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Critical Strategies for Mitigating Corrosion of Reinforcing Steel in Concrete

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ABSTRACT

Premature deterioration of reinforced and pre-stressed concrete structures is being witnessed all over the world. Amongst various factors affecting early deterioration, corrosion of reinforcing steel in concrete is one of the most widespread and serious governing factor. In fact, it has assumed a form of an epidemic in some parts of the world.

Contrary to general belief, a number of reinforced concrete structures in cities and metropolis located in the vicinity of the long coastal areas and industrial belts in India are witnessing considerable premature deterioration, most often owing to corrosion of reinforcing steel in concrete. Unfortunately, no reliable estimates of such deterioration are available. Unofficial reports however indicate that one cannot afford to ignore this phenomenon any longer.

Considering the experience of many advanced countries, where the premature deterioration has assumed the form of an epidemic, the author urges to take immediate steps to ensure long-term durability of the new concrete structures.

The paper presents a broad overview of the concrete durability scenario and highlights main factors which are responsible for the premature deterioration of structures. It briefly explains the salient features of both chloride-induced and carbonation induced corrosion.

Although a number of measures are available to ensure the long-term durability of concrete structures, the paper focuses attention on three critical measures, namely, the urgent need to

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undertake revision in the exposure class definitions of IS 456, use of concrete having low waterbinder ratio along with higher percentage replacement of OPC by SCMs and specifying tests on durability in construction specifications.

The paper also presents the pros and cons of the Rapid Chloride Ion Permeability Test (RCPT), which in spite of many shortcomings, is now receiving wider acceptance as a reliable durability test.

EARLY DETERIORATION OF RC AND PSC STRUCTURES

With the average per capita world consumption of 2.5 tonnes/annum, concrete has the distinction of being the "largest man-made material" on earth. Concrete has been and continue to be the material of choice for a variety of applications such as residential and commercial buildings, bridges, highways, airports, industrial structures, water-contact structures, etc. The credit for this achievement goes to well-known advantages of concrete such as easy availability of ingredients, adequate engineering properties for a variety of structural applications, adaptability, versatility, relative low cost, and excellent ecological profile compared with other materials of construction.

However, simultaneous with this spectacular growth in the utilization of concrete, the problem of early deterioration of some of the reinforced and pre-stressed concrete structures has also come to the forefront in recent years.

It has been observed that some of the reinforced/pre-stressed concrete structures – even those built conforming to the prevailing standards and specifications – have shown signs of distress and damage within few years of commissioning, while quite a few structures built more than half a century ago are still in a good serviceable condition. In some countries facing hostile weather conditions, the phenomenon of early deterioration of concrete structures has now assumed serious proportions. The seriousness of the problem is reflected in the high cost of repairs in these countries. It is estimated that in the USA alone, the cost of bringing back the deteriorated infrastructure into serviceable state would be a staggering US \$ 3 trillion¹! In most of the advanced countries, nearly 40 percent of the construction industry's budgets is spent on repair, restoration and strengthening of the damaged concrete structures².

INDIAN SCENARIO

Fortunately, the problem of early deterioration of concrete structures is not as severe in India as that in the western world. This could mainly be attributed to two factors. Firstly, as compared to the western countries the total stock of the concrete structures in India is far less. Secondly, a majority of the concrete structures are generally subjected to moderate environmental conditions, excepting of course the coastal and industrial belts and certain extreme climatic zones, in which concrete structures do face aggressive chemical attack. It is in these areas that the problems of deterioration of concrete are causing concern in India. Further, shortage of good quality aggregates and sand, use of site-mixed concrete, poor workmanship and environmental pollution are some of other important factors responsible for accelerating deterioration of concrete – especially the poor-quality concrete – in major cities.

The country has a large coastal line and a number of cities and metropolis located in the vicinity of the coastal belt are witnessing considerable deterioration of reinforced concrete structures. Same is the fate of a number of bridges, jetties, docks, harbours, etc. in these areas. Further, a number of civil engineering structures in chemical, petro-chemical, fertilizer, and other industries, which are

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subjected to aggressive chemical attack are facing serious problems. Unfortunately, no reliable estimates of such deterioration are available. However, it is fact that India cannot afford to ignore the problem of early deterioration of reinforced and pre-stressed concrete structures.

Quite often, it is said that some old concrete structures have withstood the test of time well, while a number of recently-constructed structures have shown signs of premature deterioration. This is true to a certain extent. Numerous Indian examples of durable concrete structures, which are still in good shape today, can be cited below (The figure in bracket indicates the year of construction of the structure.)

- Gateway of India (1930),
- Race course stand, Mumbai (1928),
- Mumbai Central Station building (1930),
- Marine Drive, Mumbai (1928),
- Dum-Dum Bridge, Kolkata (1926),
- Coronation bridge, West Bengal (1940)

No systematic study has been done in India to find out the reasons behind the longevity of these structures. However, the topic of durability is studied in great depth in some advanced countries and we now have a plethora of literature on the subject, which has enriched our understanding of the subject.

PREMATURE DETERIORATION OF CONCRETE: MAIN FACTORS

The principal causes of deterioration of concrete can be broadly divided into two types, namely, physical and chemical causes of deterioration. Mehta³ has further sub-divided these causes in the following categories:

Physical causes

- Progressive loss of mass due to abrasion, erosion, or cavitation
- Cracking due to normal temperature and humidity gradients, crystallization pressure of salts, structural loading, and exposure to temperature extremes such as frost action and fire.

Chemical causes

- Hydrolysis of the components of cement paste
- Cation-exchange reaction between aggressive fluids and cement paste
- Reactions involving the formation of expansive products.

Two recent papers, one by Prof. P K Mehta and the other by Prof R N Swamy throw more light on the factors governing concrete deterioration in recent years^{4, 5}. The main points emerging from their analysis are briefly listed below.

• *Too much emphasis on compressive strength:* Most of the civil engineering contracts are governed by 28-day compressive strength. There is a deep-rooted belief in many quarters that higher strength concretes are, per se, durable!

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- *High cement contents:* Some specifiers do specify certain limits on minimum cement contents, maximum free water-binder ratios, cover to reinforcement, etc. However, here too, there is a general tendency to only specify higher cement contents, without bothering too much on water/binder ratio. The use of high cement contents has often resulted in higher shrinkage of concrete, leading to cracking and deterioration. Further, these concretes are difficult to place in view of the low water contents and have resulted in many durability problems.
- High-early strength cements: Modern cements, to cater to the demand of faster speed of construction, are basically manufactured for strengths and that too high-early strength. These cements have high C₃S and C₃A contents and/or are usually finely ground. A critical review of the compound (Bogue) composition of many Portland cements showed that there has been a significant increase in the C₃S/C₂S ratios from about 1.5 to 5.0⁵. With such cements, it is possible to achieve high strengths even with higher water/binder ratios. Although the resulting concretes may have high strengths, they may necessarily have low porosity and permeability, leading to premature deterioration. Incidentally, such cements gave high-early strengths but the later age strength development was marginal.
- *High heat of hydration:* Another result of the increase in C₃S/C₂S ratio is the increase in the heat of hydration, and more importantly, in the evolution of heat at early ages. The increase in peak temperature and its much earlier occurrence can give rise to undesirable thermal gradient. The internal micro-cracking induced by the thermal gradients is slow to heal and hard to stop. As a result of such cracking, the concrete is prone to attack by aggressive agents, leading to durability problems.

The above factors are very much valid in the present-day Indian conditions.

WHAT IS DURABILITY OF CONCRETE?

Durability is broadly understood as resistance of concrete to a variety of physical and chemical attack. ACI 201⁶ defines durability of Portland cement concrete as "its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration" to which the concrete may be exposed during service. According to Indian Standard IS 456, a durable concrete is one that performs satisfactorily in working environment during its anticipated exposure conditions during service life.

Durability of concrete is governed by two primary factors – the concrete system, and the service environment. The concrete system can be further subdivided into the materials area and the processing, while deterioration in service conditions can be owing to physical or chemical factors.

Concrete is considered to be a three-phase material, consisting of hydrated cement paste (HCP), the aggregate and the transition zone between the HPC and the aggregate⁷. With the passage of time, the characters of HCP and the transition zone continue to change. Therefore, the durability of concrete structure is not a static property but depends on the phase changes of concrete in its service conditions. Further, durability of reinforced/pre-stressed concrete is also dependent on a host of other factors including structural design and detailing, cover to reinforcement, type and properties of the various concrete ingredients, quality control and quality assurance practices, concrete processing involving transporting, placing, compaction and curing etc.

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In actual practice, deterioration of concrete is seldom due to a single cause. On most of the occasions, more than one deleterious phenomenon is found to be responsible for material degradation. Both the physical and chemical causes of deterioration are so closely intertwined that it is difficult to separate them and identify the primary cause of deterioration.

According to Mehta⁴, the major causes of deterioration, in order of their decreasing importance are:

- Corrosion of reinforcing steel
 - Owing to chloride attack
 - Owing to carbonation
- Sulphate attack
- Alkali-aggregate reaction
- Acid attack
- Freezing and thawing.

CORROSION OF REINFORCING STEEL

Corrosion of reinforcing steel in concrete is one of the most widespread and serious phenomenon of deterioration which is taking a heavy toll of concrete structures all over the world. It is basically an electrochemical phenomenon, which has been described in detail by many authors. Mallick⁸ has summarized the basic mechanism of corrosion in terms of an anode and cathode process as below:

Anode: Fe
$$\rightarrow 2^{e_-} + Fe^{2+}$$
 (1)
(Metallic iron)

(2)

Cathode: $O_2 + H_2O + 2^{e-} \rightarrow 2(OH)^{-1}$

And the corrosion undergone by steel is due to the combination of iron and (OH⁻) ions;

 $Fe + O_2 + H_2O \longrightarrow Fe_2 + 2(OH) \longrightarrow iron hydroxide (rust)$ (3)

A simplified model of the electrochemical process of corrosion of steel in concrete is given in Figure 1.



Figure 1: Simplified model representing corrosion mechanism⁸

There are four basic pre-requisites for the corrosion to take place: an anode, where the ions go into solution and electrons are released; a cathode, where the electrons are consumed in the presence of water and oxygen; a conductor (steel itself), which permits the transfer of electrons from the anode to the cathode, and an electrolyte (the moist concrete), which permits the movement of ions between the cathode and anode.

Water and oxygen which are normally available in exposed concrete, are required for corrosion to occur. But corrosion is prevented because of the high alkalinity (pH > 13) that exists in concrete. At this high pH, a dense layer of iron oxide (Fe_2O_3) forms on the surface of the steel and protects the steel from corrosion. This layer of iron oxide is called a passive layer and when it is protected the steel is said to be passivated.

As long as the high pH remains and chloride ions are not present, steel that is embedded in concrete will remain passive indefinitely. This makes reinforced concrete an excellent composite material. However, owing to the aggressive environmental conditions on the one hand and the imposition of service loads on the structures, the protection to steel is lost during service.

There are two factors that can lead to the corrosion of steel in concrete; these are:

- Carbonation of the concrete cover
- The presence of chloride ions at the steel surface.

Carbonation

The high alkalinity of concrete results from the high concentration of alkali hydroxides, in the pore solution and the availability of solid calcium hydroxide, $(Ca(OH)_2)$, in the paste. If carbon dioxide (CO_2) , from the atmosphere penetrates into the concrete it will react with these hydroxides to form carbonates. The reaction can be represented by the following (simplified) equation:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

(4)

NIGIS * CORCON 2017 * 17-20 September * Mumbai, India Copyright 2017 by NIGIS. The material presented and the views expressed in this paper are solely those of the author(s) and do not necessarily by NIGIS. This process leads to a loss in the alkalinity of the concrete; the process is called carbonation and the concrete is said to be carbonated. The pH falls from 13 to lower levels, and in extreme cases in the region of 8 due to the process of carbonation. Unfortunately, at this lower pH, the passive layer on the steel is no longer stable and if the carbonation front reaches the steel, the steel will start to corrode. Fortunately, the rate of carbonation is slow in good quality concrete and, provided there is sufficient cover to the steel, the carbonation front may not penetrate as far as the steel during the normal service life of concrete.

Concrete will carbonate more rapidly when exposed to dry conditions, but under such conditions carbonation is generally not an issue as there is insufficient moisture to sustain corrosion when the carbonation front reaches the steel. Concrete that is frequently exposed to moisture will carbonate very slowly as the pores are generally full of water making it difficult for CO₂ to penetrate. Concrete that is exposed outdoors but not directly exposed to water or precipitation is most vulnerable to carbonation-induced corrosion. Examples include the underside of beams, balconies and suspended slabs. The rate of carbonation increases significantly with increases in the water-binder ratio. Extending the period of moist curing significantly reduces the rate of carbonation.

Research has documented that use of SCMs will not reduce the pH in concrete to levels that can cause the initiation of corrosion. Concrete containing high levels of pozzolan or GGBF, however, are likely to be more prone to carbonation than concrete of the same water-binder ratio without SCM. This shortcoming can be overcome by using lower water/binder ratio while using SCMs.

Chloride-induced Corrosion

When the sufficient concentration of chlorides is present at the steel surface, the passive layer starts reducing and the steel is de-passivated. Corrosion of steel commences, provided of course that sufficient oxygen and water are available.

Sources of Chlorides

Chlorides may be present as components of the concrete mixture (internal sources) or may penetrate the concrete from external sources.

Internal sources: These include chlorides in unwashed sea-dredged aggregates, the use of saline water for mixing, or the use of calcium chloride admixtures as set accelerators. The presence of chlorides in non-reinforced concrete does not present a problem. In reinforced concrete and prestressed concrete, the chloride content of the concrete should be limited to prevent corrosion of the steel.

In India, the IS 456 specifies the limiting values of maximum permissible acid-soluble chloride content expressed in kg/m³ of the mass of concrete as shown in Table 1.

Table 1.13 436 Limits on Chionde Content								
Type or use of concrete	Maximum total acid soluble chloride content expressed kg/m ³ of concrete							
Pre-stressed concrete	0.4							
Concrete containing metal and steam cured at elevated temperature	0.4							
Reinforced concrete or plain concrete containing embedded metal	0.6							

Table 1 : IS 456 Limits on Chloride content

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Concrete not containing embedded metal or	any
material requiring protection from chloride	5.0

External sources: These include seawater, deicing salts and brackish groundwater, etc.

Both carbonation-induced and chloride-induced corrosion adversely affect the service life of reinforced and pre-stressed concrete structures. Amongst the two, chloride-induced corrosion is associated with devastating consequences for the structures.

Transport Mechanisms

For protecting the reinforcing steel from corrosion, the depth and quality of cover to the reinforcement plays an important role. The rate of ingress of aggressive agents within the cover is dependent upon a host of factors. A recent paper⁹ lists out the following transport mechanisms due to which the aggressive chemicals enter into concrete.

- diffusion (movement due to concentration gradient),
- permeation (due to pressure difference),
- sorption (intake of water due to capillary action),
- absorption (bulk intake of water),
- adsorption (process of attachment of molecules on the surface),
- migration (ionic movement due to the difference in the electrical potential),
- wick action (capillary transport to an exposed surface, where liquid evaporates and any dissolved ions are precipitated) etc.

In actual practice, there is invariably a combined action of the above-mentioned mechanisms. It is because of this reason that testing of concrete durability becomes a challenging task.

IMMEDIATE TASKS TO IMPROVE LONG-TERM DURABILITY OF CONCRETE STRUCTURES

It is unfortunate in India that the problem of durability of concrete structures has not received due attention. India does face the problem of premature deterioration of concrete structures, the intensity of which varies from place to place and region to region. The problem should not be underestimated. Looking at the experience of many advanced countries, it would be advisable to take immediate steps to ensure long-term durability of the new concrete structures that we are constructing today. Although a number of measures can be highlighted to ensure the long-term durability of concrete structures, the present discussion aims to concentrate only on three key measures, namely, urgent need to undertake revision in the exposure class definitions of IS 456, use of concrete having low water-binder ratio along with higher percentage replacement of OPC by SCMs and thirdly make a beginning in specifying tests on durability.

EXPOSURE CLASS DEFINITIONS

During the planning and design of concrete structures, the architect/designer needs to take into account the possible environmental exposure conditions in which the structure needs to function during its service life. The Indian Code IS 456-2000 for plain and reinforced cement concrete specifies five exposure classes namely, mild, moderate, severe, very severe and extreme. The definitions of these classes seem arbitrary and prescriptive in nature regarding durability

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requirements. Further, they do not address the relevant mechanisms of concrete deterioration adequately.

The present author reviewed durability-centric provisions in the Australian, European, North American and Canadian standards, highlighting mainly the changes in the definitions of exposure classes and the limiting values of the properties of concrete for different classes¹⁰. The review revealed that the definitions of exposure conditions in most of the international standards have been expanded and are aligned with the anticipated severity of exposure during the service life of structures. In line with this international trend, the present author suggested changes in the definitions of exposure classes in IS 456:2000. The existing definitions of exposure classes in IS 456 have been expanded and made more rational by aligning them to the anticipated degradation mechanisms. The suggested major exposure classes include: carbonation (C), corrosion (Cr), sulphate attack (S), and penetration resistance (P). These are further divided into 16 sub-classes. Limiting values of concrete properties are suggested for the new exposure classes. While doing so, an attempt was made by the present author to keep the limiting values of minimum cement content and maximum water-binder ratio more or less similar to those in the existing IS 456:2000.

Ramalingam and Santhanam¹¹ later slightly modified the exposure classes proposed by the present author. They analysed concrete mix designs from several construction sites across India executed by the Central Public Works Department in the light of different codal provisions from various countries.

USE OF CONCRETE HAVING LOW W/B RATIO AND SCM

Low permeability is the crux of durability. Based on the large R&D work done throughout the world on durability, it is proved beyond doubt that low-permeability concrete can be produced by:

- Maintaining a low water-binder ratio
- Judicious use of supplementary cementing materials (SCM) such as fly ash, slag, silica fume, • microfine slag
- Good curing •
- Minimize cracking.

While the first two areas come under the jurisdiction of the concrete producer, the latter two come under the scope of the contractor. While it is the responsibility of the specifier and the concrete producer to design concrete having lowest possible water-binder ratio along with judicious use of SCMs, the contractor needs to compliment their efforts by proper placement and curing of the concrete.

TESTS ON DURABILITY

Durability is one of the most extensively researched topics in concrete technology. A large number of durability-centric tests have been developed by a number of researchers. These test methods address specific transport mechanism and/or type of aggressive agent, namely, liquid, gas, or ionic species (e.g. chloride). A recent paper provides a compilation of some of the widely used methods (Table 2).

Table 2: Some widely used durability tests								
SI. No.	Category	Test method	Durability Parameter					
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0. Come suidely used durability tests

Test	Test methods to assess gas penetrability								
		Diffusion cell							
1.1	Gas diffusion	(1) by Lawrence and	Gas diffusion coefficient						
1 2	tests	(2) by Richardson	Depth of carbonation						
1.2	-	Natural earbonation test	Depth of carbonation						
1.5		Water vanour transmission tests (ASTM							
1.4	Water vapour	E 96)	Permeance						
1.5	diffusion tests	Water vapour transpiration test	Water vapour transpiration						
1.6		Figg's method	Air permeability index						
1.7		Schönlin& Hilsdorf	Air permeability index						
1.8		Autoclam method	Air permeability index						
1.9		Torrent method (SIA 262/1:2003)	Coefficient of air permeability						
1.10	Gas	Permeability exponent	Permeability exponent						
1.11	tests	CEMBUREAU method	Permeability coefficient						
1.12		Oxygen Permeability Index Test	Oxygen Permeability Index						
1.13		Zia-Guth double chamber method	Permeability constant						
1.14		TUD (Technical University of Delft) method	TUD time						
1.15		Hong - Parrot method	Apparent permeability						
Test	methods to asses	s chloride ion penetrability							
2.1		Bulk diffusion test	Non-steady state diffusion						
	Diffusion tests	Salt Ponding	Non-steady state diffusion						
2.2		(AASHTO T 259/ ASTM C1543)	coefficient						
2.3		Steady state diffusion test	Steady state diffusion coefficient						
2.4		Chloride profiling method	Surface chloride concentration, the apparent diffusion coefficients						
2.5		Steady state migration test	Steady state migration coefficient						
2.6		Rapid Chloride Permeability Test (ASTM C 1202)	Charge passed						
2.7	Migration tests	Rapid Migration Test (NT BUILD 492)	Non-steady state migration coefficient						
2.8		Multi regime method (UNE 83987)	Steady and non-steady state chloride diffusion coefficients						
2.9		Permit ion migration test	In-situ chloride migration coefficient						
2.10		Whiting method	Total charge passed						
2.11	Resistivity or	Direct resistivity test (UNE 83988 – 1)	Resistivity						
2.12	tests	Concrete resistivity test (Wenner 4 probe)	Resistivity						

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2.13		Two point method	Resistance				
2.14]	Disc method	Resistivity				
2.15		Chloride conductivity test (DI Testing manual, South Africa)	Chloride conductivity				
2.16	Pressure penetration techniques	Pressure penetration techniques	Chloride profile and depth of chloride ion penetration				
Test	methods to asses	water penetrability					
3.1	Wator	Autoclam method	Water permeability index				
3.2	permeability	Germann Water Permeability test	Surface permeability				
3.3	tests	Water Permeability test (DIN 1048 Part 5)	Depth of water penetration				
3.4		Initial surface absorption test	Initial surface absorption value				
3.5		Autoclam method	Sorptivity index				
3.6	Capillary	Water sorptivity test (DI Testing manual, South Africa)	Sorptivity index				
3.7	absorption tests	Method for measurement of rate of absorption of water by hydraulic cement concrete (ASTM 1585)	Initial and final rate of water absorption				
3.8		Water Absorption test (RILEM CPC 11.2)	Capillary absorption of water				
3.9	Absorption tests	Water Absorption and Porosity (ASTM C642)	Absorption after immersion, Absorption after immersion and boiling, Bulk density, dry Bulk density after immersion Bulk density after immersion and boiling, Apparent density, Volume of permeable voids				
3.10	Field tests	Field permeability test	Apparent coefficient of permeability				
3.11		Figg poroscope method for water absorption	Poroscope absorption time				

Although a number of durability tests have been developed, selection of appropriate test for the desired application and expected environmental conditions is not easy. Further, it is a fact that there is considerable variability in the results of durability tests. Therefore, unlike compressive strength, reliability of durability test results for acceptance or rejection of concrete is always lacking.

With a view to provide proper guidance on the problem of variability of durability tests, the Indian Concrete Institute's Durability Committee recently decided to undertake round-robin testing of selected tests addressing gas, water and ionic penetrability for two different concrete mixes prepared using the materials available locally at Chennai. The objective of the study was to identify the extent of variability in different durability methods, with the purpose of selecting the best methods for durability design of concrete.

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A total 9 established laboratories spread over different parts of the country participated in the testing program. A detailed investigation report is presented in a recent paper¹². The overall assessment of variability in the results, irrespective of the grade of concrete, is summarized in Table 3.

Test method	COV (%)								
Compressive strength (IS 516)	10 – 11								
Rapid chloride permeability test	25 – 40								
(ASTM C 1202)									
Chloride migration test (NT Built 492)	50 – 75								
Sorptivity test (ASTM C 1585)	50 - 80								
Water penetration test (DIN 1048 part	55 – 80								
V)									
Water absorption test (ASTM C 642)	25 – 60								

Table 2. Veriabilit		different teste	
Table 3: Variabilit	y observed in	amerent tests o	on durability

Following were the main observations of the round-robin test study:

- Caution needs to be exercised when deciding on limiting values and acceptance criteria while specifying the durability tests in construction projects.
- The acceptance criteria for compressive strength cannot be applied to durability parameters, since there is a vast difference in the associated variability.
- Interesting, the Rapid Chloride Permeability Test (RCPT) provided the lowest level of variability.

Rapid Chloride Permeability Test (RCPT)

Since corrosion of reinforcing steel caused mainly by chloride ingress is observed to be one of the most serious phenomena threatening the long-term durability of concrete, use of a reliable test method to determine the resistance of concrete to chloride ingress is essential.

Chloride ingress in concrete cannot be determined directly in a time frame that would be useful as a quality control tool. Therefore, for assessing chloride ingress, a test method that accelerates the process is needed to allow the assessment in a reasonable time.

A number of test methods to determine the penetration resistance of chloride in concrete have been developed. Stanish *et al* presents a review some of the common methods¹³. These methods include, amongst others, the salt ponding method (AASHTO T 259 and ASTM C 1543)^{14,15} and bulk diffusion test (NordTest NT Build 443)¹⁶. One of the important limitations of these methods is that they are very time-consuming and tedious and hence impractical for use as a tool for quality control and quality reduces with age due to the continued hydration process.

With a view to overcome some of the above limitations, accelerated test methods were evolved. Amongst these methods, the rapid chloride ion permeability test (RCPT) has become a widely used test in North America and many other countries. This test which was originally developed by the Portland Cement Association (PCA) for the Federal Highway Administration (FHWA), USA¹⁷ was later codified as the AASHTOO 277¹⁸ and ASTM C 1202¹⁹.

The RCPT is performed using 51-mm long, 95-mm diameter cylindrical specimens cut from cores (alternatively, the test can be performed using 95-mm diameter cast cylinders). ASTM C 1202

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provides a qualitative relationship between the results of the test and the chloride ion permeability, Table 4.

Charge passed (coulombs)	Chloride ion permeability
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

Table 4: Chloride ion permeability based on charge passed

Contrary to what the name indicates, RCPT does not measure the permeability or chloride diffusion in concrete. The test measures ionic movement. It was observed that the application of the test induces change in pore structure and resistivity of concrete specimens tested²⁰. Hence, it can be considered to be simply a conductivity or inverse resistivity test²¹. Initial work by researchers found good correlation between the coulomb values of RCPT and the results of ponding test performed on specimens of the same mixture for a wide variety of concretes^{22, 23}. However, many other researchers criticized this test²⁴⁻²⁸. The main criticisms pertained to following aspects:

- (i) lack of adequate relationship with salt ponding test,
- (ii) test measures electrical conductivity and not permeability
- (iii) the current passed is related to all ions and not just chloride ions,
- (iv) heating of sample during the 6-hour test,
- (v) misleading results are possible when calcium nitrite is admixed into concrete

Hooton and others have tried to provide convincing answers to the above criticism^{29, 30}. It is argued that RCPT is a rapid index test that mainly provides a measure of conductivity, which is governed by the volume, size and connectivity of pores and the pore fluid conductivity. Thus, RCPT values provide a good indication of the degree of penetrability of concrete. Provided appropriate analytical procedures are used, the relationship between RCPT data and diffusion coefficients calculated from ponding tests is quite good and appears to hold for a wide variety of concretes³⁰. It is true that the test gives misleading values when calcium nitrite is admixed with concrete; however, this limitation is clearly mentioned in ASTM C 1202.

In spite of the criticism of the test and its certain limitations, RCPT has been used extensively in North America and many other countries and has been incorporated in the national specification of one country, i.e. Canada (CSA A23.1.04)³¹. It has been specified for evaluating the quality of supplied and in-place concrete for highway bridges, parking structures, tunnel liners, etc. Therefore, as stated by Hearn *et al*, "in spite of other developments, it is likely that this test will remain as an index test for permeability for many years to come"²¹.

Current Practice in India

It is heartening to note that awareness about designing concrete structures for durability is slowly increasing in India. However, it is far from assuming a dominant trend. There is a long way to go. The practice for specifying durability test for qualifying the concrete mixes began with the infrastructure sector – mainly road and bridges. It was the water penetration test (DIN 1048- part V) which was specified for few bridge projects – mainly the bridges on the Konkan Railway. This test

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was also included in the Specifications of road bridges of the Ministry of Road Transport & Highways (MORT&H).

The other durability test which has found favour with the Indian specifiers is the Rapid Chloride Ion Penetration test (RCPT), ASTM C 1202. Here also, it was the infrastructure sector which took the lead in specifying this test. RCPT has been specified for most of the metro rail projects as well as many road bridges in the country. It has also been included in the specifications of the Indian Roads Congress (IRC- 112). The IRC specification provides the limiting values for three exposure conditions as given in Table 5.

Exposure Class	RCPT @ 56 days				
Severe	1500				
Very severe	1200				
Extreme	800				

 Table 5: Limiting values of RCPT specified in IRC 112

Recently, RCPT is also specified for certain tall building projects for pre-qualifying the concrete mixes. The results of this test for different grades of concrete are included in Table 6.

										•••••			
Grade of concrete	M50	M60	M70	M70	M70	M70	M80	M80	M70	M40	M50	M60	M70
Total Cementitous materials (CM), kg	560	600	640	575	625	630	665	670	755	500	560	630	660
Water-binder ratio (w/cm)	0.27	0.25	0.22	0.25	0.23	0.23	0.22	0.21	0.19	0.30	0.27	0.27	0.21
Average RCPT, Coulomb	1149	956	876	901	856	744	790	814	871	1298	1112	963	872

Table 6: RCPT Test results for different water-binder ratio and cementitious content

An attempt is also made to find out the correlation between Coulombs values of RCPT versus water-binder ratio as well as the cementitious contents (see Figures 2 and 3).



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Figure 2: Correlation between RCPT results and W/B ratio

Figure 3: Correlation between RCPT results and cement content

It can be very clearly seen that RCPT is dependent on both the water-binder ratio and the amount of SCM within the mix. As the water-cement ratio is reduced, Coulomb values of RCPT also decrease. Also, the Coulomb values of RCPT also decrease with the increase in the SCM contents.

CORROSION PROTECTION STRATEGIES

There are many options for extending the service life of reinforced concrete exposed to chloride ions. These include the following:

- Use low water-binder ratio accompanied with higher percent replacement of OPC by SCMs.
- Application of membranes, coatings or sealers to the exposed surface of the concrete
- Use of low-permeability, high-performance concrete
- Increasing the depth of cover
- Use corrosion inhibitors
- Use of coated steel reinforcement (e.g. fusion-bonded epoxy-coated bars, stainless-steel clad bars)
- Use of corrosion-resistant metals (e.g. stainless steel, galvanized steel, MMFX steel)
- Use of non-ferrous reinforcement (e.g. fiber-reinforced plastic bars)
- Installing cathodic protection (usually used for repair but may be installed during construction of new structures)

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