Cement and Concrete Research 78 (2015) 155–164

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Service life prediction and performance testing — Current developments and practical applications

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ARTICLE INFO

Article history:
Received 11 April 2015
Received in revised form 8 May 2015
Accepted 11 May 2015
Available online 10 June 2015

Keywords:
Chlorides (D)
Corrosion (C)
Service life prediction
Performance testing

ABSTRACT

The paper reviews the current status of service life prediction and performance testing for concrete structures. Part I emphasizes the advantages of performance-based approaches to durability prediction, from which flows service life modeling. It also deals, inter alia, with issues around performance specifications, durability indicators, and developments in code approaches. In Part II, a practical application of the performance approach to marine concrete is given by way of data from laboratory and site-based tests. It is shown that chloride-transport tests as well as rapid indicators based on electrical properties can be used as inputs to models to provide reasonably reliable predictions of performance with certain limitations. Conversely, predictive models can be used to determine performance parameters to evaluate candidate mixtures to ensure the required performance in a given marine-exposure condition. Of necessity, the review is limited, and the interested reader is referred to the literature for further information.

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http://dx.doi.org/10.1016/j.cemconres.2015.05.013
0008-8846/

1. Introduction — part I: background and current developments

Huge developments in modern infrastructure development worldwide in the last half century or so have been due largely to the remarkable success of concrete as a functional, efficient, and universally available construction material. The built environment sector accounts for about 70% of all global material flows; taken as a percentage of materials usage in the built environment, concrete accounts for roughly 30% [1]. Part of the efficiency of concrete relates to its generally proven and excellent durability performance. Further, despite the negative perceptions of the sustainability of concrete (largely because of CO_2 emissions from cement production), it performs better than most other common construction materials, based on many measures. For example, using the sustainability metrics of embodied energy and CO_2 emissions, normal concrete achieves values of about 0.95 MJ/kg and 0.13 kg $CO_{2,eq}$/kg respectively, whereas the corresponding values for fired clay bricks are 3.00 MJ/kg and 0.22 kg $CO_{2,eq}$/kg respectively, and for steel 35 MJ/kg and 2.80 kg $CO_{2,eq}$/kg respectively [2]. Considering concrete as a bulk construction material without which human development would not be possible in the modern age, the material performs remarkably well.

As mentioned, concrete generally has excellent durability performance, as witnessed by the many concrete structures and buildings that continue to perform adequately with minimum maintenance for many decades. Even when concrete does deteriorate, repair options are usually available. Notwithstanding the ability of concrete to provide useful and long-lasting infrastructure, concrete structures on occasion face durability problems mainly due to premature deterioration, which threatens economic growth, natural and non-renewable resources, and human safety [3–5]. Considering purely the economic losses due to premature concrete deterioration, these are substantial with the annual cost of corrosion worldwide estimated at US$ 2.2 trillion (2010), which is about 3% of the world's gross domestic product (GDP) of US$ 73.33 trillion [6], and concrete corrosion contributes in some measure to this. A particular example of where concrete is subjected to very harsh environmental conditions is the Arabian Gulf, due to high temperatures and salinities. For instance, the annual cost of repair and rehabilitation due to corrosion in the United Arab Emirates (UAE) is estimated at US$ 14.26 billion (2011), which is about 5.2% of the country's GDP over three years (2009–2011) [6]. These examples of costs of repair and maintenance of RC structures serve to illustrate the scale of the problem and to highlight the threat to the concrete construction industry worldwide.

In view of the above, it is appropriate to consider how designers and engineers control the problem of concrete deterioration in structures. Put in other words, what are the approaches to ensure *durability* in concrete construction, particularly in aggressive environments? The balance of this paper seeks to address this question, by considering: current and emerging approaches to durability design and specifications for concrete structures including code developments; and an example of a practical application using a case study of concrete exposure from the Treat Island site in the USA.

2. Design and specification for control of concrete durability

Almost universally, the current approach to design and specification for control of concrete durability is still the so-called prescriptive method, long-standing in concrete practice. This is in contrast to emerging trends towards performance-based design and specification. These different approaches are dealt with below.

2.1. Prescriptive design and specifications for control of concrete durability

This approach sets limiting values for concrete mix compositions and materials – typically w/b ratio, minimum binder content, and binder type, which might include requirements for use of supplementary cementitious materials (SCMs) – and for concrete strength grade and nominal cover. It may also provide guidelines on execution of construction. These limiting prescriptive values are based on laboratory and field tests, empirical relationships, and past experience.

The prescriptive approach, however, has major drawbacks. The main problems are that the specified requirements are difficult if not impossible to verify in-situ, it cannot account for rapid developments in new materials and processes, it stifles innovation such as use of novel cements and aggregates, and perhaps most telling that, despite the prescriptions becoming ever more onerous with time, the quality of concrete construction has in general not shown corresponding improvement [7]. Material and construction variability are not taken into account, and even if intensive site supervision is carried out, it is difficult to ensure that all specified requirements are achieved [8]. Moreover, requirements such as maximum w/b ratio and minimum cement content are impractical or costly to verify in practice [9]. The general consensus is that these requirements have limited effectiveness and often stifle innovation [10].

Considering the title of this paper, the prescriptive approach is also completely unable to account explicitly for a specific *service life* requirement, i.e. it provides no rational way in which to predict a given period of time during which the structure is to remain serviceable without undue deterioration. Thus, it is also not possible to undertake proper economic analysis of the structure's performance or to budget adequately for on-going service life maintenance.

In view of the shortcomings of the prescriptive approach, there has been a strong move, at least in terms of research effort, towards *performance-based* approaches to concrete durability design and specification. This is discussed in the next section.

2.2. Performance-based design and specifications for control of concrete durability

In essence, the argument is that durability is a material performance concept for a structure in a given environment, and as such it cannot easily be assessed through simple mix parameters [11,12]. A performance approach focuses importantly on *measurement* of relevant properties of the concrete, in particular transport-related properties for durability. Consequently, robust and industry-accepted test methods are required to underpin this approach, with test results that can be shown to be accurate, reliable and reproducible. In the past, this issue of acceptable test methods, which are 'proven' to represent the relevant durability properties of concrete, has been the stumbling block to more rapid and general adoption of performance-based methods.

In practice, performance approaches represent either a partial approach (termed 'hybrid', see later), or a full performance-based approach. Both encompass key elements such as: reliable and meaningful tests by which to characterize the desired performance; definition and specification of performance limits by which to judge acceptable performance; and importantly, integration of durability requirements and durability design through service life models in order to estimate service life of the RC structure [13,14]. Crucially, in a full performance approach, specified concrete properties should be measurable in situ to ensure *as-built* quality is actually achieved. This leads on to questions of *performance testing* and *performance specifications*, dealt with below.

2.2.1. Performance testing

Performance testing requires the development and 'proving in practice' of reliable and meaningful test methods and the imposition of suitable performance limits. In some cases the appropriate limit may come from service life models — e.g. deriving a chloride diffusion coefficient such as from the Life-365 model [15]. In other cases, particularly where service life models are not well developed, the limits may come from best judgment and experience, with the intent to modify or improve these limits as better models are developed. Further, performance tests may be used in different ways. Typically they are used for pre-