case of plain concrete and M-20 grade in case of reinforced concrete”. Special attention is required to be given in the design of the mix to obtain the densest possible concrete.

A minimum cement content of  $360 \text{ Kg/M}^3$  is recommended in the non alternate wetting and drying zone. In the splash zone, the minimum cement content shall be  $400 \text{ kg/M}^3$ . This is in the consonance with the recommendation made in the ICOLD Bulletin “Exposure of dam concrete to special aggressive agents”.

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Water-cement ratio is an important parameter in so far as the design of concrete mixes for plain concrete and RCC are concerned. ACI 318 (1988) recommendations for exposure of plain concrete and RCC to special exposure conditions are given in Table 6. As far as possible, preference shall be given to pre-cast members unreinforced, well cured and hardened without sharp corners, and having trowel-smooth surfaces free from crazing, cracks or other defects; plastering should be avoided.

In reinforced concrete structures, care needs to be taken to protect the reinforcement from the exposure to saline atmosphere during storage and fabrication. Calcium chloride as an admixture is not recommended. For corrosion protection, maximum water soluble chloride ion concentration in hardened concrete at ages from 28 to 42 days contributed from the ingredients including water, aggregates, cementitious materials, and admixtures shall not exceed the limits given in Table 4.

**Table 6 : Requirements for special exposure conditions**

Exposure condition	Max water-cement ratio, normal weight concrete
Concrete intended to be water tight:	
a) Concrete exposed to fresh water	0.50
b) Concrete exposed to brackish water or sea water	0.45
For corrosion protection for reinforced concrete exposed to deicing salts, brackish water, sea water or spray from these sources	0.40*

- “When concrete will be exposed to external sources of chlorides in service, such as deicing salts, brackish water, sea water, or spray from these sources, concrete must be proportioned to satisfy the exposure requirements of minimum air content, maximum water cement ratio, minimum chloride ion content and cement type. Additionally, for corrosion protection, a minimum concrete cover for reinforcement of 5.08 cm for walls and slabs and 6.35 cm for other members is recommended for precast concrete manufactured under plant controlled conditions. For the minimum concrete cover is increased by 1.27 cm, water-cement ratio may be increased to 0.45 for normal weight concrete.

Sulphate resistant cement should be used for the manufacture of concrete. The cement should be tested for its quality and also certain important parameters such as chloride and alkali contents. The former (Chloride) is useful for the point of corrosion and the later (alkali) for ASR –alkali silica reaction in concrete. IS:12230-1988 stipulates that the tri calcium aluminate ( $C_3A$ ) content of the sulphate resisting cement shall not be more than 5% by wt. of cement.

Corrosion inhibitors such as usage of sodium nitrite and micro silica have been cited to be useful to reduce attack on the reinforcement. Various coatings for reinforced steel have been suggested as means for preventing or minimizing corrosion. These include metals, such as nickel, zinc (galvanizing) and non metals such as epoxy resins and other organic materials. An application of anti corrosive paints found to be effective apart from cathodic protection for use as anti corrosion techniques. Further, coating of the concrete surface or structural member with asphalt, epoxy resin and polyester resin can be considered as barriers for the entry of aggressive ions.

### CONCLUSION

It is well understood that the physical/chemical properties of soil/water of pile foundations need to be evaluated as per relevant National and International codes. The data obtained thereof coupled with its competent interpretation would help to decide cement type, applicable concrete mix design factors to ensure long term durability of the structure. Application of the anti corrosion techniques especially in aggressive environments provide added safety to durability aspect.





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