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Exposure classes for designing durable concrete

Vijay R. Kulkarni

Recent years have witnessed numerous cases of premature deterioration of reinforced concrete structures. Simultaneously, the urgent need to inculcate sustainability approach in the design and construction of structures has come to the forefront. As a result, durability design provisions in standards of many countries including India have become more stringent. The paper describes some of the latest durability-centric provisions in the Australian, European, North American and Canadian standards, mainly highlighting the changes in the definitions of exposure classes and the limiting values of the properties of concrete for different classes. With a view to align the provisions of Indian Standard IS 456:2000 to the international trend, the paper suggests changes in the existing definitions of exposure classes of this standard. These definitions have been expanded and made more rational by aligning them to the anticipated degradation mechanisms. Limiting values of concrete properties are suggested for the new exposure classes. While doing so, an attempt has been made to keep the limiting values more or less similar to those in the existing IS 456:2000.

Concrete is the most versatile material of construction the world over. It has achieved the distinction of being the "largest man-made material" with the average per capita consumption exceeding 2 kg. Concrete is the material of choice for a variety of applications such as housing, bridges, highway pavements, industrial structures, water-carrying and retaining 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, etc. Moreover, concrete has an excellent ecological profile compared with other materials of construction.

With the continuing expansion of infrastructure and housing construction, especially in the developing countries of Asia, Africa and South America, the rate of consumption of cement and concrete is rising and is bound to grow further.[1, 2] In India, concrete construction scenario has been witnessing considerable growth in recent years. The cement production in the country has witnessed a sharp increase from 45.25 million tonnes in 1989-90 (beginning of decontrol era) to 102.4 million tonnes in 2001-02 — more than two-fold increase in production in just 12 years! With around 155.7 million tonnes of production in 2006-07, India is currently the second largest cement producer in the world, after China and this is indeed a laudable achievement.[3] However, the per capita cement consumption in the country is amongst the lowest in the world. Currently, it stands at around 120 kg, which is much below the world average of about 250 kg. The nation has to go a long way to catch up with the rest of the world.

Problem of durability

While this spectacular growth has been occurring in concrete production, the problem of early deterioration of some of the reinforced and prestressed concrete structures has also come to the forefront in recent years. It has been observed that some recently-constructed structures — even those built conforming to the latest specifications — has shown early signs of distress and damage, sometimes within a few years of commissioning, while quite a few structures built more than half a century ago are still in a good serviceable condition. The phenomenon of early deterioration of concrete structures is tending to assume alarming proportions in some countries, especially those facing hostile weather conditions. The seriousness of the problem is reflected in the high cost of repairs in these countries. It has been estimated that in the USA alone, the overall cost of repairing and replacing all deteriorated concrete structures would a staggering $ 200 billion![4] In this country, out of 600,000 bridges on record, roughly 40 percent are either structurally deficient or functionally obsolete.[5] In the United Kingdom, nearly £ 500 million are spent annually on concrete repairs.[6] In most of the advanced countries, nearly 40 percent of the construction industry's budget is spent on repair, restoration and strengthening of the damaged concrete structures[7]. All this has tarnished the image of concrete as a "durable, maintenance-free" material. Thus, durability of concrete has become an important issue today.

Table 1. End uses of cement: CMA Study

Year	Residential buildings	Non-residential buildings	Roads and bridges	Railways	Other constructions	Repairs and maintenance
1993-94	19.5	18.8	3.3	1.6	20.2	36.6
1994-95	19.1	19.6	4.1	1.4	20.1	35.7
1995-96	18.3	20.5	3.6	1.2	19.3	37.1
1996-97	18.3	20.8	3.3	1.2	18.7	37.7
1997-98	18.5	20.2	3.8	1.0	17.9	38.6
1998-99	17.4	22.7	3.4	0.8	20.9	34.8

Source: Cement Statistics 2000, Cement Manufacturers' Association (CMA),

Durability: 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. The growth in infrastructure and housing sectors is a recent phenomenon. Secondly, a major part of the country is 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 environment. It is in these areas that the problems of deterioration of concrete are causing concern in India. Of course, poor quality of construction using labour-intensive site-mixed concrete has also lead to early deterioration of concrete structures located even on moderate climate zones. Further, environmental pollution in major cities has increased steeply in recent years and it is accelerating deterioration of concrete — especially the poor quality concrete — in these 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 the phenomenon of early 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 subjected to aggressive chemical attack are facing serious problems. Unfortunately, no reliable estimates of such deterioration are available. One indirect way to judge this is to look for the estimate of cement used for repair and maintenance. The Cement Manufacturers Association (CMA) has published data on end uses of cement based on a market survey conducted in the late nineties and the details of the same are provided in *Table* 1.[8] It indicates that nearly 35 percent of the cement produced in the country goes into repair and maintenance. This is indeed a very high figure for a developing country like India.

Sustainability

Besides durability of structures, sustainability is yet another important issue confronting the construction sector. A steep increase in population during the 20th century combined with the phenomena of industrialization and urbanization have resulted in unlimited exploitation of non-renewable natural resources. It is believed that if this trend continues unabated, very little resources will be left for the future generations. Besides, the emission from Green House Gases (GHGs) — especially CO_2 and NO_x — has reached an alarming level, resulting in an unprecedented rise in ambient temperature throughout the globe. The Inter-

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governmental Panel on Climate Change (IPCC) has warned that while the average global temperature rose only by 0.6°C in the last 100 years, the same is expected to rise between 1.4 to 5.8°C over the next 100 years.[9] It is now established that the climate change phenomenon is responsible for the rise in frequencies of floods and droughts, wrecking havoc to human habitat[10]. It would thus be obvious that if the GHGs emissions are not controlled and the unlimited exploitation of non-renewable natural resources is not reversed, the very existence of humankind will be in danger.

Since the construction sector is the largest user of natural resources it is widely accepted that this sector has to play a major role towards achieving the sustainable development of our society. Fortunately, concrete, which is the most widely used man-made material, possesses potential to be used in an environmentally beneficial way. It is now established beyond doubt that use of supplementary cementitious materials (SCMs) such as fly ash, blast-furnace slag, metakaolin, silica fume, etc. not only helps in minimizing the use of Portland cement — thereby reducing the GHGs emissions — but also improves a host of properties of concrete, including its durability. Fortunately, the use of SCMs, either in the form of blended cements or as separate additions to concrete is today increasing.

One of the surest ways of enhancing the sustainability of concrete construction is by improving its long-term durability and thus the useful service life of the structure. However, the currently-available codal provisions and specifications practiced in different countries are not conducive in achieving these objectives. The current approach of "assuming" that long service life can be ensured following certain "prescriptive" specifications has many limitations. It does not exactly define what service life is and what constitutes the end of service life. Further, limited account is taken of construction quality and methods and the risk of premature deterioration exists even when "prescriptive" specifications are followed. This highlights the need for adopting performance-based specifications and a holistic approach based on life-cycle cost.[11] Service-life design can contribute to sustainable development by helping satisfy client needs in a cost-effective manner, avoiding wastages emanating from structures that are over-designed from a durability perspective or premature, costly repairs arising from poor quality design and materials.

Durability design approaches in major countries

Codes and specifications followed in different countries play an important role in ensuring the durability of concrete structures. The vast majority of international codes on structural concrete are basically "prescriptive" in nature, in that they specify the limiting values of the following four parameters for code-defined exposure conditions:

1. minimum cement (cementitious) content
2. maximum free water-binder ratio
3. minimum grade of concrete
4. cover to reinforcement.

Two papers provide a detailed comparison of international standards for durability of reinforced concrete structures and give recommendations for revision of Indian standard, IS 456:2000.[12,13] However, these papers provide review of standards published prior to the year 2000. During the past eight years, many revisions and amendments have been made in the international standards. It would therefore be appropriate to review some of the latest provisions in major international standards.

Table 2. Environmental exposure conditions

Environment	Exposure conditions
Mild	Concrete surfaces protected against weather or aggressive conditions, except those situated in coastal areas
Moderate	Concrete surface sheltered from severe rain or freezing whilst wet; concrete exposed to condensation and rain concrete continuously under water; concrete in contact or buried under non-aggressive soil/ground water; concrete surfaces sheltered from saturated salt air in coastal area
Severe	Concrete surfaces exposed to severe rain, alternate wetting and drying or occasional freezing whilst wet or severe condensation; concrete completely immersed in sea water; concrete exposed to coastal environment
Very severe	Concrete surfaces exposed to sea water spray, corrosive fumes or severe freezing conditions whilst wet; concrete in contact with or buried under aggressive sub-soil/ground water
Extreme	Surface of members in tidal zone; members in direct contact with liquid/solid aggressive chemicals

Source: Table 3 of IS 456:2000

The present paper describes some of the latest durability-centric provisions in the Australian, European, North American and Canadian standards. Here, the attempt is not to provide a comprehensive comparison of all provisions related to durability in these standards but to limit the effort to the classification of exposure classes and the limiting values of properties of concrete and its ingredients for different classes. The paper also suggests revision of the classification of exposure conditions included in the Indian code IS 456:2000 and recommends appropriate changes in the limiting values of the "prescriptive" requirements for durability.

Durability-centric provisions in major international codes

Indian Standard IS 456:2000

The Indian Standard for plain and reinforced concrete, IS 456, which was revised in the year 2000 laid emphasis on enhancing durability of concrete.[14] The prescriptive provisions on concrete durability made in the 1978 revision were thoroughly revised. The revision added two new exposure classes, namely "very severe" and "extreme" to the earlier three classes, *Table* 2. Further, the minimum grade of concrete for structural application was raised from M15 to M20 and the minimum nominal cover to the reinforcement was linked with the exposure classes, *Table* 3. The standard encouraged the use of supplementary cementitious materials such as fly ash, ground granulated blast-furnace slag, high reactive metakaolin, silica fume, rice husk ash, etc. in concrete and the prescriptive provisions for minimum cement contents were considered to be inclusive of the SCM additions. An upper limit of 450 kg/m^3 of cement content was also introduced in the standard.

European Standard EN 206-1:2000

European Standard EN 206-1, published in the year 2000, categorized exposure classes based different degradation mechanisms.[15] In fact, this was one of the first attempts to break away from the hitherto arbitrary classification of exposure classes and base the definition of the classes on a more rational footing. *Table* 4 provides the details of the European exposure classes, which are divided in the following six major categories:

- No risk of corrosion or attack
- Corrosion induced by carbonation
- Corrosion induced by chlorides other than from sea water
- Corrosion induced by chlorides from sea water
- Freeze/thaw attack with or without de-icing salts
- Chemical attack.

These categories are further sub-divided into sub-classes, totaling 18, thus widening their definitions. *Table* 4 also includes typical examples explaining different sub-classes. The European Standard also introduced the concept of "intended service life" and it provided guidance on the limiting values of concrete composition, based on the assumption of an intended working life of the structure of 50 years. The limiting values are illustrated in *Table* 5. These values refer to the use of cement type CEM I conforming to EN 197-1 (ordinary Portland cement) and aggregate with a maximum nominal size in the range of 20-32 mm.

It is likely that concrete may be subjected to more than one degradation mechanisms. In such case, the

Table 3. Values of minimum cement content, maximum w-c ratio, minimum grade of concrete and minimum nominal concrete cover for different exposure conditions specified in IS 456:2000

Exposure	Minimum cement content#, kg/m^3	Maximum free w-c ratio	Minimum grade of concrete	Minimum nominal concrete cover,* mm
Mild	300	0.55	M 20	20**
Moderate	300	0.50	M 25	30
Severe	320	0.45	M 30	45***
Very severe	340	0.45	M 35	50***
Extreme	360	0.40	M 40	75

Source: Table 5 of IS 456:2000.

Notes:

* for a longitudinal reinforcing bar in a column, nominal cover shall not be less than 40 mm, nor less than the diameter of such bar;

** for reinforcement upto 12 mm dia. bar for mild exposure, the nominal cover may be reduced by 5 mm;

*** for exposure conditions severe and very severe, reduction of 5 mm may be made, where concrete grade is M 35 and above. The actual concrete cover should not deviate from the required nominal cover by +10 mm.

Cement content mentioned in the code is irrespective of the grades of cement and it is inclusive of the additions (fly ash, GGBS, silica fume, high reactive metakaolin, rice husk ash, etc.) mentioned in clause 5.2 of IS 456.

Table 4. Exposure classes: EN 206-1:2000

Class/ designation	Description of environment	Informative example where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: all exposures except where there is freeze/ thaw, abrasion or chemical attack	
	For concrete with reinforcement or embedded metal: very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation (Where concrete containing reinforcement or other embedded metal is exposed to air and moisture)		
XC1	Dry or permanently wet	Concrete inside buildings with low humidity. Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete subjected to long-term water contact. Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity. External concrete sheltered from rain.
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
3 Corrosion induced by chlorides other than from sea water (Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts from sources other than sea water)		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools. Concrete exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides. Pavements. Car park slabs
4 Corrosion induced by chlorides from sea water (Where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water)		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5 Freeze/thaw attack with or without de-icing salts (Where concrete is exposed to significant attack from freeze-thaw cycles whilst wet)		
XF1	Moderate water saturation, without de-icing agents	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agents	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agents	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents. Concrete surfaces exposed to direct spray containing de-icing agents and freezing. Splash zones of marine structures exposed to freezing
6 Chemical attack		
XA1	Slightly aggressive chemical environment according to Table 2*	
XA2	Moderately aggressive chemical environment according to Table 2*	
XA3	Highly aggressive environment according to Table 2*	

Table 2 (of EN 206-1:2000) provides limiting values of SO_4, pH, CO_2, NH_4, Mg for ground water and SO_4 and acidity of natural soil for XA1, XA2 and XA3.

standard states that "environmental conditions to which it is subjected may thus need to be expressed as a combination of exposure classes".[15] It further states that "for a given structural component, it is likely that different concrete surfaces may be subjected to different environmental actions".

Australian Standard AS 3600: 2001

The Australian Standard AS 3600:2001 categories exposure environment into the following six main classes and 17 sub-classes [16]:

Exposure environment	*Sub-classification*
In contact with ground	4 (A1, A2, U)
In interior environment	2 (A1, B1)
Above ground	6 (A1, A2, B1, B2)
In water	4 (A1, B1, B2, U)
Other environment	1(U)

The detailed definition of the exposure classes is in given in *Table* 6.[16] One variable in determining exposure classification is the geographical location. For this purpose, the standard includes a map of Australia, dividing the country into tropical, arid and temperate zones and requirements differ according to locations. Besides these zones, structures above ground are further sub-divided to three areas, depending upon their distance from the coastline. This classification includes: coastal (up to 1 km from coastline), near-coastal (1 km to 50 km from coast) and inland (>50 km from coast). The classifications A1, A2, B1, B2 and C (*Table* 6) represent increasing degree of severity of exposure, while classification U represents an exposure environment not specified in the table but for which the degree of severity of exposure should be appropriately assessed.

The requirement for concrete for different exposure classes is summarized in *Table* 7. Besides stipulating the characteristic compressive strength for different exposure conditions, the standard also specifies minimum initial period of continuous curing and the average compressive strength at the completion of curing. The standard relates the required cover to reinforcement with the characteristic strength and specifies the cover thicknesses for different classes of concrete when standard formwork and compaction are used (*Table* 8) and when rigid formwork and intense compaction are used (*Table* 9). The minimum strength required for different abrasion-resistance characteristics is also included in the code and this is given in *Table* 10.

Table 5. Recommended limiting values for composition and properties of concrete in EN 206

	Exposure classes																	
	No risk of corrosion or attack	**Carbonation-induced corrosion**				**Chloride-induced corrosion**						**Freeze-thaw attack**				**Aggressive chemical environments**		
						Sea Water			**Chloride other than from sea water**									
	XO	XC 1	XC2	XC3	XC4	XS1	XS2	XC3	XD1	XD2	XD3	XF1	XF2	XF3	XF4	XA1	XA2	XA3
Maximum w/c	-	0.65	0.60	0.55	0.50	0.50	0.45	0.45	0.55	0.55	0.45	0.55	0.55	0.50	0.45	0.55	0.50	0.45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content, kg/m^3	-	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content, percent	-	-	-	-	-	-	-	-	-	-	-	-	4,0[a]	4,0[a]	4,0[a]	-	-	-
Other requirement												Aggregate in accordance with EN 12620 with sufficient freeze/ thaw resistance.					Sulfate-resisting cement [b]	

[a] Where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze/ thaw resistance for the relevant exposure class is proven.

[b] When So_4^{2-} leads to exposure Classes XA2 and XA3, it is essential to use sulfate-resisting cement. Where cement is classified with respect to sulfate resistance, moderate to high sulfate resisting cement should be used in exposure Class XA2 (and in exposure Class XA1 when applicable) and high sulfate-resting cement should be used in exposure Class XA3.

Table 6. AS 3600-2001: Exposure classification

Surface and exposure environment	Exposure classification	
	Reinforced or prestressed concrete members (Note 1)	Plain concrete members (Note 1)
1. Surface of members in contact with the ground		
(a) Members protected by a damp-proof membrane	A1	A1
(b) Residential footings in a non-aggressive soils	A1	A1
(c) Other members in non-aggressive soils	A2	A1
(d) Members in aggressive soils (Note 2)	U	U
2. Surfaces of members in interior environments		
(a) Fully enclosed within a building except for a brief period of weather exposure during construction	A1	A1
(b) In industrial buildings, the member being subject to repeated wetting and drying	B1	A1
3. Surfaces of members in above-ground exterior environments in areas that are :		
(a) Inland (>50 km from coastline) environment being -		
(i) non-industrial and arid climatic zone (Notes 3 and 4)	A1	A1
(ii) non-industrial and temperate climatic zone.	A2	A1
(iii) non-industrial and tropical cimatic zone	B1	A1
(iv) industrial and any climatic zone	B1	A1
(b) Near-coastal (1 km to 50 km from coastline) any climatic zone.	B1	A1
(c) Coastal (up to 1km from coastline but excluding tidal and splash zones)(Note 5), any climatic zone	B2	A1
4. Surfaces of members in water		
(a) In fresh water	B1	A1
(b) In sea water		
(i) permanently submerged	B2	U
(ii) in tidal or splash zones	C	U
(c) In soft or running water	U	U
5. Surfaces of members in other environments Any exposure environment not otherwise described in Items 1 to 4	U	U

Source: Table 4.3 of AS 3600-2001
Notes:

1. In this context, reinforced concrete includes any concrete containing metals that rely on the concrete for protection against environmental degradation. Plain concrete members containing reinforcement or other metallic embedment should, therefore, be treated as reinforced members, when considering durability.
2. Permeable soils with a pH < 4.0, or with ground water containing more than 1 g per litre of sulphate ions, would be considered aggressive. Salt-rich soils in arid areas should be considered as exposure classification C.
3. The climatic zones referred to are those given in *Fig* 4.3 (AS 3600-2001), which is a simplified version of Plate 8 of the Bureau of Meteorology publication 'Climate of Australia' 1982 Edition.
4. Industrial refers to areas that are within 3 km of industries that discharge atmospheric pollutants.
5. For the propose of this Table, the coastal zone includes locations within 1 km of large expanses of salt water (e.g. Port Phillips Bay, Sydney Harbour east of Spit ands Harbour Bridges, Swan River west of the Narrows Bridge). Where there are strong prevailing winds or vigorous surf, the distance should be increased beyond 1 km and higher levels of protection should be considered. Proximity to small salt water bays, estuaries and rivers may be disregarded.

Table 7. Concrete requirement of AS 3600-2001

Exposure class	f_c', MPa	Curing requirement	
		Initial continuous curing*, days	Average compressive strength at completion of curing, MPa
A1	than 20	3	Not less than 15
A2	Not less than 25	3	Not less than 15
B1	Not less than 32	7	Not less than 20
B2	Not less than 40	7	Not less than 25
C**	Not less than 50	7	Not less than 32
U	Concrete shall be supplied to ensure durability under the particular exposure environment		

*Provision will not apply for concrete cured by accelerated methods. However, average compressive strength requirement at the completion of accelerated curing will govern.
** Where the strength requirement for Class C cannot be satisfied due to inadequate aggregate strength, concrete with f_c' not less than 40 MPa may be used, provided that cement content of the mix is not less than 470 kg/m^3 and cover requirements are increased by 10 mm.

Table 8: Required cover as per AS 3600-1 where standard formwork and compaction are used

Exposure classification	Required cover, mm				
	Characteristic strength ($f'c$)				
	20 MPa	25 MPa	32 MPa	40 MPa	≥50 MPa
A1	20	20 30	20 25 40	20 20 30 45	20 20 25 35
A2	(50)				
B1	-	(60)			
B2	-	-	(65)		50
C	-	-	-	(70)	

Source: AS 3600-2001, Table 4.10.3.2
Notes:

1. Bracketed figures are the appropriate covers when concession given in Clause 4.3.2, relating to the strength grade permitted for a particular exposure classification, is applied.
2. Increased values are required if Clause 4.10.3.3 applies.

Table 9. Required cover as per AS 3600-1 where rigid formwork and intense compaction are used

Exposure classification	Required cover, mm				
	Characteristic strength ($f'c$)				
	20 MPa	25 MPa	32 MPa	40 MPa	≥ 50MPa
A1	15	15	15	15	15
A2	(35)	20	15	15	15
B1	-	(45)	30	25	20
B2	-	-	(50)	35	25
C	-	-	-	(55)	40

Source: AS 3600-2001, Table 4.10.3.4
Note: Bracketed figures are appropriate covers when the concession given in Clause 4.3.2 relating to the strength grade permitted for a particular exposure classification, is applied.

There is another Australian standard, AS 1379-1997, on specification and supply of concrete, which includes two types of concrete, namely, "normal grade" and "special grade".[17] While the normal grade concrete can be produced by ready-mixed plants throughout Australia, "special grade" concrete require characteristics additional or different from normal grade which are not available from all plants. To ensure long-term durability, the suppliers of both types of concretes have to determine and record chloride and sulphate contents and shrinkage of most frequently supplied mixes every six months. Production assessment requires statistical control based on a mix designated by the supplier as a controlled grade that is expected to be most frequently tested over a six month period. Additional cylinders of the controlled grade mix are also required to be tested at an early age after standard or accelerated curing as an indication of potential strength.

Canadian Standard CSA A23.1: 2004

The Canadian Standards Association's (CSA's) main standard on concrete is CSA A23.1 which was revised in 2004.[18,19] The standard caters to the following five major classes of exposure:

- Class C for concrete exposed to chloride exposure
- Class F for concrete exposed to freezing and thawing without chlorides
- Class N for concrete exposed to neither chlorides nor freezing and thawing

Table 10. AS 3600-2001: Strength requirements for abrasion

Member and / or traffic	Minimum characteristic strength ($f'c$) MPa
Footpaths and residential driveways	20
Commercial; and industrial floors not subject to vehicular traffic	25
Pavements or floors subject to:	
(a) Light pneumatic-tyred traffic (vehicles up to 3 t gross mass)	25
(b) Medium or heavy pneumatic-tyred traffic (vehicles heavier than 3 t gross mass)	32
(c) Non- pneumatic-tyred traffic	40
(d) Steel-wheeled traffic	To be assessed but not less than 40

Source: AS 3600-2001, Table 4.7
Note: f'_c refers to the strength of the wearing course.

- Class A for concrete exposed to severe manure and/or silage gases and liquids
- Class S for concrete subjected to sulphate exposure.

For better clarity of the exposure definitions, the above-mentioned five classes are further sub-divided and each sub-class is explained with typical examples. CSA's definitions of exposure classes are reproduced in *Table* 11.

The Canadian Standard also specifies the limiting values of prescriptive requirements for different exposure classes. These include: the water-to-cementing materials ratio, minimum compressive strength and the age at test, air content, type of curing regime, limits on cementitious materials and maximum chloride ion permeability. The abridged requirements of these parameters are reproduced in *Table* 12.[19] It may be pointed out that the Canadian standard has specified 56-day compressive strength for certain exposure classes instead of the usual 28-day strength. Further, different curing regimes are specified for different exposure classes. What is also noteworthy is the fact that the Canadian Standard is one of the first amongst the world standards to specify limits on chloride ion permeability. It can be seen from *Table* 12 that for the two extreme exposures, maximum coulomb limits are given based on ASTM 1202 chloride ion permeability test.

North American Standard ACI 318:2008

The American Concrete Institute's (ACI's) building code requirement for structural concrete, namely, ACI 318 was recently revised in 2008 and the revised version included a significantly restructured chapter on durability.[20] One of the main changes in the standard relates to an improved definition of exposure classes, which are based on the anticipated severity of exposure. The standard divided these classes into following four categories:

- Class 'F' for concrete exposed to freezing and thawing
- Class 'S' for concrete exposed to sulphates
- Class 'C' for concrete subjected to corrosion
- Class 'P' for concrete requiring low permeability.

Detailed classification of the exposure classes is reproduced in *Table* 13. These are further sub-divided into sub-classes, depending upon the degree or level of contact with moisture, chlorides, sulphates, etc. For

Table 11. Exposure classes of Canadian Standard CSA 23.1-04

Class	Definitions of C, F, N A and S classes of exposure
C-XL	Structurally reinforced concrete exposed to chlorides or other severe environment with or without freezing and thawing conditions, with higher durability performance expectations than the C-1, A-1 or S-1 classes.
C-1	Structurally reinforced concrete exposed to chlorides with or without freezing and thawing conditions. Examples: bridge decks, parking decks and ramps, portions of marine structures located within the tidal and splash zones, concrete exposed to seawater spray, and salt water pools.
C-2	Non-structurally reinforced (i.e. plain) concrete exposed to chlorides and freezing and thawing. Examples: garage floors, porches, steps, pavements, sidewalks curbs and gutters.
C-3	Continuously submerged concrete exposed to chlorides but not to freezing and thawing. Example: underwater portions of marine structures.
C-4	Non-structurally reinforced concrete exposed to chlorides but not to freezing and thawing. Examples: underground parking slabs on grade.
F-1	Concrete exposed to freezing and thawing in a saturated condition but not to chlorides. Examples: pool decks, patios, tennis courts, freshwater pools and fresh water control structures.
F-2	Concrete in an unsaturated condition exposed to freezing and thawing but not to chlorides. Examples: exterior walls and columns.
N	Concrete not exposed to chlorides nor to freezing and thawing. Examples: footings and interior slabs, walls and columns.
A-1	Structurally reinforced concrete exposed to severe manure and / or silage gases, with or without freeze-thaw exposure. Concrete exposed to the vapour above municipal sewage or industrial effluent, where hydrogen sulphide gas may be generated. Examples: reinforced beams, slabs, and columns over manure pits and silos, canals, and pig slats; and access holes, enclosed chambers and pipes that are partially filled with effluents.
A-2	Structurally reinforced concrete exposed to moderate to severe manure and / or silage gases and liquids, with or without freeze-thaw exposure. Examples: reinforced walls in exterior manure tanks, silos and feed bunkers, and exterior slabs.
A-3	Structurally reinforced concrete exposed to moderate to severe manure and / or silage gases and liquids, with or without freeze-thaw exposure in a continuously submerged condition. Concrete continuously submerged in municipal or industrial effluents. Examples: interior gutter walls, beams, slabs and columns; sewage pipes that are continuously full (e.g. force mains); and submerged portions of sewage treatment structures.
A-4	Non-structurally reinforced concrete exposed to moderate manure and / or silage gases and liquids, without freeze-thaw exposure. Examples: interior slabs on grade.
S-1	Concrete subjected to very severe sulphate exposures.(Tables 2 and 3)
S-2	Concrete subjected to severe sulphate exposure (Tables 2 and 3)
S-3	Concrete subjected to moderate sulphate exposure. (Tables 2 and 3)

Source: Canadian Standards Association, CSA 23.1-04

Notes:

(i) 'C' classes pertain to chloride exposure.

(ii) 'F' classes pertain to freezing and thawing exposure without chlorides.

(iii) 'N' class is exposed to neither chlorides nor freezing and thawing.

(iv) All classes of concrete shall comply with the minimum requirements of 'S' class noted in other Tables.

Table 12. Abridged requirements in CSA A23.1.04 for specifying concrete based on class of exposure

Class of exposure	Maximum water-to-cementing materials ratio*	Minimum specified compressive strength (MPa) and age (d) at test*	Air content (for 20 mm aggregate shown here)	Curing type Normal concrete (Not high volume SCM)	Cement restrictions	ASTM C1202 chloride ion penetrability test requirement and age at test**
C-XL	0.37	50 within 56d	4-7 or 5-8 % if exposed to freezing	Extended	-	<1000 coulombs within 56 d
C-1or A-1	0.40	35 at 38 d	4-7 or 5-8 % if exposed to freezing.	Additional	-	<1500 coulombs within 56 d
C-2or A-2	0.45	32 at 28 d	5-8 %	Additional		
C-3or C-4	0.50	30 at 28 d	4-7 %	Basic		
C-4**** or A-4	0.55	25 at 28 d	4-7 %	Basic		
F-1	0.50	30 at 8 d	5-8 %	Additional		
F-2	0.55	25 at 28 d	4-7 %****	Basic		
N***	For structural design	For structural design	None	Basic		
S-1	0.40	35 at 56 d	4-5 %	Additional	HS or HSb	
S-2	0.45	32 at 56 d	4-7 %	Basic	HS or HSb	
S-3	0.50	30 at 56 d	4-7 %	Basic	MS or MSb$^+$	

Source: Hooton R.D., Hover K. and Bickley J.A., *The Indian Concrete Journal*, December 2005.

Paraphrased notes:

* The water-to-cementing materials ratio shall not be exceeded for a given class of exposure, regardless of exceeding the strength requirement.

** Where calcium nitrite corrosion inhibitor is to be used, the same concrete mixture, but without calcium nitrite, shall be pre-qualified to meet the requirements for the permeability index in this table.

***To allow proper finishing and wear resistance, Type N, concrete intended for use in an industrial concrete floor with a troweled surface exposed to wear shall have a minimum cementing materials content of 265 kg/ m^3

**** The requirement for air-entrainment should be waived when steel troweled finish is required. Interior ice rink slabs and freezer slabs with a steel troweled finish have been found to perform satisfactorily without entrained air.

+Other types of cements meeting LH, HS, HSb are also allowed. Although LH cements are for low heat, they are allowed for moderate sulphate resistance based on C_3A content).

each category a "not applicable" class is provided for the design engineer to indicate that the exposure category does not apply to a structural member.

For each of the sub-classes, the maximum water-cementitious ratio, minimum compressive strengths and certain additional requirements are specified. These requirements are reproduced in *Tables* 14 to 18. The additional requirements pertain to guidance on cementitious materials requirement (*Table*s 15 and 16), and chloride ion limits and cover for concrete that may be subjected to corrosion (*Table* 17).

While revising the definition of exposure classes, it was ensured that the w/cm ratio and compressive strength requirements as made in ACI 318-05 are not significantly changed[21, 22].

When designing reinforced concrete structures conforming to ACI 318-08, the designer needs to select relevant exposures for each component of the structure and pick up the one that requires greatest resistance in terms of lowest w/cm ratio, highest minimum concrete strength and other additional requirements, if any. It would thus be clear that different elements in a structure will have to be designed for different exposure conditions. *Figure* 1 and *Table* 19 provide an example of different exposure classes for individual elements of a model structure [21].

Summary of main trends

The review of the some of the recent changes in the standards of selected countries discussed above revealed the following main trends:

Table 13. Exposure classes specified in ACI 318: 2008

Exposure Class	Sub-Class	
F Freezing and thawing	F0 (Not applicable): For concrete not exposed to cycles of freezing and thawing	
	F1 (Moderate): Concrete exposed to freezing and thawing occasional exposure to moisture (no deicing salts)	
	F2 (Severe) : Concrete exposed to freezing and thawing and in continuous contact with moisture	
	F3 (Very severe): Concrete exposed to freezing and thawing and in continuous contact with water and exposed to de-icing salts	
S Sulfate	SO (Not applicable):	SO4 < 0.10 % (soil) SO4 < 150 ppm (water)
	S1 (Moderate)	0.10 ≤ SO4 < 0.20 % (soil) 150 ≤ SO4 < 1500 ppm (and sea water)
	S2 (Severe)	0.20 ≤ SO4 ≤ 2.00 % (soil) 1500 ≤ SO4 ≤ 10,000 ppm (water)
	S3 (Very severe)	SO4 > 2.00 % (soil) SO4 > 10,000 ppm (water)
C Corrosion	C0 (Not applicable): Concrete that will be dry and protected in service	
	C1 (Moderate): Concrete exposed to moisture but not to external source of chlorides in service	
	C2(Severe): Concrete exposed to moisture and an external source of chlorides	
P Permeability	P0: (Not applicable): Concrete where low permeability to water is not required	
	P1 : Concrete required to have low permeability to water	

Table 14. Requirements for concrete subject to freezing and thawing exposures

Exposure class	Max w/cm	Min f_c , MPa (psi)	Entrained air	Limits on cementitious materials
F0	-	--	-	-
F1	0.45	31 (4500)	Lower	-
F2	0.45	31 (4500)	Higher	-
F3	0.45	31 (4500)		Yes

Table 16. Suitability of cementitous materials for concrete exposed to water-soluble sulfate

Exposure Class	Maximum Expansion when tested using ASTM C 1012
S1	0.10% at 6 months
S2	0.05% at 6 months or 0.10% at 12 months
S3	010% at 18 months

Table 17. Requirements for Concrete in exposures needing corrosion protection of reinforcement

Exposure class	Max. w/cm	Min f_c MPa (psi)	Chloride ion limit (water soluble chloride by % wt. of cement)	Additional minimum requirements
Reinforced concrete				
C0	-	-	1.00	-
C1	-	-	0.30	-
C2	0.40	34.5 (5000)	0.15	Cover
Prestressed concrete				
C0	-	-	0.06	-
C1	-	-	0.06	-
C2	0.40	34.5 (5000)	0.06	Cover

Table 18. Requirements for concrete in contact with water requiring low permeability

Exposure class	Max w/cm	Min f_c MPa (psi)	Additional minimum requirements
P0	-	-	-
P1	0.50	27.6 (4000)	-

Table 15. Requirements for concrete in contact with water-soluble sulfates in soil or water

Exposure class	Max w/cm	Min f_c , MPa (psi)	Required cementitious material - Types			Additional minimum requirement
			ASTM C 150	ASTM C 595	ASTM C 1157	
S0	-	-	-	-	-	-
S1	0.50	31 (4000)	II	IP(MS) IS (<70)(MS)	MS	-
S2	0.45	31 (4500)	V	-	HS	No calcium chloride admixtures
S3	0.45	31 (4500)	V + pozzolan or slag	-	HS + pozzolan or slag	

- The definition of exposure conditions is aligned with the anticipated severity of exposure during the service life of structures

- Each exposure class is further sub-divided into sub classes for more clarity. Typical examples are included for the guidance of designers.

- Depending upon the severity of exposure, limiting values for composition and properties of concrete are specified. While the minimum values of water-binder ratio and compressive strengths are specified in the North American, Canadian and Australian standards, minimum cement content is added to the recommended limiting values in the European Standard.

- Wherever essential other additional requirements are also specified; for example, permissible chloride ion limit in concrete (ACI 318); cement type for sulphate exposure (EN 206-1, ACI 318, CSA A 23.1), curing period and type of curing (AS 3600 and CSA A23.1), minimum cover to reinforcement; etc.

Exposure classes for Indian conditions

On the background of recent changes in the durability provisions of international standards, the existing classification of exposure classes in IS 456:2000 (*Table* 2), which is based on arbitrary definitions in categories such as mild, moderate, severe, very severe and extreme classes, seems inadequate and restrictive. Such definitions certainly need to be expanded and made more rational. Considering the international trends, it would be appropriate for the Indian Standard to align its exposure classes based on the anticipated severity of exposure during the service life of structures. If such changes are made in the definitions the designer would be constrained, right at the design stage, to give a detailed thought to the likely degradation mechanisms to which the structure would be subjected to during its service life. Further, such definitions would be helpful in evolving performance-based specifications for concrete structures at a later stage.

India is basically a tropical country and the major environmental parameters that influence degradation mechanisms in reinforced concrete are temperature variations and fluctuations in the levels of moisture, chlorides, sulphates and carbon dioxide. The phenomenon of freezing and thawing is generally not experienced in the country, excepting certain pockets,

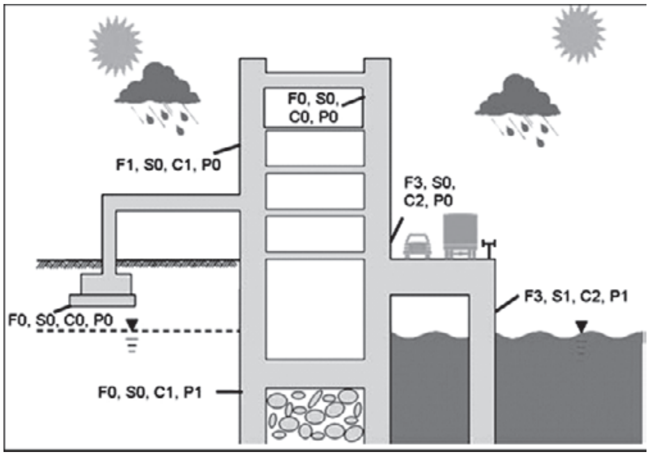

Figure 1. Typical example of durability exposure categories for elements of a concrete structure

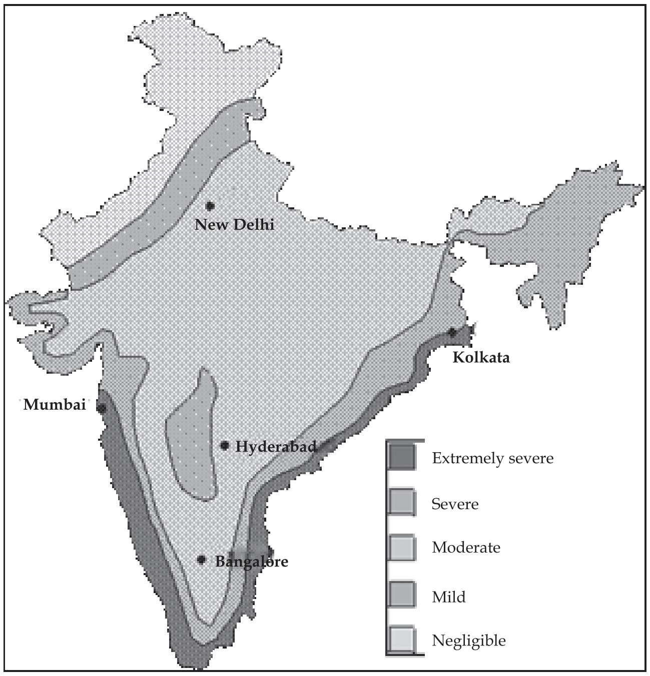

Figure 2. The corrosivity map of India

Source: http://corrosion-doctors.org/AtmCorros/mapIndia.htm

Table 19. Sample schedule of requirements for structural members on a project

Building members	Loads	Durability Categories			
	f_c MPa (psi)	F	S	C	P
Foundations and slabs on grade	20.7 (3000)	F2	S0	C1	P0
Interior columns, beams and slabs	27.6 (4000)	F0	S0	C0	P0
Exterior columns, beams and walls	27.6 (4000)	F1	S0	C1	P0
Exterior slabs	27.6 (4000)	F2	S0	C1	P0

Table 20. Suggested exposure classes for India

Exposure class	Sub-Class	Definition of exposure class	Typical example of exposure class
C Carbonation	C0	No risk of carbonation	Well protected concrete which will remain dry during service life; e.g. inside of buildings
	C1	Moderate to high humidity	Concrete subjected to moderate to high humidity; e.g. exposed concrete but sheltered from rains
	C2	Cyclic wet and dry	Exposed concrete not sheltered from rains
Cr Corrosion	Cr0	No risk of corrosion	Plain concrete; concrete with reinforcement or embedded metal that is well protected and will remain dry during service
	Cr1	Moderate humidity and chlorides from sources other than sea water	Concrete structures located in "moderate" region of the corrosivity map of India
	Cr2	Exposed to chlorides from sources other than sea water	Concrete structures located in "severe" region of the corrosivity map of India
	Cr3	Exposed to airborne salts, but not in direct contact with sea water	Concrete structures located in the "extremely severe" region of the corrosivity map of India
	Cr4	Tidal, splash and spray zones of sea water	Sea-defense structures, concrete structures located in creeks, sea
	Cr5	Carbonation-induced corrosion	Structures subjected to severe carbonation leading to corrosion of reinforcement
S Sulphate attack	S0	No risk of sulphate attack	SO3 < 0.2 % (soil) SO3 < 300 ppm (water)
	S1	Risk of mild sulphate attack	0.2 < SO3 < 0.5% (soil) 300 < SO3 < 1200 ppm (water)
	S2	Risk of moderate sulphate attack	0.5 < SO3 < 1.0% (soil) 1200 < SO3 < 2500 ppm (water)
	S3	Risk of severe sulphate attack	1.0 < SO3 < 2.0% (soil) 2500 < SO3 < 5000 ppm (water)
	S4	Risk of very severe sulphate attack	SO3 > 2.0% (soil) SO3 > 5000 ppm (water)
P Penetration resistance	P0	No risk of water contact	Concrete elements where resistance against permeability to water is not essential, e.g. interior elements of building mainly remaining dry
	P1	Exposure to water/moisture	Concrete elements requiring low permeability; e.g. elements exposed to heavy rainfall (> 2000mm) or those subjected to high humidity or those in contact with water (water retaining structures)

Note: The above table addresses general exposure conditions only. Special exposure conditions such as concrete structures that may be exposed to alkali-aggregate reactivity, abrasion, aggressive chemical attack due to sources other than sulphates, shrinkage, creep etc. shall be dealt with separately by the design engineer by consulting the relevant literature on the topic.

close to the vicinity of the Himalayas. Similar is a case for phenomena like alkali-aggregate reaction and aggressive chemical attack from sources other than sulphates, which again are likely to be encountered only in certain few pockets. Therefore, it is felt that exposures to alkali-aggregate reactivity, aggressive chemical attack due to sources other than sulphates, freezing and thawing, abrasion, shrinkage, creep etc. should be considered as special cases and may not be included in the general definition of exposure classes. They may be dealt with separately by the design engineer by consulting the relevant expert literature on the topic. For general purpose, it is suggested that the main classification of exposure classes in IS 456:2000 may be based on the following commonly-encountered conditions:

- Class 'C' for concrete exposed to carbonation
- Class 'Cr' for concrete subjected to corrosion
- Class 'S' for concrete exposed to sulphates
- Class 'P' for concrete requiring low penetration resistance or permeability.

It is further suggested that the above-mentioned main classes may be divided into following sub-classes:

Table 21. Recommended limiting values of concrete properties for exposure classes in Table 20

Exposure class	Exposure sub-class	Max. w/b ratio	Minimum cementitious content, kg/m^3	Minimum grade of concrete	Minimum nominal cover to reinforcement, mm	Recommendation on cementitious materials* #	Special requirement
C Carbonation	C0	0.55	300	M20	20	OPC, PPC, PSC	
	C1	0.45	320	M30	30	OPC, PPC, PSC	
	C2	0.45	340	M35	45	OPC, PPC, PSC	
Cr Corrosion	Cr0	0.55	300	M20	20	OPC, PPC, PSC	The total acid-soluble chloride content in fresh concrete should not exceed the values stipulated in Table 7 of IS 456.
	Cr1	0.45	320	M30	30	OPC, PPC, PSC	
	Cr2	0.45	340	M35	45	OPC, PPC, PSC	
	Cr3	0.40	360	M40	50	OPC, PPC, PSC	
	Cr4	0.40	400	M50	75	OPC, PPC, PSC	
	Cr5	0.45	340	M35	45	OPC, PPC, PSC	
S Sulphate attack	S0	0.55	300	M20	20	OPC, PPC, PSC	When chlorides are also encountered along with sulphates, it is not advisable to use SRPC**
	S1	0.50	330	M25	30	OPC, PPC, PSC	
	S2	0.50	330	M25	30	SRPC, PPC, PSC	
	S3	0.45	370	M40	45	SRPC, supersulphated cement	
	S4	0.40	400	M50	75	SRPC, supersulphated cement with protective coating	
P Penetration resistance	P0	0.55	300	M20	20	OPC, PPC, PSC	Permeability to chlorides may become essential in special cases**
	P1	0.45	340	M35	45	OPC, PPC, PSC	

*Cementitious contents recommended in this tables are irrespective of the grades of cement used and they are inclusive of the additions mentioned in clause 5.2 of IS 456. In case of PPC the proportion of pozzolana (e.g. fly ash) should lie between 15 and 35%, as stipulated in IS 1489 (Part I)-1991 and in case of PSC the proportion of ground granulated blast-furnace slag (GGBS) should be between 35 to 70% as per IS 455:1989.

In place of PPC or PSC, separate addition of SCMs to OPC such as flaysh, GGBS, silica fume, and high reactive metakaolin are permitted , provided it is ensured that they have the requisite physical and chemical properties as stipulated in IS codes and a high-efficiency mixer such as that used in a typical ready-mixed concrete facility is used in producing concrete. As regards proportion of SCMs, the upper and lower limits suggested in the codes should be adhered with.

** When chlorides are also present along with sulphates, it is preferable to use OPC having C_3A content lying from 5 to 8 %. Alternatively, PPC or PSC can also be used; however, it should be ensured that the PPC contain a minimum of 25% flyash and PSC contains a minimum of 50% GGBS.

*** In corrosion-prone exposures, lower permeability to chlorides will also be essential in addition to lower water permeability

- Carbonation "C" – 3 (C0, C1, C2)
- Corrosion "Cr"– 6 (Cr0, Cr1, Cr2, Cr3, Cr4, Cr5)
- Sulphate attack "S" – 5 (S0, S1, S2, S3, S4)
- Penetration resistance "P"– 2 (P0, P1).

Thus, there would be a total of 16 sub-classes and the detailed description of each one of them is included in *Table* 20. The division of sub-classes is based upon the risk of the likely levels of moisture/humidity, chlorides, sulphates and carbon dioxide. It may be pointed out that a provision for "no risk" class is made in each of the main exposure classes. This provision is particularly important as it will make the designer to categorically state if there is a risk or otherwise of a particular degradation. Thus, the designer cannot remain ambiguous regarding the possibility of a particular degradation.

Corrosion

It is well known that corrosion of reinforcement in concrete is an electrochemical phenomenon and there are three main pre-requisites for corrosion to occur: threshold level of chloride ions at anode, reasonable humidity (moisture), and cathode having access to oxygen. Once the chloride ion concentration at reinforcement exceeds the threshold level and sufficient amount of moisture and oxygen are available in the system, corrosion of reinforcement can proceed fast. Corrosion is a destructive phenomenon. Once the structure is affected by corrosion, it is difficult to mitigate the damage.

Corrosion can be induced by carbonation. Once the carbonation front reaches the reinforcement level, the alkalinity of the cementitious paste around reinforcement is reduced, thus creating conditions for the onset of corrosion. Carbonation is generally a slow process. Corrosion induced by chloride ions is considered to be more destructive than carbonation-induced corrosion.

Chloride-induced corrosion is a common cause of concrete deterioration in all types of structures located in coastal belt. The damage occurs at a much rapid pace in warmer climate (e.g. India). It is reported that most chemical reactions double in the rate for every 10^0C increase in temperature.[23]

India has a long coast line and the risk of corrosion exists in structures located in the close vicinity of the coast. For this purpose, the corrosion map of India (*Figure* 2) could be a good guide. The corrosion map of India was reportedly prepared by the Corrosion Advisory Bureau, Metals Research Committee (Council of Scientific & Industrial Research) Jamshedpur. The map was drawn on the basis of data collected over the 5 year period from 1963 to 1968 and published in 1970.[24] Unfortunately, it seems that this map was not updated in recent years. While there is an urgent need of updating the map, the same is used in the paper in absence any other published data.

From *Figure* 2 it can be deduced that the risk of chloride-induced corrosion would be highly imminent in the "extremely severe" and "severe" regions of southern and north-eastern parts of India.

The degree of corrosion damage would depend upon a host of factors. Hence, the corrosion-prone area indicated in *Figure* 2 could be sub-classified into more sub-categories, depending upon severity of exposure factors; chief amongst which would include relative humidity, ingress of chlorides (from sea water or other than sea water), direct contact with sea water, location in splash zone, etc. Depending upon these conditions, corrosion class "Cr" is sub-divided into six types, *Table* 20.

Carbonation

Carbon-dioxide present in air reacts with the alkaline constituents of concrete. The reaction changes alkalinity and the pore system of concrete. With the passage of time, more and more portion of concrete gets carbonated and the carbonation front shifts from the outside face towards the reinforcement. When the alkalinity of cover concrete decreases below a pH value of around 10, reinforcing steel can no longer be passivated. It can lead to corrosion of reinforcement. The rate of carbonation mainly depends upon the following factors:

1. level of humidity/water saturation of concrete : wet concrete will not carbonate!
2. water/binder ratio: lower the w/b ratio, slower would be carbonation
3. curing : poor curing can lead to rapid carbonation
4. cementious materials: materials like fly ash and blast-furnace slag are more vulnerable to carbonation; however, for equal strengths, the carbonation of both OPC concrete and concrete with supplementary cementitious materials is observed to be similar.

Carbonation would be a major deterioration factor in the interior parts of India. It would be safe to assume that structures located in interior parts of the country, excepting areas marked as "extremely severe" and "severe" in *Figure* 2, would be prone to carbonation. This does not mean that areas in "extremely severe" and "severe" regions would not be subjected to carbonation. However, since chloride-induced corrosion is more severe and fast than the carbonation-induced corrosion, it is suggested that design for chloride-induced corrosion would automatically provide protection against carbonation[23]. Incidentally, carbonation-induced corrosion is categorized under category "Cr5" and the same is already described above.

As carbonation is dependent upon the level of humidity, the degree of protection and level of saturation of concrete structures, the carbonation exposure class (C) is further sub-divided into three sub-classes, *Table* 20.

Sulphate attack

In addition to carbonation and corrosion, structures could be subjected to the risk of sulphate attack, depending upon the level of SO_3 in ground water and/or soil. Sub-classes under sulphate attack are therefore divided based on the levels of SO_3. The existing provision in IS 456:2000 (see *Table* 4 of the code) are also based on the levels of SO_3 in ground water and soil. Here, it is proposed that the provisions of classification be maintained similar to the one given in *Table* 4 of IS 456:2000. Thus, the provisions in this *Table* 4 of IS 456 are brought into *Tables* 20.

Penetration resistance

It is well known that the penetration resistance or permeability of concrete is the crux of its durability. The presence of water/moisture is crucial for any major degradation. The latest literature on durability puts considerable emphasis on controlling the penetration resistance of concrete to ensure its long-term durability. The revised exposure classification therefore includes penetration resistance to water/moisture as a separate class of exposure, *Table* 20. This class of exposure may become governing in case of all water-contact and water-retaining structures. In corrosion-prone exposures, lower penetration resistance to chlorides will also be essential in addition to lower permeability to water/moisture.

Limiting values of concrete properties

Table 21 presents limiting values of the properties of concrete. The recommended values include maximum water/binder ratio, minimum cementitious content, minimum grade of concrete, minimum nominal cover to reinforcement, recommendation on cementitious materials and special requirements. It needs to be emphasized here that the revised values suggested in *Table* 21 are more or less similar to those included in the existing standard (*Table* 3). This is done purposely. Excepting certain urban and semi-urban locations where ready-mixed concrete has today made inroads, an overwhelming majority of concrete in India is still being done by following the age-old site-mix practices. Considering this, it is considered prudent to keep the limiting values of concrete properties on a conservative side, more or less similar to those in IS 456:2000.

Cementitious contents recommended in *Table* 21 are irrespective of the grades of cement used and they are inclusive of the additions mentioned in clause 5.2 of IS 456. In place of PPC or PSC, separate addition of SCMs such as flaysh, GGBS, silica fume, and high reactive metakaolin to OPC can be permitted, provided it is ensured that they have the requisite physical and chemical properties as stipulated in relevant IS codes and a high-efficiency mixer such as that used in a typical ready-mixed concrete facility is used in producing concrete.

For the "no risk" class, the minimum grade of M20 is recommended with a maximum water/binder ratio of 0.55 and minimum cementitious content of 300 kg/m^3.

For certain critical classes of exposures, it would be appropriate to specify durability-centric tests such as water permeability (e.g. water penetration by DIN 1048) and/or chloride ion permeability test (e.g. rapid chloride ion permeability test ASTM C 1202) and/or any other proven test for initially qualifying the concrete mixes in the laboratory. However, since these are specialised tests and are presently available only in selective laboratories, it is suggested that these may be adopted for special projects. Therefore neither of these tests nor their limiting values is included in *Table* 21.

Performance-based specifications for durability

Considering the growing trend of premature deterioration of concrete structures and the need to adopt sustainability approach in concrete design and construction, a holistic approach to durability is highly essential.[25] The need for adopting service life design approach based on life cycle costing is also being felt and substantial work is presently in progress on this subject.[26, 27] Performance-based specifications for durability are also being evolved as an alternative to prescriptive specifications.

In the USA, the ready-mixed concrete producers have realized the importance of the performance-based specifications. Led by the National Ready Mixed Concrete Association (NRMCA), the ready mixed concrete industry has established the "P2P" initiative to promote a shift from traditional prescriptive specifications to performance specifications for concrete.[28]

The present author is of the opinion that the suggested changes in the definition of exposure classes augur well for developing performance-based specifications in India.

Conclusion

Based on the above discussion, the following conclusions may be drawn:

- Considering the trend of premature deterioration of reinforced concrete structures and considering the need to achieve sustainability, durability specifications in many countries have become stringent.
- 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.
- The limiting values of concrete properties for different exposure classes in international standards have been made stringent; yet remained "prescriptive" in nature.
- In line with the international trend, the paper suggests changes in the definitions of exposure classes in IS 456:2000. The existing definitions 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 has been made to keep the limiting values more or less similar to those in the existing IS 456:2000.

Suggested future work

The limiting values of concrete properties for various exposure conditions as suggested in the paper need to be validated with systematic laboratory work. This may be done for an assumed service life of say 50 years and use of accelerated tests on carbonation, chloride-induced corrosion, water permeability, etc. Similarly, efforts are needed to update the corrosion map of India."

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Mr. Vijay R. Kulkarni is presently a consultant with the Ready Mixed Concrete Manufacturers' Association (RMCMA), Mumbai. He is the former Editor of the The Indian Concrete Journal. The areas of his activities include design of bridges and buildings, R&D in concrete, NDT and repair and rehabilitation, high-performance concrete, etc.

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