Environmental exposure classifications for concrete construction – A relook

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Durability of concrete structures is dependent on the design mix used (i.e. ratio and quality of ingredients namely water, cement, fine and coarse aggregates, additives etc.), the concreting practices adopted (i.e. transportation, placing, compaction, curing, formwork used, cover adopted etc.) and on the exposure conditions to which it is subjected to during its life. The Indian Code IS 456:2000 for plain and reinforced cement concrete specifies five exposure classifications namely, mild, moderate, severe, very severe and extreme, which seem to be arbitrary and prescriptive in nature regarding durability requirements. Further, the classifications do not necessarily address the relevant mechanisms of concrete deterioration adequately. Given the importance of environmental effects on concrete service life and performance, it is necessary to have detailed classifications catering to all exposure conditions, which address the appropriate mechanisms of deterioration. This paper describes an attempt to propose a new environmental classification system for concrete construction in India. The shortcomings of the present system are described first, followed by a summarisation of the international developments in exposure classifications. Concrete mix designs from several construction sites across India executed by Central Public Works Department are then presented and analyzed in the light of the prescriptions made by codal provisions from a number of countries across the world. The results of the analyses, along with the relevant features of international developments, are used to finally propose a rational system for classification of concrete exposure conditions.

Introduction

Concrete is the most widely used material in the world next to water. Despite the availability of know-how and equipment for quality concrete construction, in the recent past many concrete structures have undergone premature deterioration resulting in early reconstruction or major repairs involving huge expenditures. This could be due to inadequate anticipation of severity in exposure conditions, poor quality of construction using site mixed concrete, increased severity due of environmental pollution etc. With the spurt in growth of infrastructure work and ever growing demand for residential accommodation, the problem of premature deterioration is to be effectively dealt with.

In addition to durability of concrete structures, sustainability is an important issue for the construction industry. Growth of population, combined with overall growth of the country, has necessitated development of industries, residential accommodation and commercial offices. Concrete use will increase many-fold in the years to come. As concrete consumes non renewable natural resource of aggregates, in addition to emission of around 1 kg of carbon dioxide for every kg of cement produced, sustainability has to be seriously addressed. One of the best ways to address sustainability is to have a more durable concrete.

The common durability problems in concrete occur due to a host of factors that act independently or in combination, chief amongst them are carbonation, corrosion of reinforcement, sulphate attack, alkali aggregate reaction and freezing and thawing. Durable concrete can be obtained by proper mix design, adopting good practice of concreting, proper compaction and curing, adopting adequate cover and anticipating the proper severity of exposure.

Environmental exposure conditions have been classified into five categories by Indian Standards in IS 456-2000 as Mild, Moderate, Severe, Very Severe and Extreme.[1] There are a set of exposure conditions clubbed into each classification. The limiting values of important parameters such as minimum compressive strength, minimum cement content, maximum water cement ratio and cover to be adopted, have been specified for each exposure classification. Concrete satisfying these criteria is deemed to be durable.

The inadequacy of the general characterisation of exposure conditions has been realised in a number of countries around the world, and new classifications of exposure for concrete construction have been adopted, and used, in some cases, for almost ten years or more. There has been a tremendous spurt in construction in India in the past decade, and infrastructure projects are proceeding at a feverish pace across our country. The time is ripe for elaborate discussions on how we can adopt performance based requirements for concrete to promote durability, and thus sustainability, in concrete construction. The first step towards this goal would be a relook into our environmental classification systems, and to come up with realistic exposure condition assessments that address the appropriate durability mechanisms, such as chloride or carbonation induced corrosion and chemical attack.

This paper summarises the developments in re-classification of exposure conditions by major codal agencies across the world and analyzes the mix designs adopted in various projects of the Central Public Works Department (CPWD) in India in the light of the recommendations in these codal provisions. Finally, a new set of environmental exposure conditions is proposed, along with limiting values of concrete compositions for achieving durability.

Exposure classifications defined by IS 456 2000

IS 456:2000, or the Indian Standard for Plain and Reinforced Concrete – Code of Practice, was revised in 2000 for the fourth time.[1] This new revision, although still lacking in many respects with regard to concrete, does reflect to some extent the advances in concrete technology since the previous revision in 1978. Particularly, the clause on durability has been elaborated and sampling and acceptance criteria for concrete have been revised. However, the exposure classifications of Mild, Moderate, Severe, Very Severe & Extreme seem to be restricted / inadequate and need more elaboration. Particularly, the classifications need to address the relevant deterioration mechanisms. Additionally, provisions for defining coastal zone, tidal zone and spray zone, along with exposure to abrasive action, can be included.

Though simple to follow, the IS 456:2000 is arbitrary in exposure conditions and lacks in depth. Since clear-cut definition of exposure classes is not available, the use of IS recommendations at times becomes confusing and leads to differing interpretation. For a better approach, the classification should be based on deterioration mechanisms and their severity. Inadequate /improper classifications could lead to erroneous or poor anticipation of exposure conditions resulting in pre-mature deterioration of structure. This leads to huge investment in construction cost of new structures or huge cost of repairs and rehabilitation at an early date. Premature deterioration may also lead to sudden failure of structures leading to loss of life and property. To address the above problems and to align the exposure classifications in line with the existing international codes, revision of the existing exposure classifications becomes a necessity. In the next section, the existing international exposure classifications are reviewed.

International developments

The salient features of various environmental classification systems from across the world were critically analysed and presented by Kulkarni.[2] It is not the intention of this paper to repeat a detailed analysis of the classification systems; So only salient features are presented.

The European code, EN 206-1:2000, has a radical approach on classifying the exposure conditions based on deterioration mechanisms like carbonation, corrosion due to chlorides, chemical attack, freeze thaw, etc.[3] Though EN 206-1:2000 and IS 456:2000 have been published in the same year, EN 206-1 is not based on arbitrary classification of exposure classes as in IS 456-2000. Further, an intended service life of 50 years has been assumed on the limiting values of concrete composition, while no such design life is considered in IS 456-2000. Concrete designation, minimum cement content and maximum water cement ratio are comparable with other codes published subsequently till date.

The British standard BS 8500 1:2006 is complementary to EN 206 1:2000.[4,3] The exposure classifications are the same as in EN 206 1:2000, with more informative examples applicable in the United Kingdom. The one major difference is the extensive coverage of sulphate and other chemical attack. Different prescriptions are made for different service life spans, namely, 50 and 100 years. Nominal cover is given as minimum cover plus an allowance in design for deviation (Δc) to accommodate fixing precision. This allowance is normally in the range of 5 mm to 15 mm for surfaces against formwork. Where concrete is to be cast against ground, a significantly higher allowance in design for deviation is required.

The American structural concrete code – ACI 318 – was revised in 2008.[5] Exposure classifications are based on mechanisms of corrosion such as freezing and thawing, sulphates, corrosion and permeability. Further sub classifications are based on the intensity of exposure. For each of the sub classes, minimum compressive strength, maximum water cement ratio and some additional requirements are prescribed. Although significantly enhanced from its previous versions, ACI 318 does not offer the same degree of depth as its European (particularly British) counterparts.

The Australian code, AS 3600:2009, includes an extensive coverage of the deterioration mechanisms pertaining to coastal zones, and sub-classifies the environment based on the distance from the coast.[6] Further, the exposure classifications are divided into above ground and below ground. Though exposure classifications are better in certain issues like definitions of coastal zone, tidal zone, spray zone and climatic zones., there still seems to be arbitrary clubbing of exposure conditions. In addition to other normal prescriptions, the code specifies minimum initial period of curing and the average compressive strength at the completion of curing.

Kulkarni's proposed classification system is primarily based on the ACI 318 model, with some inputs from the AS 3600 and EN 206.[2,5] The classifications have some reference to the corrosivity map of India, which was prepared in 1980, in deciding the sub-classifications for the concrete in chloride induced corrosion-prone areas. However, there are some deficiencies in the proposed model, in that it does not define the coastal, tidal and splash zones; further, there is some confusion in the proposal for the carbonation classification, as the carbonation induced corrosion appears in the 'Cr' category, and not in the 'C' category that deals with carbonation.

The latest development in India is in the provisions for durability indicated in IRC 112:2011, the Code of Practice for Concrete Road Bridges.[7] The primary deterioration mechanisms have been addressed, and four environments are described for corrosion of steel, which relate to the carbonation and chloride induced mechanisms of corrosion. An integrated table has been provided for concrete mix proportions (including maximum w/c, minimum cement content, and minimum concrete grade) and cover for a design service life of 100 years. Adjustment in cover requirements for certain special cases is also provided. However, the details of the service life model used, or the database used for the same, have not been provided. Durability provisions for sulphate attack are provided separately, and these are similar to the clauses in IS 456, with one difference that in IRC112, along with minimum cement content and w/c, the concrete grade requirement is also provided.

A detailed comparison of the durability provisions (including environmental classification) is provided in the work by Saravanan.[8] Some of these are highlighted in the table provided in the Appendix, in order to help the reader understand the abbreviations used in the next section.

Comparison of various codal provisions for newly executed projects by CPWD

Several projects executed by CPWD over the past couple of years were chosen to compare the final mix designs with the prescriptive values suggested by various codes, for the given service environment. While a comprehensive analysis is available elsewhere, a few examples are presented for understanding.[7]

Example 1

The first example is that of a concrete framed structure in the Bandra-Kurla area of Mumbai, at a distance of about 1.5 km from the coast. The following environmental classifications from different codes were selected for comparison:

A. EN 206-1 (2000): Classifications adopted and their requirements given below.

1. Corrosion induced by carbonation: XC3, moderate humidity requiring minimum cement content of 280 kg/m^3, w/c ratio of 0.55 and C 37 grade of concrete.

2. Corrosion induced by chlorides other than sea water: XD1, moderate humidity, concrete surfaces exposed to air borne chlorides, requiring minimum cement content of 300 kg/m^3, w/c ratio of 0.55 and C 37 grade of concrete.

3. Corrosion induced by chlorides from sea water: XS1, exposed to air borne salt but not in direct contact with sea water, structures near to coast, requiring minimum cement content of 300 kg/m^3, w/c ratio of 0.50 and C 37 grade of concrete.

4. Chemical Attack: XA1, slightly aggressive chemical environment requiring minimum cement content of 300 kg/m^3, w/c ratio of 0.55 and C 37 grade of concrete.

The most critical requirement of XS1 with 0.50 w/c ratio, 300 kg/m^3 of cement content and C 37 concrete grade adopted for comparison as per EN 206-1.

B. BS 8500-1 (2006): Classifications adopted (For intended working life of at least 50 years) and their requirements given below. (Assuming Δ "C", allowance in design for deviation as 15 mm & values taken from column of 45 + Δc)

1. Corrosion induced by carbonation: XC3, moderate humidity requiring minimum cement content of 280 kg/m^3, w/c ratio of 0.60 and C 35 grade of concrete.

2. Corrosion induced by chlorides other than sea water: XD1, moderate humidity, concrete surfaces exposed to air borne chlorides, requiring minimum cement content of 320 kg/m^3, w/c ratio of 0.55 and C 40 grade of concrete.

3. Corrosion induced by chlorides from sea water: XS1, exposed to air borne salt but not in direct contact with sea water, structures near to coast, requiring minimum cement content of 340 kg/m^3, w/c ratio of 0.5 and C 32/40 grade of concrete.

4. Freeze thaw attack: Not applicable.

5. Chemical attack: Not applicable.

The most critical requirement of XS1 with 0.5 w/c ratio, 340 kg/m^3 of cement content and C 32/40 concrete grade adopted as per BS 8500-1 2006.

C. AS 3600 (2009): Classifications adopted and their requirements given below.

1. Surface of members in contact with the ground: Members in non-aggressive soils A2.

2. Surface of members in interior environments, fully enclosed within a building except for a brief period of weather exposure during construction: Non residential: A2.

3. Surface of members above ground exterior environment (b) Near coastal 1 to 50 km) any climate zone: B1.

The most critical requirement of B1 requiring M 32 concrete with minimum average cylinder compressive strength at the time of stripping forms as 20 MPa and required cover of 40 mm adopted as per AS 3600 2009.

D. ACI 318 M-08: Classifications adopted and their requirements given below.

1. Freezing and Thawing: Not applicable.

2. Sulfate: Moderate. S1: requiring w/c ratio of 0.50 and M28 grade of concrete.

3. Permeability: Not applicable.

4. Corrosion protection of reinforcement: C1 Moderate, requiring M 17 grade of concrete (cylinder strength).

The most critical requirement S1 is selected for comparison purposes.

E. Kulkarni (2009) proposal: Classifications adopted and their requirements given below.

1. Carbonation: C1, moderate to high humidity, requiring minimum cement content of 320 kg/m^3, w/c ratio of 0.45 and M 30 grade of concrete.

2. Corrosion: Cr3, exposed to air borne salts, but not in direct contact with sea water. Concrete structure located in the "extremely severe" region of the corrosivity map of India, requiring minimum cement content of 360 kg/m^3, w/c ratio of 0.4 and M 40 grade of concrete.

3. Sulphate Attack: S2, risk of moderate sulphate attack requiring minimum cement content of 330 kg/m^3, w/c ratio of 0.50 and M 25 grade of concrete.

4. Penetration Resistance: P1, exposure to water/moisture, requiring minimum cement content of 340 kg/m^3, w/c ratio of 0.45 and M 35 grade of concrete.

The most critical requirement due to Cr3 is adopted for comparison with minimum cement content of 360 kg/m^3, w/c ratio of 0.40 and M 40 grade of concrete.

The 7 days and 28 days compressive strength are respectively 26.6 and 39.0 MPa as observed at site. The

Table 1. Comparison of exposures for the building at Bandra-Kurla, Mumbai

	Adopted at site	EN 206-1	BS 8500 2006	AS 3600-2009	ACI 318 M-08	Kulkarni Proposals	IS 456-2000
Environmental classification	**Severe**	XS1	XS1	B1	S1	Cr3	**Severe**
Concrete grade	**M 30**	C 37	C 40	M32 cylinder strength	M28 cylinder strength	M 40	**M 30**
Max W/C ratio	**0.45**	0.50	0.50	-	0.50	0.40	**0.45**
Min cementitious content, kg/m^3	**420**	300	340	-	-	360	**320**
Cover, mm	**Column - 50** **Beam - 40** **Slab - 25**	35	45	40	40	50	**45**

comparison of the requirements vis a vis the adopted mix design is shown in Table 1. The values in Table 1 clearly show the distinct differences between the requirements as per different codes.

According to the classification provided in IRC 112:2011, the area would be characterised as 'Severe' (since it belongs to a humid condition and in the coastal region). For this environment, for a 100 year design life, it is suggested to use at least M30 grade concrete with maximum w/c of 0.45, minimum cement content of 360 kg/m^3, and minimum cover of 45 mm. With the exception of the strength criterion that is more stringent in the European and British codes, the new IRC requirement matches with the European counterpart.

Example 2

Next, let us consider an example of an inland structure in Trichy, more than 100 km from the coast. The range of relative humidity prevalent in this region is around 50 – 70%, which is conducive for carbonation. However, as there are no provisions in the IS 456 for carbonation induced durability problems, the area comes under the 'Moderate' category. The following environmental classifications from different codes were selected for comparison:

A. EN 206-1 (2000): Classifications adopted and their requirements given below. (Moderate air humidity assumed)

1. Corrosion induced by carbonation: XC3, Concrete inside buildings with moderate or high air humidity requiring minimum cement content of 280 kg/m^3, w/c ratio of 0.55 and C 37 grade of concrete.
2. Corrosion induced by chlorides other than sea water: Not applicable.
3. Corrosion induced by chlorides from sea water: Not applicable.
4. Chemical Attack: Not applicable

The most critical requirement of XC3 with 0.55 w/c ratio, 280 kg/m^3 of cement content and C 30/37 concrete grade adopted as per EN 206-1.

B. BS 8500-1 (2006): Classifications adopted (For intended working life of at least 50 years) and their requirements given below. (Values taken from column of cover 30 +Δ c)

1. Corrosion induced by carbonation: XC3, reinforced concrete surfaces inside enclosed structures except areas of structures with high humidity requiring minimum cement content of 280 kg/m^3, w/c ratio of 0.60 and C 28/35 grade of concrete.
2. Corrosion induced by chlorides other than sea water: Not applicable.
3. Corrosion induced by chlorides from sea water: Not applicable.
4. Freeze thaw attack: Not applicable.
5. Chemical attack: Not applicable.

The most critical requirement of XC3 with 0.6 w/c ratio, 280 kg/m^3 of cement content and C 35 concrete grade adopted as per BS 8500-1 2006.

C. AS 3600-2009 Classifications adopted and their requirements given below. Non-industrial / non-residential and tropical climate zone assumed.

1. Surface of members in contact with the ground: Members in non-aggressive soils A2.

2. Surface of members in interior environments, fully enclosed within a building except for a brief period of weather exposure during construction: Non residential: A2.

3. Surface of members above ground exterior environment (a) Inland (> 50 kms from coast line) Non industrial and tropical climate: B1.

The most critical requirement of B1 requiring M 32 (cylinder strength) with minimum average cylinder compressive strength at the time of stripping forms as 20 MPa & required cover of 40 mm adopted as per AS 3600-2009.

D. ACI 318 M-08: Classifications adopted and their requirements given below.

1. Freezing and Thawing: Not applicable.

2. Sulfate: Not applicable.

3. Permeability: Not applicable.

4. Corrosion protection of reinforcement: C1 Moderate, requiring M 17 grade of concrete (cylinder strength). This was selected for comparison, being the only applicable environment.

E. Kulkarni (2009) proposal: Classifications adopted and their requirements given below.

1. Carbonation: C2, Cyclic wet and dry: Exposed concrete not sheltered from rain requiring minimum cement content of 340 kg/m^3, w/c ratio of 0.45 and M 35 grade of concrete.

2. Corrosion Cr1, moderate humidity, located in the "moderate" region of the corrosivity map of India, requiring minimum cement content of 320 kg/m^3, w/c ratio of 0.45 and M 30 grade of concrete.

3. Sulphate Attack: S0, No risk of sulphate attack requiring minimum cement content of 300 kg/m^3, w/c ratio of 0.55 and M 20 grade of concrete.

4. Penetration Resistance: P1, exposure to water/moisture, requiring minimum cement content of 340 kg/m^3, w/c ratio of 0.45 and M 35 grade of concrete.

The most critical requirement of Cr1 is adopted for comparison with minimum cement content of 340 kg/m^3, w/c ratio of 0.45 and M 35 grade of concrete.

The 7 days and 28 days compressive strength are respectively 24.5 and 34.8 MPa, as achieved at site. The comparison of the requirements vis a vis the adopted mix design is shown in Table 2.

Because of the humidity of the region, it would fall into the 'Very Severe' category of IRC 112-2011. For this regime, a minimum grade of M40, along with cement content of 380 kg/m^3, maximum w/c of 0.40, and cover of 50 mm are suggested. Of course, if the design life were reduced to 50 years, the cover can be reduced to 45 mm. These criteria would make the IRC requirement the most stringent one to match in the given circumstances. Adopting this guideline would provide the strongest defence against corrosion due to carbonation.

The data in Table 2 indicates that while the desired result was obtained with the use of the specific mix design on site, the strength requirement is deemed to be higher as per the international codes, with the exception of ACI 318. In the case of EN and BS specifications, the minimum cement content suggested for this exposure

Table 2. Comparison of exposures for the building at Trichy

	Adopted at Site	**EN 206-1**	**BS 8500 2006**	**AS 3600-2009**	**ACI 318 M-08**	**Kulkarni Proposals**	**Remarks (IS 456:2000)**
Environmental classification	**Moderate**	XC3	XC3	B1	C1	Cr1	**Moderate**
Concrete grade	**M 25**	C 37	C 35	M32 cylinder strength	M17 cylinder strength	M 35	**M 25**
W/C ratio	**0.45**	0.55	0.60	-	0.55	0.45	**0.50**
Cement content, kg/m^3	**380**	280	280	-	-	340	**300**
Cover, mm	**Column - 50 Beam - 30 Slab - 25**	35	30	40	40	45	**30**

condition is much lower than the value adopted at site, while the opposite trend is seen in the w/c.

In both the examples, the cement content chosen for the project was higher than the specified values as per different codes, and the w/c was well below the specified values. In spite of this, the compressive strengths achieved on site are lower than the requirements set forth by the EN and BS proposals (as well as Kulkarni's proposal). There are two primary issues at play here: (a) the quality of construction, and quality of concrete specimen preparation on site, and (b) the gradation of aggregates. In general, European concretes have a good proportion of fines (< 150 μm) in their aggregate, which leads to good packing, lowering the need for high cementitious contents for a specific strength.

The above examples are just two out of many such cases that can be used for comparison. Overall, the message from such comparisons is quite clear – substantial changes need to appear in the exposure classifications in IS 456. Further, while incorporating these changes, the provisions for performance specifications can also be included – however, that is not the focus of this paper. In the next section, a new system of classification for the Indian standards will be proposed – this is based primarily on the EN / BS systems, as they tend to define their exposure classes based on the prevalent mechanisms of deterioration.

New environmental classes for IS 456

The primary mechanisms of concrete deterioration that need to be considered to appropriately classify the environments are: (i) Chloride induced corrosion, (ii) Carbonation induced corrosion, (iii) Sulphate and other chemical attack, and (iv) Freezing and thawing. Out of these, the last one, i.e. freezing and thawing, is not a major problem in India. In any case, it can be taken care of easily by the provision of air entrainment, and suitable low w/c for the concrete. One can also base the limiting values for cement content and w/c (along with amount of air) from one of the international standards. Thus, the new system proposed in this paper would only be limited to the first three mechanisms of deterioration. Within each category of classifications, the limiting values in terms of minimum grade of concrete, minimum cementitous content (inclusive of mineral admixtures), maximum w/c, and minimum clear cover are specified.

1. Exposure classification for concrete exposed to air borne chloride but not in direct contact with sea water: Coastal (Based on distance from coast)

The distance from coast for this classification has been divided into three portions in Table 3.

1. Portion up to 10 km from coast has been classified as D1.

2. Portion beyond 10 and up to 50 km classified as D2.

3. Portion beyond 50 km classified as D3.

IS 456-2000 does not specify the limit of distance from the seawater front to be treated as coast. Since CPWD Specifications categorically state that distances up to 10 km be treated as coast, the same is proposed in the above table with classification as D1. The portion beyond 50 km is treated as inland and classified as D3 (On the lines of AS 3600-2009). The portion between 10 and 50 km is classified as D2.

Most international codes prescribe concrete grade of M 40 for the type of exposure classification represented here as D1.[2 to 6] Hence M 40 is suggested as the concrete

Table 3. Exposure classification for corrosion in concrete due to air borne chloride but concrete not in direct contact with sea water

Distance from coast	Exposure classification	Minimum grade of concrete	Minimum cementitious content, kg/m^3	Maximum, w/cm	Minimum clear cover, mm	Remarks
Up to 10 km from coast	D1	M 40	360	0.40	50	Based on CPWD Specifications (Distance up to 10 km to be treated as coast)
Beyond 10 km and up to 50 km	D2	M 30	320	0.45	40	
Beyond 50 km (Inland)	D3	M 25	300	0.50	30	Based on AS3600 (Distance beyond 50 km to be treated as inland)

Table 4. Exposure classification for concrete in contact with sea water

Exposure classification	Minimum grade of concrete	Minimum cementitious content, kg/m^3	Maximum w/cm	Minimum clear cover, mm
SW1	M 40	360	0.40	50
SW2	M 50	400	0.40	75

grade for D1. The water to cement ratio and cement content are suggested in line with other codes.

Comparing the above values with the requirements provided for the "Very Severe" classification in IRC 112:2011, it can be seen that the category D1 matches all the IRC requirements with the exception of the cementitious content, which is lower by 20 kg/m^3. [7] However, the IRC criterion of 380 kg/m^3 cementitious content is for a suggested design life of 100 years, whereas design life criteria have not clearly been incorporated in the suggested classifications in this paper. In the extreme case, the values suggested may conform to the design life of 50 years, in line with the BS8500 recommendations.

2. Exposure classification for concrete in contact with sea water

As the severity of exposure conditions is going to be different for concrete completely immersed in sea water and the concrete in spray / tidal zone, two classifications of SW1 and SW2 are proposed for concrete in contact with sea water as shown in Table 4.

SW1: Concrete completely immersed in sea water

SW2: Concrete in spray / tidal zone.

In this case, SW1 would fall under the "Severe" category of IRC 112, while SW2 would come under "Extreme" category. The maximum w/c suggested for SW2 is 0.40 as against the value of 0.35 suggested by IRC112. However, the higher strength requirement suggested here would make up for the difference in w/c. Cementitious content and clear cover are the same in both cases. SW1 in Table 4 is more stringent than the requirements for "Severe" condition in IRC 112.

3. Exposure classification for concrete exposed to sulphate

Since sulphate attack depends on the concentration of SO_3 in the ground water and soil, the classification of concrete exposed to sulphate is categorised as S0, S1, and S2 based on the sulphate concentrations, as shown in Table 5. The minimum cement content, cement to be used, water / cement ratio are selected in line with other codes. An additional clause (S3) is included to account for Magnesium attack, in a magnesium sulphate environment, which is known to be more severe than other forms of sulphate attack.

S0: No risk: SO_3<0.2% (soil), <300 ppm (water)

S1: Moderate risk: SO_3: 0.2% to 1.0% (soil), 300 to 2500 ppm (water)

S2: Severe risk: SO_3>1% (soil), >2500 ppm (water)

S3: Severe risk with magnesium sulphate SO_3>1% (soil), >2500 ppm (water)

Compared to the clauses pertaining to sulphates given in IS 456:2000 and IRC 112:2011, the following aspects can be noted:

1. Only three levels of severity are considered here as compared to five levels in IS 456 to maintain simplicity. An additional clause for magnesium sulphate has been added to address the issue of magnesium attack.

2. OPC in combination with slag and silica fume as mineral admixtures is permitted for even the

Table 5. Exposure classification for concrete exposed to sulphate

Exposure classification	Minimum grade of concrete	Minimum cementitious content, kg/m^3	Maximum w/cm	Minimum clear cover (mm)	Type of cement
S0	M 25	300	0.50	30	OPC
S1	M 35	340	0.45	40	SRC, PPC, OPC with slag or silica fume
S2	M 50	400	0.40	50	SRC, PPC, OPC with slag or silica fume
S3	M 50	400	0.40	50	SRC, PPC

higher levels of severity, as opposed to IS 456 where OPC is not permitted for sulphate contents in soil above 0.5%.

3. Concrete grade and cover requirements have been built in as part of the table, rather than providing a separate table for cover as in IS 456.

4. Supersulphated cement has not been included here as it is not readily available in the Indian market

4. Exposure classification for corrosion in concrete due to carbonation

The effect of carbonation on concrete is dependent on many factors like humidity level, wetness of concrete etc., hence three classifications are proposed as shown in Table 6.

CO: No risk of carbonation (i.e.) concrete which will remain dry during its service life or concrete permanently submerged in water.

C1: Moderate to high humidity (i.e.) concrete inside buildings with moderate to high humidity, exposed concrete sheltered from rain.

C2: Cyclic wet and dry (i.e.) concrete exposed to rain and not sheltered.

Table 6. Exposure classification for corrosion in concrete due to carbonation

Exposure classification	Minimum grade of concrete	Minimum cementitious content, kg/m^3	Maximum w/cm	Minimum clear cover, mm
C0	M 25	300	0.50	30
C1	M 30	320	0.45	40
C2	M 35	340	0.40	40

In the above table, the category C0 corresponds to the "Moderate" condition in IRC 112:2011. With the exception of the grade of concrete, all other requirements are more stringent in the IRC document. On the other hand, categories C1 and C2 correspond to the "Very Severe" and "Extreme" environments as per IRC 112. On the whole, the prescriptive values suggested in Table 6 are significantly different from the very stringent guidelines presented in IRC 112 with respect to carbonation. Possibly, a greater understanding of this issue is required with respect to carbonation in Indian service environments. This can be made possible by long term studies, which are not available currently in India.

Discussion on limiting values suggested in the new classifications

(a) Grade of concrete

The minimum grade of concrete suggested in these tables is M 25. Strength grades lower than M 25 can be produced with nominal mixes, while the limiting values provided in these tables are primarily for design mixes. It is the authors' opinion that durable concrete for structural purposes should have a minimum grade of M 25.

(b) Cementitious content

The minimum 'cementitious' content provided in the tables is inclusive of mineral additives at the appropriate replacement levels (these levels may be decided as per the current guidelines).

Additionally, the clause for maximum cement content in the concrete of 450 kg/m^3 can still be maintained, with an added limit for the maximum cementitious content of 550 kg/m^3. When the cementitious content becomes higher than this level, concrete can be subjected to a number of problems such as increase plastic and autogenous shrinkage, thermal stresses, etc.

(c) Water to cement ratio

All values suggested for the water to cement ratio in these tables actually refer to the water to cementitious materials ratio (w/cm). When higher replacement levels of mineral admixtures are used, suitable adjustment for the workability should be provided by the use of water reducing admixtures, without compromising the suggested w/cm.

(d) Cover

The specified cover is the minimum cover to the outer most reinforcement from the face of the concrete member. Though logically the cover should be based on the type of structural member like column, beam, slab, foundation etc., for simplicity purposes a single value is suggested in the table. However the specified cover can be appropriately modified in the following circumstances:

1. Cover may be reduced for slabs and fins / thin sections suitably.

2. Cover may be reduced when higher grades of concrete are used in a specific service environment.

3. For foundations, cover of 50 mm must be maintained (in line with current specifications).

Whenever reduction in cover is envisaged, the cover provided should definitely be greater than maximum aggregate size plus 5 mm. In a performance based specification, the cover value should be checked on the structural concrete using suitable cover meters.

(e) General comments

All the codes mostly follow prescriptive approach for durability requirements by specifying limiting values of few parameters. The common approach of most of the codes is to prescribe minimum cement content, maximum water cement ratio, minimum concrete grade and minimum cover to reinforcement. Since durability is a complex issue and the fact that mere adherence to prescribed specifications alone may not result in a durable concrete, it is better to restrict the number of parameters for specifying the concrete.

In reality, specifying minimum concrete grade and maximum water to cement ratio alone along with cover should be sufficient, as it is the responsibility of the concrete provider to get the specified grade of concrete with least cement content to optimise the cost of concrete. In any case, when the minimum strength grade and maximum w/c are specified, the cement content automatically gets fixed by the mixture design. Thus, there need not be a separated provision for minimum cement content. However, the upper limit of cement / cementitious content can still be maintained to avoid early shrinkage cracks and thermal cracking.

Conclusions

A new set of environmental classifications for concrete construction have been proposed in this paper. The distinct advantages of the new classifications over the existing system are that the mechanism of deterioration has been taken into account, suitable inputs have been included from international codes that have been recently updated, and the cover value is integrated into the classification system.

Limiting values of concrete properties have been suggested based on comparison of worldwide codes. These values have to be authenticated with laboratory tests and with all the exposure conditions. Use of accelerated tests on concrete exposed to varying intensity of carbonation, chloride attack, and sulphate attack should be done with different sets of cement content and water to cement ratio to verify the suggested limiting values of concrete properties.

In the long term, the limiting values would become obsolete, as performance specifications would call for the measurement of performance of the concrete in structure, rather than prescriptions of the mixture to achieve durable concrete. The new system of classification, which addresses the mechanisms of deterioration, would be suitable for the identification of appropriate test methods and durability indicators to devise the performance specifications for a given service environment. In other words, the use of the new classification system would pave the way for successful implementation of performance specifications.

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Appendix: Comparison of major durability requirements from different codes

	IS 456 2000	ACI 318 M-08	EN 206-1 2000	BS 8500-2006 (50 years design life)	BS 8500-2006 (100 years design life)	AS 3600 2009
Environmental classifications	Mild, Moderate, Severe, Very severe and Extreme	Freezing and Thawing : F0, F1, F2 and F3 Sulfate : S0, S1, S2 and S3 Requiring Low permeability : P0 and P1 Corrosion protection of reinforcement : C0, C1 and C2	No risk of corrosion or attack: X0 Corrosion induced by carbonation: XC1, XC2, XC3 and XC4 Corrosion induced by chlorides other than from sea water: XD1, XD2 and XD3. Corrosion induced by chlorides from sea water: XS1, XS2 and XS3. Freeze / thaw attack with or without de-icing agents: XF1, XF2, XF3 and XF4. Chemical attack: XA1, XA2 and XA3.	No risk of corrosion or attack: X0 Corrosion induced by carbonation: XC1, XC2, XC3 and XC4 Corrosion induced by chlorides other than from sea water: XD1, XD2 and XD3. Corrosion induced by chlorides from sea water: XS1, XS2 and XS3. Freeze / thaw attack with or without de-icing agents: XF1, XF2, XF3 and XF4. Chemical attack: XA1, XA2 and XA3.	No risk of corrosion or attack: X0 Corrosion induced by carbonation: XC1, XC2, XC3 and XC4 Corrosion induced by chlorides other than from sea water: XD1, XD2 and XD3. Corrosion induced by chlorides from sea water: XS1, XS2 and XS3. Freeze / thaw attack with or without de-icing agents: XF1, XF2, XF3 and XF4. Chemical attack: XA1, XA2 and XA3.	A1, A2, B1, B2, C1, C2 and U.
Design / Anticipated life(in years)	Not specified	Not specified	50 years	50 years	100 years	50 years + or – 20% (40 to 60 years)
Definition of coastal zones	Not specified	Not specified	Not specified	Not specified	Not specified	Distance from coast defined in three categories. 1) Up to 1 km. 2) Beyond 1 km and up to 50 kms 3) Beyond 50 kms with different exposure classifications.
Definition of tidal and Spray zones	Not specified	Not specified	Not specified	Not specified	Not specified	Tidal /splash zone is the zone 1 m below lowest astronomical tide (LAT) and up to 1 m above highest astronomical tide (HAT) on vertical structures and all exposed soffits of horizontal structures over the sea. Spray zone is the zone from 1 m above wave crest level.
Exposure to sulphate attack	For varying concentration of sulphates (expressed in SO_3) in soil, ground water the type of cement, minimum cement content and maximum water cement ratio to be used is specified.	Concretes exposed to injurious concentration of sulphates from soil and water to be made with sulphate resisting cement. Details on the type of cement and w/c provided in tables.	Values of chemicals like sulphates, magnesium, pH etc. in soil and water specified for different classifications in table.	Extensive classification system proposed for sulphates		Classifications based on sulphate contents in soil ground water & pH values.
Chlorides in concrete	Based on type / use of concrete maximum total acid soluble chloride content specified varying from 0.4 to 3.0 kg/m^3	Chloride limits for new construction specified varying from 0.06 to 0.2 % by mass.	Maximum chloride content by mass of cement specified for different classifications ranging from 1 to 0.2%.			
Requirement of concrete cover	Nominal cover to meet durability requirements specified varying from 20 to 75 mm for different exposure conditions. Minimum cover of footings to be 50 mm.	Cover to meet durability requirements separately proposed for concrete exposed to or protected from earth / weather, separately for precast and cast-in-situ concrete.	Concrete cover as per EN 1992. Cover decided by the structural class (strength grade) of concrete.	Concept of Δc introduced which is defined as allowance in design for deviation. Different compressive strength specified for different exposures with various values of Δc.	Concept of Δc introduced which is defined as allowance in design for deviation. Different compressive strength specified for different exposures with various values of Δc.	Covers specified from 20 mm to 60 mm based on environmental classification and characteristic strength of concrete.

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