Corrosion survey of bridges

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At the instance of the Ministry of Shipping and Transport, (Roads Wing), New Delhi, the Central Electrochemical Research Institute, Karaikudi, undertook a national survey on the corrosion susceptibility of concrete bridges in India. A few representative coastal bridges situated along the east and west coasts were surveyed and investigated using different chemical, physical, electrical and electrochemical techniques. Methodology of investigation is briefly described. A major factor contributing to accelerated corrosion was found to be the atmospheric salinity prevailing at the bridge sites. A chloride content of more than 100mg/m^2/day was found to be quite aggressive. Loss of alkalinity to less than 0.04N around the steel reinforcement and chloride contamination in excess of the tolerable limit of 0.10 percent were the direct contributing factors to rapid reinforcement corrosion. The actual concrete thicknesses provided were generally less than the recommended values for such exposure conditions.

India has a long coastal belt and many of the strategic bridges are situated along the coast. A preliminary survey had indicated that many of these coastal bridges had started showing signs of distress within a reasonably short period. The planning and implementation group of the Bridge Research Scheme-B6 of the Ministry of Shipping and Transport, Roads Wing, Government of India, decided to conduct a national survey of the corrosion damages so far experienced in both inland and coastal bridges with an analysis of the causes of corrosion or absence thereof, to find out the constructional defects and other factors.

A research team from the Central Electrochemical Research Institute (CECRI) visited some selected bridges and conducted on-the-spot investigations, which included:

1. collection of historical and structural details
2. collection of concrete samples for chemical analysis
3. alkalinity and carbonation tests, wherever feasible
4. surface potential and resistance measurements
5. open circuit potential measurements with refek rence to rebar
6. study of atmospheric pollution.

This paper gives the consolidated statement of results of the electrochemical measurements and laboratory analysis of the various bridges surveyed.

Methodology

Surface potential measurements: During corrosion process, an electric current flows between the cathodic and anodic sides through the surrounding electrolyte and this flow can be detected by measurement of potential drop in the electrolyte. Surface potential survey can, therefore, be used as a non-destructive method of detecting corrosion of reinforcement embedded in concrete[1].

Two copper-copper sulphate half-cells or two saturated calomel half-cells are used as electrodes for potential measurements. One half-cell is kept fixed at a suitable place on the structure or on the ground and is known as fixed electrode. The other half-cell is used as a moving electrode and is moved along the surface of the structure. The surface of the structure is suitably marked both vertically and horizontally at 20cm to 30cm intervals. The potential of the movable electrode, when placed at these points, is measured against the fixed electrode using a digital multimeter. The potential between different points along the surface of a reinforced concrete structure is plotted and the contours of the same potential (equipotential contours) are obtained. A more positive surface potential will indicate anodic regions and a more negative surface potential will indicate cathodic regions. The greater the potential difference between anodic and cathodic regions, the greater is the probability of corrosion.

The resistivity values are measured along the surface of the structure in a way similar to potential survey mentioned above and plotted. The lower the resistivity values, the greater is the probability of corrosion. Resistivity of more than 60kilo-ohm-cm may indicate zero-percent deterioration.

Corrosion-cell ratio: Corrosion-cell ratio is the ratio of the maximum potential difference between anodic and cathodic regions to the average resistivity in the anodic region. If the ratio is greater than 5 microamperes, it may be inferred that the embedded reinforcement is undergoing corrosion in the anodic regions[2].

Cover thickness measurements: A proprietary instrument called the PROFOMETER* was used. Measurements are based on the damping of a parallel resonant circuit. An alternating current with a given frequency flows through the probe coil, thus creating an alternating magnetic field. Metal objects within the range of this field alter coil voltage as a function of cover and bar diameter. The position and alignment of metal reinforcement embedded in concrete is determined by systematic scanning of the probe on the surface. The probe is positioned directly over a metal bar when maximum deflection is indicated on the neutral scale of the instrument.

After position and direction of the rebars have been ascertained, thickness of the concrete cover will be known directly, if the rebar diameter is preset.

Depth of carbonation in concrete: The depth of carbonation of the concrete in various parts of the structure was ascertained by using bromo-cresol purple as an indicator. The indicator turns yellow in an acidic medium and violet in an alkaline medium. The depth of yellow colour gives the depth of carbonation.

Alkalinity of concrete[3] : 100g of powdered concrete is shaken with 100cm^3 of distilled water in a conical flask in a microid flask shaker for 1 hour. The extract is then filtered through a Whatman filter paper. Next, 10cm^3 of filtered solution is titrated against N/10 standard acid solution, using methyl orange indicator. The normality of the solution is calculated from the titration.

Table 1. Structural details of the bridges surveyed

Sr. No.	Details	Name of the bridge				
		Taloja	Ekdara	Bavaliary	Devipattinam	Mukkani
1.	Location	Maharashtra (West coast)	Maharashtra (West coast)	Gujarat (West coast)	Tamil Nadu (East coast)	Tamil Nadu (East coast)
2.	Distance from the sea	25km	1km	6km	1km	22km
3.	Year of construction	1973	1964	1974	1976	1954
4.	Year in which distress was noticed	1977	1977	-	1980	1983
5.	Length	134m	90m	170m	130m	235m
6.	Width	7.5m	7.5m	7.5m	7.5m	7.5m
7.	Span arrangement	4 spans of 33.5m each	2 end spans of 26.5m and central span of 35.4m	28 spans of 6m each	42 vents of 3m each	38 vents of 6m each
8.	Foundation	Well foundation Steining of 1:3:6 mix Curb and plug of 1:2:4 mix	Well foundation Steining of 1:3:6 mix Curb and plug of 1:2:4 mix	Reft foundation of 1:4:8	Raft foundation	Well foundation
9.	Substructure	Beam-type short piers and abutments in M 16 mix	-	Plain 1:3:6 mix in piers and abutments with temperature steel	-	Plain c.c. in piers and abutments
10.	Superstructure	Prestressed concrete T-beam and reinforced concrete slab in 1: 2: 4 mix	Prestressed concrete balanced-cantilever beam and slab in 1:2:4 mix	Prestressed concrete solid slab in 1:2:4 mix	Prestressed concrete box	Prestressed concrete slab
11.	Handrails	Reinforced concrete	Reinforced concrete	-	Reinforced concrete	Reinforced concrete

Soluble chloride: A 50cm^3 of filtered solution is taken and the chloride is estimated by silver nitrate titration, using potassium chromate as indicator (Mohr's method).

Soluble sulphate[4] : A 50cm^3 of filtered solution is taken and the sulphate estimated as SO_3 by barium sulphate precipitation method.

Atmospheric pollution: The chloride and sulphur dioxide present in the atmosphere were determined by wet candle method.

Chlorides: The chloride in the atmosphere is estimated by "Salinity candle method". The method is based on the absorption of chlorides present in the atmosphere by the wet gauze, which is then digested with hot distilled water to remove all chlorides. The chloride is estimated volumetrically by Mohr's method[4] .

Sulphur dioxide: The sulphur dioxide candle is covered by means of a gauze cloth containing lead peroxide paste. The sulphur dioxide in the atmosphere reacts with lead peroxide forming lead sulphate. The lead sulphate is made to react with sodium carbonate with the formation of sodium sulphate. The sulphate is precipitated as barium sulphate by the addition of barium chloride.

Results and discussion

Out of the five bridges surveyed, three bridges are located on the west coast and two on the east coast. The names of these bridges are: Taloja and Ekdara creek bridges (Maharashtra), Bavaliary bridge (Gujarat) and Devipattinam and Mukkani bridges (Tamil Nadu). Whilst the distances of these bridges from the sea varied from 1km to 25km, their ages varied from 8 years to 30 years. Different signs of distress had been noticed at different stages in these bridges.

Out of the five bridges, three bridges have been provided with well foundations and two with raft foundations. In the Taloja creek bridge, the substructure consists of beam-type short piers and abutments in reinforced concrete, M16 mix, and the superstructure is in prestressed concrete of T-beam-and-slab type. In the case of Ekdara and Devipattinam bridges, the superstructure directly rests on foundations. A balance dcantilever beam-and-slab type of superstructure has been adopted for the Ekdara creek bridge.

A reinforced concrete solid slab having 1: 2: 4 mix has been used in the Bavaliary creek bridge. The Devipattinam bridge is of reinforced concrete box-culvert type. Reinforced concrete

Table 2. Chloride and sulphate pollution levels at different bridge sites

Sr. No.	Details	Name of the bridge					
		Taloja (before monsoon)	Taloja (after monsoon)	Ekdara (after monsoon)	Bavaliary (during monsoon)	Devipattinam (before monsoon)	Mukkani (after monsoon)
1.	Chloride content in the atmosphere, mg/m^2/day	256	443	200	180	4,254	26
2.	Sulphate content in the atmosphere, mg/m^2/day	217	739	330	310	107	32
3.	Chloride content in the water sample, ppm	-	10,500	-	-	21,360	150
4.	Sulphate content in the water sample, ppm	-	1,338	-	-	3,855	40

Table 3. Observed minimum cover thicknesses, cm, at different bridge sites

Sr. No.	Details	Name of the bridge				
		Taloja	Ekdara	Bavaliary	Devipattinam	Mukkani
1.	Foundation	6	-	-	-	5
2.	Substructure	>12	-	2.5	-	-
3.	Girders:					
	top flange	4 to 5	3.5	-	<2.0	-
	web	4	2.5	-	-	-
	bottom flange	3 to 4	3.2	-	-	-
	soffit	0 to 1.5	-	-	-	-
4.	Cross diaphragm	2 to 3 (0 at one place)	3.2	-	-	-
5.	Deck slab	2 to 3	2.2	2.2	<2.0	<2.0
6.	Handrails	<2.0	2.5	-	<2.0	<2.0

Table 4. Negative open circuit potentials of rebar with reference to saturated calomel electrode, milli Volts

Sr. No.	Details	Name of the bridge					
		Taloja (before monsoon)	Taloja (after monsoon)	Ekdara	Bavaliary	Devipattinam	Mukkani
1.	Foundation	-	-613	-	-	-	-179
2.	Substructure	-42	-	-	-643	-	-
3.	Girders	-96	-283	-189	-	-562	-
4.	Cross diaphragm.	-95	-236	-238	-	-	-
5.	Deck slab	-50	-93	-308	-696	-400	-224
6.	Handrails	-180	-332	-336	-	-159	-397

solid slab type of structure has been provided for the Mukkani bridge. Table 1 compares different features of the various bridges surveyed. It can be seen that various types of bridges had been selected for the condition surveys to study the behaviour of each under marine conditions.

Pollution at bridge sites: Table 2 gives the atmospheric and water pollution at different bridge sites. Salinity and lead dioxide candles were exposed in a number of locations on the bridge structure. After exposing them for about a week to the atmosphere prevailing at the different bridges, they were collected with utmost care and taken to the laboratory. They were then analysed by standard methods and chloride and sulphate pollution in the atmosphere at the different bridge locations were estimated. Water samples were also collected near the bridge sites and were analysed in the laboratory for chloride and sulphate contents to estimate the pollution of water at the bridge sites. The chloride contents in the atmosphere at the different bridge sites varied from 26mg/m^2/day to as high as 4,254mg/m^2/day. The chloride content in the atmosphere was very low at the Mukkani bridge site, while it was very high at the Devipattinam bridge site. At the Bavaliary, Taloja and Ekdara bridge sites, it was sufficiently high to cause severe corrosion. The atmosphere at Devipattinam was comparable with that of Mandapam, one of the worst places subjected to very severe corrosion.

The sulphate content in the atmosphere varied from 32mg/m^2/day to 739mg/m^2/day. The sulphate contents in the atmosphere at Taloja, Ekdara and Bavaliary bridge sites were 8 to 10 times higher than that at Mukkani bridge and 2 to 3 times higher than that at Devipattinam bridge site. Even the lower value of sulphate content at Mukkani bridge site was considered higher from the point of view of corrosion. Taloja

Table 5. Percentage of total half-cell potentials indicating percentage probability of corrosion/no corrosion

Sr. No.	Details	Name of the bridge									
		Taloja		Ekdara		Bavaliary		Devipattinam		Mukkani	
		Cor	No cor	Cor	No cor	Cor	No cor	Cor	No cor	Cor	No cor
1.	Foundation	80.60 100	0.0.0	-	-	–	-	-	-	0.0	50.90
2.	Substructure	-	-	-	-	(8)100 (2)0	(8)0 73,100	-	-	-	-
3.	Girders	(35)0	(34)100 50.33	(47)0	(42)100 80.66 (3)30	-	-	(9)33 (2)5,12 (2)16,20 (3)22 28,30 (2)40 (2)50,55 (4)60 (3)80,90	(6)0 (2)5 (3)12 (2)16,24 (2)30 (3)33 (2)40 45,50 (3)55	-	-
4.	Cross diaphragm	(8)0,12 (3)16	(5)100 80,66,55 (2)50,33 16	(4)0,12	(5)100	-	-	(2)40 (2)50,55 (4)60 (3)80,90	-	-	-
5.	Deck slab	(7)0	(7)100	(12)0 16,50 50	(9)100,80 (2)33,16 (2)0 (2)0	92,80 (2)70,0	(4)0,100	(9)0 (5)5 12,16 20,22 30,33	100,90 (2)80 (2)70 (2)66 (6)44 33,30 5.0	(14)0	(11)100 (2)80,63
6.	Handrails										
	left side	5	66	12	16	-	-	-	-	25	20
	right side	10	60	3	13	-	-	-	-	9	26

Table 6. Minimum values of electrical resistivity of concrete cover at anodic region, kg ohm cm

Sr. No.	Details	Name of the bridge					
		Taloja (before monsoon)	Taloja (after monsoon)	Ekdara	Bavaliary	Devipattinam	Mukkani
1.	Foundation	-	487	-	-	-	-
2.	Substructure	-	-	-	30	-	160
3.	Girders	14	48	48	-	16	-
4.	Cross diaphragm	9	207	128	-	-	-
5.	Deck slab	75	239	32	38	32	1,216
6.	Handrails	82	49	96	-	32	600

site showed increase in sulphate content after monsoon by twice the value obtained before monsoon. The chloride and sulphate contents in the water samples collected at Taloja and Devipattinam were very high. The water sample at Devipattinam had twice the amount of chloride and thrice the amount of sulphate contents, when compared with the sample at Taloja. The values of chloride and sulphate contents were very low in the water sample collected at Mukkani bridge site.

Cover thickness: The thicknesses of cover in foundation structures were, respectively, 60mm and 50mm for the Taloja creek bridge and Mukkani bridge. In the substructure, the cover thicknesses were 120mm and 25mm, respectively, at Taloja and Bavaliary creek bridges. The cover in the girders of Taloja creek bridge varied from 30mm to 50mm. But at soffits, it fluctuated between 0 and 15mm. At Ekdara, the values were between 25mm and 35mm. At Devipattinam bridge, it was 20mm. The cross diaphragm at Taloja had a cover of 20mm to 30mm with no cover at one place. It was 32mm at Ekdara bridge. The thickness of cover in the deck slab of Taloja bridge was 20mm to 30mm as against 22-mm cover in the deck slabs of Ekdara and Bavaliary bridges, and 20mm in both Devipattinam and Mukkani bridges. Invariably, handrails had 20-mm cover in all the bridges, except the Ekdara bridge. The various cover thicknesses at different bridges are given in Table 3.

Open circuit potential

As in any other environmental combination, the electrochemical potential of steel in concrete is determined by a balance between anodic arid cathodic reactions. The only cathodic process to be considered in normal concrete is the reduction of oxygen. The rate of this reaction is limited by severe polarisation effects at the steel surface, diffusion resistance in the concrete and, often, by restricted oxygen availability at the surface of the structure. The potential of steel in concrete has been found to be anywhere from the theoretical maximum of +115mV against saturated calomel electrode to about -1 ,025mV in water saturated concrete in environments of low oxygen contents. For concrete structures exposed to the atmosphere, potentials of embedded steel, hereinafter called open circuit potentials, are likely to be in the range of -200mV to +100mV. Potentials lower than approximately -200mV will often indicate that some part of the steel is corroding actively, making the surrounding steel more cathodic[6,7].

Based on the above theory, potential measurements were made in all the bridge structures surveyed. Two types of potentials were measured :

1. open circuit potential of rebar with reference to saturated calomel electrode
2. surface potentials with reference to saturated calomel electrodes.

Table 4 gives the values of open circuit potentials (OCP) for different members of various bridges. The OCP value in the foundations, i.e. the splash zone of Taloja bridge is very high compared to that of Mukkani bridge. For substructure, the value of OCP in Bavaliary creek bridge is higher than that measured at Taloja before monsoon. So far as the girders are concerned, Ekdara bridge shows a low value of OCP compared to Devipattinam and Taloja bridges. The cross diaphragms of both the Taloja and Ekdara bridges have almost equal OCP values. The deck slab of Bavaliary bridge shows the highest value of OCR followed by the Devipattinam, Ekdara, Mukkani and Taloja bridges. The hand rails of Mukkani bridge show the highest OCP value followed by Ekdara, Taloja and Devipattinam bridges.

Table 7. Average values of electrical resistivity of concrete cover, kg ohm cm

Sr. No.	Details	Name of the bridge					
		Taloja (before monsoon)	Taloja (after monsoon)	Ekdara	Bavaliary	Devipattinam	Mukkani
1.	Foundation	-	495	-	-	-	-
2.	Substructure	-	-	-	673	-	1,600
3.	Girders	391	840	561	-	215	-
4.	Cross diaphragm.	281	826	807	-	-	-
5.	Deck slab	263	947	851	814	243	1,596
6.	Handrails	165	396	516	-	234	900

Table 5 gives the percentage of total half-cell potentials, indicating probability of corrosion or no corrosion as per ANSI/ASTM standards C876-80[8]. According to this standard, if potentials over an area are numerically less than —125mV versus SCE (— 200mV versus CSE), there is a greater than 90 percent probability that no reinforcing steel corrosion is occurring in that area at the time of measurement, and this is classified as 'No cor' in the above table. If the potentials over an area are numerically greater than — 275mV versus SCE (-350mV versus CSE), there is a greater than 90 percent probability that reinforcing steel corrosion is occurring in that area at the time of measurement, and this is classified as 'Cor' in the above table.

From Table 5, it can be seen that only the foundation portion shows the probability of corrosion in the case of Taloja creek bridge. In the case of Ekdara creek bridge, deck slab and cross diaphragms show probability of corrosion to a different extent. In Bavaliary creek bridge, deck slab shows 70 percent to 90 percent probability of corrosion whereas the substructure shows 100 percent probability of corrosion. When Devipattinam bridge is considered, the uncertainity portion is maximum. However, the vertical faces seem to be affected more when compared with the bottom of the deck slab. As regards Mukkani bridge, it is seen that only hand rails show some probability of corrosion and foundations and deck slabs show zero-percent probability of corrosion.

Electrical resistivity of concrete

Surface potential measurements alone cannot give a quantitative picture of corrosion of steel embedded in concrete. It has to be coupled with the resistivity of concrete to obtain a parameter called corrosion-cell ratio which, according to Stratful, could throw some light on the phenomenon of corrosion of reinforcement in concretes[5]. The resistance was measured by using the four probe resistance-meter. Table 6 gives the minimum value of the resistivities at the anodic region. It is seen that the resistivity of the foundation of Taloja creek bridge is high, while the substructure of Bavaliary bridge shows a lower resistivity than that of Mukkani bridge. In the girder portions, Taloja, Ekdara and Devipattinam bridges have low electrical resistivities. In the cross diaphragm, Taloja bridge shows a very low value of resistivity before the monsoon but moderately high after the monsoon; Ekdara bridge's cross diaphragm also shows a high value. The deck slab portions of Ekdara, Bavaliary and Devipattinam bridges show very low resistivities. The deck slab of Taloja bridge gives a moderately high resistivity. The Mukkani bridge deck slab has a high resistivity. The hand rails of Taloja bridge (after monsoon) and Devipattinam bridge show low resistivity values. The resistivity is high in the case of Mukkani bridge and moderately high in Ekdara creek bridge.

Table 7 gives the average values of electrical resistivities of different parts of the various bridges. Again, the average resistivity of Taloja creek bridge foundation is high. Though the substructure of Bavaliary bridge has an average resistivity of 673k ohm cm, the concrete was subjected to corrosion, leaving it porous. This porous nature of the concrete was responsible for the very high value of resistivity. The Mukkani bridge substructure also showed a very high value of resistivity, but the concrete appeared to be good from visual observation. In the girders, the lowest resistivity was observed at Devipattinam bridge, followed by Ekdara and Taloja bridges. The resistivities in the cross diaphragms of Taloja bridge (after monsoon) and Ekdara bridge are the same, although they are on the high side. But generally, the cross diaphragms appeared to be porous, which might be the cause of the high resistivity readings. The deck slabs of Devipattinam bridge show the lowest resistivity, followed by high

Table 8. Maximum corrosion-cell ratios, micro ampheres

Sr. No.	Details	Name of the bridge					
		Taloja (before monsoon)	Taloja (after monsoon)	Ekdara	Bavaliary	Devipattinam	Mukkani
1.	Foundation	-	0.65	-	-	-	1.68
2.	Substructure	3.20	-	-	8.70	-	-
3.	Girders	6.00	3.90	3.63	-	16.60	-
4.	Cross diaphragm.	1.74	0.61	1.18	-	-	-
5.	Deck slab	1.10	0.88	9.40	7.30	19.10	0.54
6.	Handrails	4.33	2.64	2.20	-	-	0.68

Table 9. Average corrosion-cell ratios, micro ampheres

Sr. No.	Details	Name of the bridge					
		Taloja (before monsoon)	Taloja (after monsoon)	Ekdara	Bavaliary	Devipattinam	Mukkani
1.	Foundation	-	0.44	-	-	-	1.68
2.	Substructure	1.23	-	-	1.89	-	-
3.	Girders	1.07	0.36	0.47	-	3.35	-
4.	Cross diaphragm.	0.51	0.27	0.625	-	-	-
5.	Deck slab	0.41	0.34	1.50	1.85	3.17	0.54
6.	Handrails	1.82	1.22	0.68	-	-	0.68

Table 10. Free chloride and sulphate contents in capillary water in 1: 2: 4 concrete

Sr. No.	Value	Chloride content ppm	Sulphate as SO_3 content ppm
1.	Minimum	2	14
2.	Average	100	30
3.	Maximum	2,360	70

resistivities at Bavaliary, Ekdara, Taloja and Mukkani bridges. The deck slab resistivity of Taloja bridge, measured before the monsoon, is equal to that of Devipattinam bridge. The average resistivity value of hand rails was the lowest in Devipattinam bridge followed by Taloja bridge (after monsoon), Ekdara and Mukkani bridges. The value of resistivity in Taloja bridge, measured before the monsoon, was less than that of Devipattinam bridge.

Corrosion-cell ratios

The surface potential measurements and surface potential mapping will indicate the anodic and cathodic regions in the particular portion of the bridge structure, as discussed earlier. However, this alone does not give a quantitative idea of the corrosion of reinforcement. Similarly, the resistivity measurements will, to some extent, reflect only tile quality of the concrete. But, if these two are clubbed together and if a parameter known as corrosioncell ratio is obtained, it may give some quantitative picture about the corrosion of steel embedded in concrete. However, it should be noted that the results obtained by this non-destructive test method are only indirect.

Corrosion-cell ratio is expressed as a ratio of the maximum surface potential difference between anodic and cathodic regions to the average specific resistance in the anodic region. Generally, if the ratio is greater than 5 micro ampheres, it may be inferred that the embedded rebars are undergoing corrosion in the anodic regions. For a very high corrosion-cell ratio, the potential difference between anodic and cathodic regions should be high and the resistivity should be low.

Maximum corrosion-cell ratios are also worked out at the various locations on the five bridges mentioned earlier, Table 8. The corrosion-cell ratios of the foundations of both Taloja and Mukkani bridges are quite low. The substructure of Taloja and Bavaliary bridges show high and very high values of corrosion-cell ratios, respectively. In the girder portions, the value at Taloja bridge, measured before the monsoon, is higher than that after the monsoon, the highest value being obtained at Devipattinam bridge. The cross diaphragms of Taloja bridge (before monsoon) give a higher value than that for Ekdara bridge and Taloja bridge (after monsoon). In the deck slab portions, Mukkani bridge shows the lowest value of corrosion-cell ratio, followed by Taloja, Bavaliary, Ekdara and Devipattinam bridges. The hand rails of Mukkani bridge have the lowest corrosion-cell ratio, followed by Ekdara and Taloja bridges. The peak value of corrosion-cell ratio for hand rails was obtained at Taloja bridge (before monsoon).

Table 9 shows the average corrosion-cell ratios in micro ampheres. Again, foundations of Mukkani bridge have a higher value than those of Taloja bridge. The substructure of Bavaliary bridge shows a higher value of corrosion-cell ratio than that of Taloja bridge. In the girders, the highest value was observed at Devipattinam bridge, followed by Taloja bridge (before monsoon), Ekdara and Taloja bridges (after monsoon). Cross diaphragms of Taloja and Ekdara bridges show low values of average corrosion-cell ratios. The highest value of average corrosion-cell ratio for deck slab was noticed in Devipattinam bridge, followed by Bavaliary, Ekdara, Taloja and Mukkani bridges. The hand rails of Taloja bridge show more average corrosion-cell ratio than for Ekdara and Mukkani bridges.

Chloride content

The minimum, average and maximum amounts of soluble chloride and sulphate present in the fresh building materials and natural waters used for building construction have been worked out by CECRI on the basis of analysis of samples of building materials and natural waters received from various places in India[9] . All these do not take part in the corrosion process. It has been found by research at CECRI that both chloride and sulphate can react with the constituents of cement and become inactive. It is only the residual chloride and sulphate contents which are responsible for promoting corrosion. The free chloride and sulphate contents likely to be present in 1:2:4 concrete after hydration were worked out at CECRI by taking into account the reaction with cement and are given in Table 10.

When minimum values mentioned in Table 10 are present, an alkalinity of only 0.01 N to 0.02N is required to obtain inhibitive conditions and this is readily obtained in good concrete. In the case of average values, even though steel can tolerate the corrosive salts at a normality of 0.04N, the

Table 11. Free chloride content in concrete samples, expressed as percentage by weight of concrete

Sr. No.	Details	Name of the bridge					
		Taloja (before monsoon)	Taloja (after monsoon)	Ekdara	Bavaliary	Devipattinam	Mukkani
1.	Foundation	-	0.020	-	-	-	-
2.	Substructure	0.160	-	-	1.112	-	-
3.	Girders	0.066	0.037	0.185	-	0.193	-
4.	Cross diaphragm.	0.030	0.051	-	-	-	-
5.	Deck slab	0.083	-	0.107	0.840	-	0.040
6.	Handrails	-	-	0.010	-	-	0.020

alkalinity is brought down by carbonation, etc., when conditions are likely to be corrosive. The environment will be highly corrosive from the beginning itself, when the maximum values are present. When the average values indicated in the above table are present, border line conditions are obtained. It is, therefore, necessary to keep the chloride and sulphate contents in concrete below these average values or raise the alkalinity of concrete so that the average values cannot destroy the passivity. It should, however, be noted that when concrete structures are exposed to polluted atmosphere containing sea salts or industrial pollutants, such as SO_2, the chloride content of concrete will gradually increase in the case of the former and the alkalinity will fall in the case of the latter. A number of concrete samples were collected at salient locations of different bridges and they were later analysed for free chloride contents at the CECRI laboratory. The values obtained from the analysis are given in Table 11.

The foundation portion of Taloja bridge shows a value of 0.02 percent, i.e., about 200 ppm by weight of concrete. In substructure portions, Bavaliary bridge concrete sample shows a very high value of 11,120 ppm, i.e., 1.112 percent, compared to the value of 0.16 percent i.e., 1,600 ppm at Taloja bridge. Even this value at Taloja is high. The girder portions of Devipattinam bridge show 1,930 ppm of chloride content, followed by 1,850 ppm at Ekdara bridge, 660 ppm at Taloja bridge (before monsoon) and 370 ppm at the same bridge (after monsoon). The cross diaphragms of Taloja bridge show a value of 300 ppm and 510 ppm before and after monsoon, respectively. In the deck slab portions Bavaliary bridge shows the highest value of 8,400 ppm, followed by 1,070 ppm at Ekdara, 830 ppm at Taloja and 400 ppm at Mukkani bridges. In the hand rail portion, Mukkani bridge sample shows 200 ppm and that of Ekdara bridge 100 ppm.

Alkalinity of concrete

It is well known that the alkalinity of wet concrete mix protects the steel at the time of laying the concrete, and that subsequent protection depends on the maintenance of this alkalinity produced during hydration and setting. CECRI studies on the aqueous extracts of cement, mortar and concrete have shown that even in the most favourable conditions, the alkalinity in the vicinity of reinforcement, when it is surrounded by mortar or concrete, is likely to be only of the order of 0.04N. CECRI experiments with hollow concrete specimens simulating the actual condition have shown that under considerable dilution, the alkalinity may go down to 0.01 N.

The investigation at CECRI has shown that corrosion of reinforcement in concrete takes place when the environment close to the reinforcement ceases to be corrosion-inhibitive as a result of fall in alkalinity or entry of corrosion constituents. As the alkalinity falls and chloride and sulphate concentration increases, a stage is reached when breakdown of passivity sets in, which is rapidly followed by the formation of pits at points where chloride is able to attack the steel. The steel is then generally covered by corrosion products from a large number of pits.

As many samples as possible were collected at the different bridges. These samples were later analysed for alkalinity. The results are given in Table 12. The concrete samples collected from substructure portions show that the sample at Taloja bridge was having more alkalinity than that at Bavaliary bridge. In the girder portions, Ekdara bridge sample shows no alkalinity, followed by Devipattinam and Taloja bridges. The cross diaphragm portion of Taloja bridge exhibits a low alkalinity. In deck slab portions, the concrete sample of Ekdara bridge shows no alkalinity, followed by Bavaliary, Taloja and Mukkani bridges. The samples collected from the hand rails of Ekdara and Mukkani bridges show no alkalinity at all.

Conclusion

Excepting the Mukkani bridge in Tamil Nadu, which has not shown any appreciable corrosion over a period of 30 years, other bridges surveyed have shown distress within about 10 years. The major factors contributing to the rapid reinforcement corrosion are:

1. Atmospheric salinity prevailing at the site is independent of the distance from the sea. The chloride and sulphate contents of the water flowing below the bridge also contribute to the aggressivity of the atmosphere. A chloride content of more than 100mg/m^2/day should be considered as quite aggressive while 10 to 100mg/m^2/day can be considered as aggressive.

2. Considering the severity of atmospheric conditions, the minimum cover specified by IRC:21 is 50 to 75mm for slabs and 65 to 90mm for beams and columns. The actual cover thicknesses provided at different bridge sites are very much lower than the specified values in all the cases. Thus, inadequate cover thickness may be the most important factor contributing to rapid penetration of salts. A protective coating to steel would have enhanced the durability under such conditions.

Table 12. Alkalinity of concrete samples, expressed as N

Sr. No.	Details	Name of the bridge					
		Taloja (before monsoon)	Taloja (after monsoon)	Ekdara	Bavaliary	Devipattinam	Mukkani
1.	Foundation	-	-	-	-	-	-
2.	Substructure	0.0035	-	-	0.00019	-	-
3.	Girders	0.0078	0.0140	0.0000	-	0.0026	-
4.	Cross diaphragm.	0.0030	-	-	-	-	-
5.	Deck slab	0.0140	-	0.0000	0.0001	-	0.0125
6.	Handrails	-	-	0.0000	-	-	0.0000

3. Open circuit potential measurement in itself cannot be taken as a reliable criterion.

4. Electrical resistivity values of less than 100k ohm cm have been obtained in all the bridges, which have shown premature corrosion. However, a high electrical resistivity does not always mean a dense concrete. A porous structure can also give high resistance values.

5. Corrosion-cell ratio of less than 1 micro amphere has been obtained in the case of Mukkani bridge. The ratios are high in other bridges. In the case of cross diaphragms, the lower values are due to the higher resistivity values measured. However, it is pointed out that porous concrete also contributes to higher resistivity. Thus, corrosioncell ratio may be misleading in some cases.

6. Loss of alkalinity seems to be another important factor contributing to the breakdown of passivity or protective film in steel reinforcement. The tolerable limit for chloride even for the normal alkaline concrete (0.04N) is 0.1 percent by weight of concrete. Excepting the Mukkani bridge, in all other cases the chloride contamination has exceeded the tolerable limit. Higher alkalinity around steel reinforcement with increased tolerable limit for chloride contamination can be achieved by applying an inhibited and sealed cement slurry coating over rebars.

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