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State of the Art Review on Prescriptive & Performance Based Approaches for Concrete Durability

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Abstract: Durability has become one of the most important requirements for the concrete structures across the globe. A durable concrete not only leads to the sustainability but serve for longer period without much repair and maintenances for the concrete members. The Concrete in various exposures such as mild, moderate, severe, very severe and extreme conditions was studied by researchers but no significance attention is given for the performance of the concrete in service. In the last few decades, many researchers investigated the causes of structures deterioration and suggested various solutions to tackle the durability issues which are mainly adopting of performance-based specifications rather than prescriptive. In this paper, the previous findings on concrete durability are reviewed. The studies on the durability problems are highlighted along with prescriptive and performance-based approaches and test methods. The effects on service life of the structures along with the solution are reviewed.

Keywords: Concrete, durability, performance, prescriptive based approach

1. Introduction

Concrete is the most consumed material, with three tonnes per year used for every person in the world. Twice as much concrete is used in construction as all other building materials combined (Colin R Gagg, 2014). Every country is investing on construction of buildings, bridges, roads for the development of the nation, hence, the structure must be safe, economical and durable. These structures are designed to serve for different intended periods depending upon the requirements. For example, a residential building may be designed for at max 50 years (Wang Cui Ping, 2015), on the other hand, a bridge structure is expected to last for at least 100 years with minimum repair and maintenance (Cliff Freyermuth, 2009). But, sometimes these structures are not able to survive even for the design period, due to durability problem in concrete. As per American Concrete Institute, the durability of hydraulic cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion or any other process of deterioration. There are some old structures which are still standing in-tact without any major defects or any significant loss in quality, the main reason is the absence of steel reinforcement in the structure. When steel is exposed to air or moisture, it will get corroded (Andrade et al., 2002). As a result, the dominant cause for the deterioration of these structures is corrosion of reinforced steel by carbonation and chloride ingress (Backus et al., 2013) which marks the end of the service life. Therefore, steel is the most important parameter for durability of the structure in the modern era of construction (Apostolopoulos & Papadakis, 2008).

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The conventional knowledge of the mix design approach is focused primarily on the compressive strength which depends on the mix design parameters such as water/binder ratio, type of aggregates and cement content etc. (Shah et al., 2000). In general, all the performance parameters including modulus of elasticity depends on cube strength of concrete, which are prepared and cured in ideal laboratory conditions and tested after 28 days. If the physical strength of the concrete specimen is in acceptable limits, the concrete will be durable for longer period. Similarly, when physical strength was not confirmatory, durability of the concrete will be the major concern (Dhir et al., 1989).

Performance approaches, in contrast, are based on the material properties deterioration and the mechanisms in serviceable environment, that is, exposure conditions (Hans Beushausen et al., 2019). The measurement of the properties of as built-structures allow actual accountability of synergies of workmanship, construction quality, permeability, environmental influence, composition, chloride threshold, diffusion coefficient, cover-crete and reinforcement type which becomes the rational basis for prediction of service life and the durability. For the performance assessment of concrete in service, either a core can be drilled out and series of tests can be carried out or specimen can be prepared in laboratory and the testing can be done in simulated environment. The obtained parameters are used for assessing the quality of the concrete.

The problems of deterioration occur due to transportation of fluids through porous and permeable concrete. Porosity and permeability need not to be directly related. The interconnectivity (tortuosity) of pores is generally responsible for a high permeability (Basheer et al., 2001). Moreover, the primary factor for permeability is the transition zone, which is highly porous due to the presence of flaws such as micro-cracks and bleed channels. Both porosity and permeability increase with an increase in the water cement ratio (Zhang et al., 2020). Many potentially aggressive substances like oxygen, carbon dioxide, chloride, etc., penetrate (permeation, sorption, diffusion and migration) through the cover-crete and reach the reinforcement (Bhattacharjee B, 2012). When these deleterious substances are accumulated in sufficient amount (threshold value) on concrete-steel interface, they damage the passive layer on rebar (or reduce the pH of concrete) which leads to the premature corrosion of steel (Raja Rizwan Hussain, 2014) and hence, mark the end of the service life.

Nowadays there are new techniques and enhanced concrete coming up in construction industry which strongly opposes the entry of the deleterious materials and hence the process of damage may be prolonged. Various cementitious materials like ordinary Portland cement, Portland pozzolana cement, limestone calcined clay cement and Portland slag cement, supplementary cementitious materials, admixtures and corrosion inhibitors are available which makes the concrete more resistive towards the foreign materials (Dhanya et al.,2018, Dhandapani et al., 2018, and Rengaraju et al.,2018).

The solely focus of this paper is to present a state-of-the-art review on performance-based approaches for concrete durability specially on durability indicators like carbonation, chloride ingress, UV effects on rebar coatings, etc. previous research and the findings are discussed and critiqued to emphasize the future development of research for concrete durability.

2. Prescriptive Approach Towards Concrete Durability

The prescriptive approaches are considered to be the old and reliable method of concrete mix design. However, they have been evolving with local experiences (Becker & Foliente, 2005), but are often conservative and generally do not perform up to the expectations of the performance objectives such as deterioration due to carbonation and chloride ingress in servicing structures. Prescriptive approaches focus on materials properties, materials proportions, mixing and transporting procedures and on a variety of processes, such as placing and curing i.e. from fresh concrete to hardened. In these specifications, the concretes' desired performance is not described for service time. Additionally, there is no direct evaluation of durability parameters in prescriptive specifications but they are done via indirect measures such as limits on strength, water to cement (w/c), and in some cases minimum cement content for a given durability exposure. The concrete is assumed to be durable for the specified service life when these prescriptive specifications are met (Beushausen & Fernandez Luco, 2016). Currently, there are no prescriptive based studies done to assess the durability of concrete so far, most of the papers are discussing on performance specifications. Hans Beushausen and Luis Fernandez (2016) performed a survey of relevant prescriptive codes and standards dealing with the durability of concrete structures, comparing them and highlighting coincidences and discrepancies as listed in Table 1.

Table 1 - Prescriptive general concrete construction codes/standards (Hans Beushausen & Luis Fernandez, 2016)

Country	Standard designation	Title or brief designation
USA	ACI-318-08	Structural concrete building code
	ACI 201.2R	Guide to durable concrete
CEN European Committee for Standardization	EN 1992-1-1 EN206 EN 13670	Eurocode 2: Design of concrete structures—Part 1: General rules and rules for buildings Concrete—Part 1: Specification, performance, production and conformity Execution of concrete structures
Australia	AS 3600-2001	Australian Standards on Concrete Structures
Germany	DIN 1045-2	Application Rules for EN 206
México	LNEC E 464	Concrete. Prescriptive methodology for a design working life of 50 and of 100 years under environmental exposure
Spain	EHE-08	Spanish Instructions on Structural Concrete
UK	BS 8500-1:2006	Concrete—complementary
	BS 8500-2:2006	British Standard to BS EN 206 Part 1: Method of specifying and guidance for the specifier. Part 2: Specification for constituent materials and concrete

As per the survey of the prescriptive codes, it is noted that the durability indicators in most of the codes, i.e. compressive strength, maximum water/cement ratio and minimum cement content may be inadequate to provide sufficient protection of the concrete structures against most aggressive species. The 28 day cube strength is the basis for acceptance criteria of concrete in most cases, however, the validity of compressive strength as durability indicator is being increasingly questioned (Swamy, 2008). Therefore, prescriptive-based Codes and Standards may fail in achieving potentially durable concrete designs. Additionally, there are no provisions made in most codes to control both the penetrability and the thickness of the concrete cover on site, which primarily is the deriving factor of service life of the concrete in service (Torrent , Fernandez Luco, 2007). Hence, conditions for steel corrosion develop and concrete becomes non-durable. However, there are few codes which have just included the durability parameters but not significantly (ISO 6240, 1980, ISO 6241, 1984, ISO 6242, 1992).

Apart from strength parameters, exposure classes are the another ambiguity in the prescriptive specifications. Different codes and standards (ACI 318, EN 206, AS 3600, EHE-08, NMX C403 & pNMX C155) define different set of exposure classes for equivalent categories. As a result, a univocal equivalence between exposure classes for different standards is impossible. For example, ACI 318, EN 206 defines 4 and 6 exposure categories respectively and within each category there may be sub-classes also. Hence, there are too many exposure classes which makes it unrealistic to expect the complexities to be fully described qualitatively or quantitatively (Trolley & Collepardi, 2003).

2.1 Point of View

Since the prescriptive specifications are materials property where there is no focus on durability. Strength is major factor which doesn't guarantee the performance of concrete in service, instead, more importance is given to 28 days' compressive strength which doesn't quantify the durability parameters in anyways. Most of the codes and standards are majorly following the old practices of prescriptive specifications. Defining exposure classes is another ambiguity in prescriptive specifications. Different codes categorize the exposure class differently, as a results, there is no univocal equivalence is possible for their quantification.

3. Performance Approaches Towards Concrete Durability

Unlike the prescriptive approaches, performance specifications specify what is required from the product and do not prescribe how the product should be produced. In other words, the primary focus is on the desired performance rather than on the concrete ingredients, materials selection, proportioning or construction methodology. Performance specifications rather focus more on the performance of the materials and methods used in construction of as-built structure than their initial prescription, to ensure long service life.

Although the performance based specifications exist since long time, yet most concrete specifications are predominantly prescriptive with some performance requirements. However, several codes have included few explicit guidelines keeping durability in mind and the severity of the anticipated exposure. Moreover, there is no consensus for the term "Performance specification" because it can be interpreted in many different ways by different codes (Bickley et al., 2006). For example, Table 2 illustrates few such codes. Hence, the concept of durability is not univocally understood, as a result, there is a dire need to do more research and focus more on performance based specifications.

Table 2 - Performance specifications definitions

Codes	Interpretation
CIB Working Commission W060(4)	The practice of thinking and working in terms of ends rather than means.
U.S. Federal highway Administration (5)	A performance specification defines the performance characteristics of the final product and links them to construction, materials and other items under contractor control.
NRMCA (National ready mixed concrete association) (3)	A performance specification is a set of instructions that outlines the functional requirements for the hardened concrete depending on the application.
Cement Association of New Zealand (3)	A performance based specification prescribes the required properties of the concrete but does not say how they are to be achieved.
NBR 15.575/2008 Residential building up to 5 stores – performance (7)	Behaviour of the product during service life to specify exposure conditions.

Durable concrete designing focuses on the properties of the concrete of as-built structure's aspects and parameters ranging from correct choice of exposure class and compliance with material requirements and concrete cover requirements practicing on-site in placing, compacting and curing procedures in construction. Performance specifications give proper room to address the material performance in service and use of innovative materials & techniques are highly encouraged in obtaining the desired results. However, the performance of new approaches included to meet durability parameters can't be assessed through simple mix parameters (Walraven 2008, Alexander et al., 2001, Simons 2004 and Day 2005). Therefore, deterioration of a structure in service is quantified using appropriate deterioration models, which measure material properties that can be used to predict the concrete's resistance against deleterious materials. Depending upon the level of sophistications for performance based design for durability, various input parameters are incorporated like decay constant, concrete cover, exposure time, chloride threshold, diffusion parameters, etc. to determine the service life and test methods for the verification of material characteristics probabilistically which is not possible in case of prescriptive specifications. At present, many performances based service life prediction models have been developed. For instance, a model for chloride ingress and carbonation into the concrete, was developed based on European performance design approach "DuraCrete" (Duracrete R17, 2000. The models were slightly revised and are described in the fib Model Code for Service Life Design (Fib bulletin, 2006). The other models dealing with chloride ingress include North American "Life-365" (Life, 2012) the South African chloride prediction model (Alexander at al., 1999), and more recent, the "Exp-Ref" model (Torrent 2015, Li Kefei & Torrent, 2016. These models are effectively used in service life prediction as per the onset of corrosion due to chloride and CO_2.

3.1 Point of View

The performance-based approach for concrete durability is the most reliable way of assessing the concrete behavior in service. This gives the actual responses of the concrete in a particular environment where the degree of damage caused to the structures can be found, which finally helps in prediction of remaining service life and the need for retrofitting and repairs. The equal attention is to be given to the cover-crete right from design to curing procedures. However, current limitations to this approach link to the circumstances that the various deterioration processes affecting RC structures are presently not fully understood in all necessary details. Test methods used in the laboratory do not always reflect real-life conditions, and the variation in concrete quality across the structure or single element is not sufficiently known Beushausen et al., 2015).

4. Miscellaneous Durability Issues

4.1 Service Life of Concrete Structures with Steel Rebars Coated with Cement-Polymer-Composites

Cement-Polymer-Composite (CPC) coating is used to coat the steel rebars to protect and delay the initiation of corrosion in RC structures. However, sometimes the CPC coating is inadequately applied on rusted bars which may lead to the initiation of premature under-film corrosion beneath the coating (Lyon et al., 2017). The coatings should be applied on well cleaned rebars (sandblasted) to give better corrosion protection and bond performance. This system with sand blasting and coating could significantly delay the corrosion initiation process because when CPC coating is applied on the sandblasted surface, it can provide (i) high resistance to chloride penetration due to better continuity of the CPC coating, ii) good adherence between the steel and CPC coating, and iii) reduced ionic transfer due to the limited availability of oxygen to the steel substrate (Kamde & Pillai, 2018). Additionally, the Fusion bonded epoxy coated steel rebars are stored at site for long periods in open exposed to UV radiations and they are not transported/handled/carried/bent with much care as a result, the coating layer damages due to scratches and cuts. This types of practice cause localized corrosion (crevice, under film, etc.), even without the presence of chlorides (Kamde & Pillai, 2017). Hence, the use of such rebars cause the severe durability problems.

4.2 Chloride Induced Corrosion

Concrete prepared as per design is used in different environmental conditions like coastal areas. Depending upon the ingredients used in the concrete preparation, it preforms differently towards the entry of the deleterious materials like chloride and carbon dioxide. Denser the concrete, better corrosion performance due to less porosity which makes it more resistive (Rengaraju et al., 2019). The water containing dissolved chloride enter the concrete and starts travelling towards the reinforced rebar. Once the sufficient chloride is accumulated in the steel-concrete interface then passive layer on steel rebar gets damaged and active corrosion starts (Alonso et al., 2000. Hence, end of the service life is marked which raises the problem of durability.

5. Progress in Durability From Historic Period

The change in design approaches have been very steady from prescriptive to performance based, and this is possibly due the rapid development in the testing methods of concrete structures in service. The first concrete strength test was conducted in 1836 in Germany which led to the origin of ASTM C39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens", dates from 1921 (Cemex 2013). However, some of the methods developed in 1980s are still used today including the RILEM-Cembureau method to measure oxygen permeability (Kollek, 1989), and the chloride migration test method, given now in ASTM (C1202). The test method to measure the diffusivity to chlorides, today covered by NT Build 492, was developed about 10 years later (NT Build 492, 1999). Several countries have included the performance based parameters in addition to the prescriptive specification. For example, The Swiss Standards SIA 262 and 262/1 (SIA 262/1, 2003), specify maximum values of water Sorptivity or chloride diffusivity (depending on the exposure classes) to cast specimens, and of air-permeability measured on site. South African codes and standards are still based on prescriptive specification but performance based specifications are being used by industries (Nganga et al., 2013, NGanga 2017). In many other parts of the world, performance-based methods have been under research and development, often with only limited practical applications so far.

6. Tests on Concrete for Durability

Listed below in table 3 are the commonly applied test methods in situ and laboratory. These are the test methods that are most frequently used in engineering practices and research and with which a significant experience is available.

Table 3 - Test Methods for Concrete Durability

No.	Name of the test	Description	Standards/Codes
1	Volume of Permeable Voids	Test for volume of permeable voids	AS 012.21/ASTM C642
2	Water permeability	Determines the resistance of concrete against water under hydrostatic pressure	DIN-1048 PART 5
3	Rapid Chloride Permeability Test	To assess chloride ingress/chloride diffusivity	ASTM C1202-97
4	Water absorption test	measures the amount of water that penetrates into concrete samples when submersed	BS 1881-122
5	Initial surface absorption test	measures the porosity of concrete	BS 1881-208
6	Freeze-thaw and de-icing salt scaling test	Used when concrete is exposed to freeze-thaw conditions	ASTM C666,C671,C682
7	Sulfate immersion test on mortar bar	To assess the performance of sulfate resistance cement in terms of chemical resistance	ASTM C1012
8	Alkali aggregate reactivity test	To measure expansion risk when using reactive siliceous aggregates	ASTM C227,C289,C295,C441,C586,C1260,C1293

9	Corrosion resistance test	Measures the carbonation acceleration when concrete is exposed to humidity and temperature conditions	ASTM C418,C779,C944,C1138
10	Accelerated carbonation test	Evaluates the carbonation resistance of concrete	ISO 1920 PART 12
11	Sorptivity test	To assess total porosity and fluid penetration	ASTM C1585
12	Nord test	Estimates the resistance against chloride penetration into hardened concrete or other cement-based materials	EN 12350-6
13	Migration test	Measures the diffusion coefficients of cracked mortar specimens	NT BUILD 492
14	Chloride diffusion test	Measures Chloride ingress	ISO 1920 PART 11
15	Non-steady state chloride migration test	Measures chloride ingress	NT build 492
16	Bulk conductivity	Chloride ingress	ASTM C1760
17	Electrical resistivity of concrete	To assess fluid penetration or chloride diffusivity	ASTM C1760 [53]
18	Mass loss test	Determines the mass loss over time due to one-dimensional drying and moisture transport in an initially saturated cylindrical specimen	ASTM C1792 ASTM C1760
19	Accelerated mortar bar test	Determines the susceptibility of aggregates to alkali attack, leading to expansive reactions	ASTM C1260
20	Concrete prism bar test	Determines the potential for alkali-silica reaction in aggregates due to its strong correlation with field behavior	ASTM C1293 [1]/ CSA A23. 2-14A [2]
21	Linear polarization resistance	Measures corrosion rate on steel rebar	RILEM TC 154-EMC [12]
22	Accelerated corrosion test	Measures effect on rebar embedded in concrete	ASTM G1, G109,Florida test method
23	Petrographic test	Examines and evaluates the optical properties and microstructural characteristics of the materials	ASTM C457
24	Salt ponding test	To assess chloride diffusion coefficient	ASTM C1556
25	Sulfate expansion test	To assess durability when concrete is exposed to sulfate environment	ASTM C1012,C452
26	Abrasion test	To assess the abrasion resistance	ASTM C944/C779

The tests listed above in the table given are used worldwide for concrete durability parameters assessment. However, the link between these tests results and the design life of the concrete of as-built structures is still being developing and will be further enhanced and refined as the more comparative data is generated. Also the final decision about a particular concrete can’t be finalized based on the results produced only by single test method, however, there should be alternate test methods to confirm the result.

7. Conclusion

Based on the literatures obtained in this study, the following conclusions are made:

1. Engineers should not rely on the 28 days’ compressive strength of concrete for durability, instead, it shall be quantified for intended function, time duration and exposure conditions as well.
2. Extra care shall be given to the cover concrete (dense) and its thickness to make it more resistive towards the entry of the deleterious substances, resulting delay in onset of corrosion.
3. The general prescriptive design specifications are being detrimental to durability of the structure.
4. The performance-based approach for concrete durability is the most reliable way of assessing the concrete as it gives the actual responses of the servicing concrete in a particular environment.
5. The rebars should be well cleaned (sandblasted) before the application of required coatings (CPC/FBEC) for better adherence which avoids under-film (crevice) corrosion. Moreover, the coated rebars shouldn’t be exposed to UV radiations for long time.
6. Use of SCMs and other admixtures can make the concrete denser, as a result, the entry of deleterious agents will be resisted leading to the delay in onset of corrosion.

8. Online License Transfer

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