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Contribution of the Durability Index Approach towards Sustainable Concrete Structures

Muigai, R. and Alexander, M.G

University of Cape Town, Rondebosch, Snape Building South Africa, Private Bag X3 E-mail: <rachel.muigai@uct.ac.za> and <mark.alexander@uct.ac.za>.

ABSTRACT

Durability and sustainability with respect to concrete structures are two important concepts that have to be defined critically to determine whether the former results in the latter.

While there is no agreement on the latter's definition, there is little disagreement that the concept is a desirable objective. This study focuses on the contribution of concrete durability through the development of the South African durability index (DI). The DI approach is based on the premise that the durability of RC structures is largely controlled by the quality and thickness of the cover layer protecting the reinforcement. The approach utilizes service life models that depend on the relevant indexes in their formulation to give performance-based specifications.

This integrated approach allows the use of marginal and new materials in concrete. In addition, the DI approach results in durable concrete structures that require minimal repair during their service life bringing about a savings in costs and material usage

INTRODUCTION

Concrete is one of the most popular materials employed in construction of civil structures and building construction projects (Wittmann et al., 2001). The current global consumption of concrete is estimated to be about 7.5 billion tonnes per year (Minerals commodity summary, 2007). This consumption is expected to increase drastically as developed countries repair and rehabilitate their ageing civil infrastructure while developing countries embark on major efforts to build theirs to provide for the needs of the rapidly increasing population. While construction with concrete continues to bring about socio-economic benefits to both developed and developing countries, it is apparent that some of the activities in the life-cycle of concrete cause a number of negative transformations to the natural environment.

Firstly, the large consumption of natural materials for concrete production diminishes the world's natural material reserves. It is estimated that globally about 9-10 billion tonnes of crushed rock, gravel and sand and about 1 billion cubic metres of water are being consumed annually in the production of concrete (Mehta, 2001). If this consumption pattern continues, then there will be fewer natural resources available in future, and the energy needed to extract the diminishing stocks and haulage distances will undoubtedly increase.

Secondly, cement, the key constituent in concrete, is energy intensive in its manufacture, and accounts for 5% of the global anthropogenic CO_2 emissions (WBCSD, 2002) as well as significant levels of SO_x [1], NO_X [2], particulate matter and other pollutants (USEPA, 1999). These greenhouse gases (CO_2 and SO_2) contribute to global warming. The cement plants have made efforts to reduce both the CO_2 emissions arising from the de-carbonation of their raw materials (CO_2-D) and those derived from the fuel burned in the kiln (CO_2-K). CO_2-D is minimized by substituting a portion of the raw materials with industrial by-products. These wastes include fly ash, silica fume, blast furnace slag and corex slag and are collectively referred to as supplementary cementitious materials (SCM's) (Mehta, 2002). CO_2-K is minimized by increasing the thermal efficiency of the kiln and by co-processing wastes, such as biomass, in the kiln. This effectively reduces the fuel consumption of the kilns and also reduces the manufacturing costs (Damtoft et al., 2008).

Lastly, concrete produces approximately 900 million tonnes of construction and demolition waste[3] (C&DW) each year (Mehta, 2002). Ideally, this waste should be recycled/reused back into concrete in order to close the life cycle loop of concrete. To facilitate the reuse and recycling of C&DW, specific regulations related to C&DW such as higher landfill fees have been introduced in some countries. However, current reuse of C&DW is restricted to minor applications such as in the construction of the granular base layer in road works and is rarely utilized for structural applications. This is mainly due to the inherent variability in the quality of recycled aggregates (RA).

Given the scale of resource flows and corresponding impacts related to current construction with concrete, sustainable development has emerged as a guiding paradigm in bringing about a balance between the society's needs and conservation of nature's resources. The meaning of the term "sustainable development" is disputed and complex. The most frequently quoted definition is given by the UN World Commission on Environment and Development (WCED) in their 1987 report 'Our common future' (Brundtland Commission Report). The report describes sustainable development as meeting "the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). The needs here refer to both economic needs (which include access to adequate livelihood or productive assets) and social needs (which include shelter protected from pollution).

In essence, sustainable development should be applied to the whole world and the people living in it now and in the future. However, the WCED definition of 'sustainable development' presents a major challenge when determining how to make it operational for use in decision making in all the different disciplines and sectors it covers.

SUSTAINABLE CONSTRUCTION

Various researches (Kibert, 1994; Spence and Mulligan, 1995; Cooper and Curwell, 1997 and Levin, 1997) have attempted to define the term 'sustainability' or sustainable development in the context of the construction industry. In general 'sustainable construction' can be summarised as an activity that minimizes use or waste of natural materials and energy resources, and one that keeps its wastes within the absorptive capacity of local and global sinks to enhance both present and future potential to meet the present and future needs. This definition makes it clear that measures of performance are needed to judge the efficacy of any construction activity on the resulting sustainability.

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[1] SO_X = Sulphur oxide

[2] NO_X = Nitrous oxide

[3] C&DW consists of non-hazardous waste resulting from the construction, remodelling, repair and demolition of structures (Macozoma, 2001)

At the design and construction stage, durability acts as an indicator of the resulting sustainability of a structure. Durability design is a strategy adopted by engineers that enables a longer life-span of full use and possibly with other uses than initially foreseen. Producing high durable elements translates to high life time expectancy and this in turn results in: (i) a decrease in material use due to reduced replacement intervals (ii) lower maintenance effort – decrease in investments for maintenance, replacement and innovation hence low life cycle costs as there is low maintenance, repair and no premature replacement (iii) The long life time will also be adequate to allow related impacts on the environment-i.e. those associated with manufacture (CO_2 emissions) and construction to be absorbed by the ecosystem e.g. through carbonation. However, over-design for durability leads to wastage of resources. It is therefore important for the design engineer to fit the material specifications to the service life requirements. The paper thus notes that the significance of durability design on the sustainability of concrete is considerable and proposes that the objectives and themes of sustainable construction be met by using the concept of durability index approach.

DURABILITY DESIGN

Background

A durable structure is defined as one that meets the requirements of serviceability, strength and stability, throughout its life-without significant loss of utility or excessive unforeseen maintenance (EN 1992). The long-term performance of concrete structures, in particular, reinforced concrete (RC) structures, depends on the interactions with the service environment, in which the penetration of deleterious substances is highly significant (Basheer et al., 2001).

Most approaches to RC durability design rely on the so-called ‘prescriptive method’, i.e. the design and specification ‘rules’ that are intended to provide for durability by prescribing limiting values for material specifications depending on the environmental conditions and life span of the structure. The specified parameters are usually the concrete cover to reinforcement, 28-day compressive strength, maximum w/c ratio, and minimum cement content. Besides the fact that these requirements can sometimes be mutually contradictory, this approach does not explicitly address rational, quantitative durability design, nor does it address sustainability issues. Regarding this latter point, prescriptive specifications relate to conventional materials and do not have the flexibility to address ‘new’ and marginal concrete materials such as recycled and site-derived materials. These materials may in certain circumstances be adequately durable but also bring a saving on raw material resource use.

Furthermore, by using the prescriptive method there is a danger of over-specification, since the prescriptive approach is inherently conservative and results in resource waste. Lastly, the approach assumes the as-built quality of concrete to be what has been specified, without the means to check actual as-built quality. It also does not account for material variability that may arise due to construction site practices such as poor workmanship and inadequate curing. Such practices may result in poor quality concrete which will require additional repair and maintenance during the structure’s service life resulting in additional unanticipated material consumption and social disruptions.

Durability Index Approach

To address some of the problems presented by ‘prescriptive approach’, performance-based approaches to durability design have been adopted and are specifically intended to limit the environmental consequences on the structure to defined acceptable levels (targets) during the structure’s service life. The approach advocates use of service life prediction (SLP) models that quantify environmental deterioration and provide an output in terms of the expected material quality. In South Africa (SA), two prediction models have been developed, related to carbonation-induced corrosion and chloride-induced corrosion[4]. The SLP models allow the expected service life of a structure to be predicted based on considerations of environmental conditions, cover thickness and concrete quality (Stanish *et al*., 2007).

For a RC structure located in a marine environment, the model represented by Equation 1 is applied to quantify the rate of chloride ingress into concrete.

$$D_i = \left[\frac{2}{x} \operatorname{erf}^{-1}\left(1 - \frac{C_{crit}}{C_S}\right)\right]^{-2} \cdot \frac{1}{t^{(-m)}} \qquad (1)$$

where, x (mm) is the distance of the reinforcing bar from the exposed surface, t represents time in seconds; C_s is the surface chloride concentration (% Cl^- by mass of cement); D_i is the initial (28-day) chloride diffusion coefficient (m^2/s), m is a coefficient representing the reduction in chloride diffusion with time, and erf^{-1} is the inverse of the error function. Equation 1 is derived from Fick’s second law of diffusion and relies heavily on the chloride conductivity test output characterizing the material quality (represented by the D_i parameter).

From this specification the designer is left with the choice of selecting a suitable material (that can be conventional, new or marginal) that will meet the requirements within the predefined acceptable level. The specified material quality is then verified on site using durability tests that characterise that quality. For chloride-induced corrosion, the chloride conductivity test (Figure 1) is applied to measure the resistance of a 30 mm thick concrete sample (Ø 68 mm) to chloride conduction under the action of an applied voltage across the specimen.

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[4] This paper specifically focuses on chloride-induced reinforcement corrosion- detailing the service life prediction model and the durability index test that relate to this type of deterioration

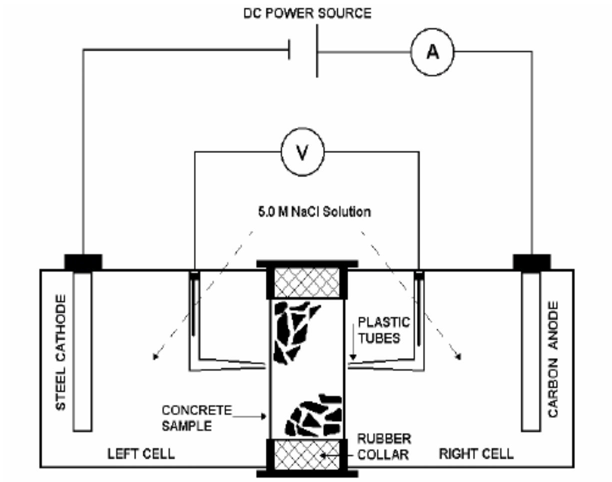

Figure 1: Chloride conductivity test schematic (Alexander et al., 1999)

From the CCT a chloride conductivity value (σ) is determined by applying Equation 2.

$$\sigma = \frac{it}{VA} \qquad (2)$$

where σ is the chloride conductivity (mS/cm), i is the measured current (mA), t is the specimen thickness (cm) and A is the cross-sectional area (cm^2). The CCT is an important test as it not only assesses the quality of the covercrete during construction but also correlates the chloride conductivity value to the diffusion coefficient, D_i, through use of an empirical relationship between the 28-day chloride conductivity value and 2 year diffusion coefficients that was established using 2 different techniques (Mackechnie and Alexander, 1996):

(i) Concrete core samples were obtained from marine structures in South Africa, and their chloride conductivity values (obtained using Equation 2) were correlated to chloride ingress values (obtained using Equation 1).
(ii) Experimental correlations were carried out between 28-day conductivity index values and chloride diffusion coefficients of controlled exposure site specimens. The specimens covered a range of binder types (100% Portland cement and combinations of PC with supplementary cementitious materials that included Fly ash and Blast Furnace Slag); water/ binder ratios and curing regimes

This test is one of the three accelerated tests developed and adopted in South Africa for characterizing the potential durability of the covercrete. The other two tests are the oxygen permeability and the water sorptivity tests which measure the permeation of gases into concrete and absorption of water into concrete respectively. Similar to the CCT, the oxygen permeability index is used in the carbonation prediction model.

In addition, uncertainties associated with the parameters in the model have been taken into account using probabilistic means as illustrated in Muigai (2008). This probabilistic approach allows for more refined service life predictions.

CONCLUSION

The durability index approach combines predictive models of deterioration with performance test methods, to give the expected concrete quality based on considerations of environmental conditions and cover thickness. The as-built concrete quality value is verified on site using the durability index test. By so doing, the method ensures that the quality of the concrete structure is sufficient to enable it meet both its service life and sustainability requirements. In this sense, the structure is sufficient from both the technological and sustainability points of view.

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REFERENCES

Alexander, M.G., Stanish, K., (2001) Durability design and specification of reinforced concrete structures using a multi-factor approach, *Conference Proceedings in Honour of Sidney Mindess*.

Alexander, M.G., Streicher, P.E. and Mackechnie, J., R., (1999), Rapid Chloride Conductivity testing of Concrete, *Research Monograph*, University of Cape Town

Basheer L., Kropp J. and Cleland D J (2001) Assessment of the durability of concrete from its permeation properties, Construction & Building Materials, 15(2-3), pp. 93-103

Cooper, I. and Curwell, S. (1997). BEQUEST – Building Environmental Quality Evaluation for Sustainability through Time. *Proc. Second International Conference on Buildings and the Environment, CSTB and CIB*, **2**, Paris, June, 515–523.

Damtoft, J S., Lukasik, J., Herfort, D., Sorrentino, D., Gartner E M., (2008), Sustainable development and climate change initiatives, *Cement and Concrete Research*, 38 (2), pp. 115-127

EN 1992 –Part 1-Eurocode 2- Design of concrete Structures-Part 1: General rules and rules for buildings

ISO 13823 (2008) General Principles on the Design of Structures for Durability, ISO TC98/SC2, Final Draft.

Kibert, C.J. (1994). Establishing principles and a model for sustainable construction. *Proc. First International Conference of CIB TG16 on Sustainable Construction*, Tampa, Florida, November, 3–12.

Levin, H. (1997). Systematic evaluation and assessment of building environmental performance (ASEABEP). *Proc. Second International Conference on Buildings and the Environment, CSTB and CIB*, **2**, Paris, June, 3–10.

Mackechnie, J.R., Alexander, M.G., (1996), Marine Exposure of Concrete under selected South African Conditions, *3rd CANMET/ACI International conference on performance of concrete in marine environment*.

Macozoma, D.S., (2001), Towards an established secondary construction materials market in SA: Some bottlenecks and solutions, CIB World Building Congress, Wellington New Zealand.

Mehta, P.K. (2001) Reducing the environmental impact of concrete, Concrete International, 23(10), pp. 61-66

Mehta, P.K., (2002), Greening of the Concrete industry for Sustainable development, *Concrete International*, 24(7), pp. 23-28

Minerals commodity summary - cement – 2007, 2007-06-01, Retrieved 2009-10-12.

Muigai R. (2008), Probabilistic modelling for durability design of reinforced concrete structures, Master's dissertation, University of Cape Town.

OECD (1995). OECD environmental data compendium 1995. OECD, Paris.

Spence, R. and Mulligan, H. (1995). Sustainable development and the construction industry. *Habitat International*, 19(3), 279–292

Stanish, K., Alexander, M. G., Ballim, Y., (2007), A Framework for Use of Durability Indexes in Performance-based Design and Specifications for Reinforced Concrete Structures, *Materials and Structures Journal*, DOI 10.1617/s11527-007-9295-0

United States Environmental Protection Agency (USEPA), (1999) , 40 CFR part 63 national emission standards for hazardous air pollutants for source categories; Portland cement manufacturing industry; final rule, USEPA, Washington, D.C.

WCED (World Commission on Environment and Development), (1987), Our common future. Oxford University Press, Walton Street, Oxford, U.K.

Wittmann, F., Gebauer, J. and Torrent R. (1996) The Versatility of Concrete, Concrete in the service of mankind: Appropriate Concrete Technology: Proceedings of the International Conference Held at the University of Dundee, Scotland, UK on 24-26 June 1996, Dhir R. K. and McCarthy M.J. (Eds.), pp. 149

World Business Council on Sustainable Development (WBCSD), (2002), Toward a sustainable cement industry, *Draft Rep.* Battelle Memorial Institute/WBCSD, Geneva.