Design of Durable Concrete Mixes for Reinforced Concrete (RC) Structures

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Abstract

In the construction industry, there are growing concerns with the use of concrete due to: i) its carbon footprint arising from the high CO_2 emissions during the production of clinker, the main constituent of cement, and, ii) lack of durability of reinforced concrete (RC) structures resulting in costly repairs and rehabilitation. Various approaches of reducing emissions from clinker production have been implemented by cement manufacturers. A further approach proposed for reducing this carbon footprint is a reduction of clinker (effectively cement) content in concrete. The reduction of clinker content, however, is not readily feasible in most design standards as a minimum cement content is required for durability. This prescriptive approach has several limitations which has resulted in a shifted to a performance-based approach. This paper is based on an ongoing study that proposes such a shift from the prescriptive approach in Kenya. An overview is given on the data collection stage that involved the use of a research questionnaire. The respondents were various parties involved in design and construction of RC structures. General observations revealed that majority of the respondents were concerned about the lack of durability of RC structures. This was mainly attributed to poor workmanship.

Keywords: sustainability, reinforced concrete (RC), durability, performance-based approach, interviews

1 Introduction

The main theme of this conference is ‘Engineering a Post Covid Future’. This raises the question, “how will a Post Covid future have an impact on how I undertake my roles in design and construction of structures as a Civil Engineer?” Will it be business as usual, and if not, what will change?

In the recent past, there have been several major infrastructural development projects in Kenya. These include the Standard Gauge Railway, the Lamu Port and South Sudan Ethiopia Transport Corridor (LAPSSET), and the Nairobi Expressway. In these projects, for the construction of structures such as bridges, interchanges and box culverts, reinforced concrete (henceforth, RC) was widely used. To ensure sustainability in these construction projects, there was a need to ensure efficient use of resources while considering the environmental impact of construction using concrete and durability (longevity) of these RC structures (Mehta and Burrows, 2001;Gjørv, 2011;Hooton and Bickley, 2014;Hooton, 2019).

For RC structures, the predominant mode of deterioration is the corrosion of reinforcement which leads to cracks and spalling of concrete cover (Bentur et al. 1997; Richardson, 2002). The corrosion of reinforcement depends on the exposure conditions and may result from penetration of chlorides (marine environments) or carbonation (e.g. in car parks). This paper provides an overview of the approach used for design of concrete mixes in Kenya and the limitations of this ‘prescriptive’ approach. It then discusses the performance-based approach and its benefits. The final sections provide an overview of data collection with the use of interviews in an ongoing study by the main author.

1.1 Design for durability of RC structures in Kenya

The provisions for concrete works in Kenya are in Chapter 17 of the Standard Specifications for Road and Bridge Construction (1987). In this document, specifications on the required properties are given for the constituent concrete materials –the cement, fine and coarse aggregates, water and admixtures.

Section 1704 in this specification outlines provisions for design of concrete mixes, which commences with consideration of class of concrete. These classes are based on compressive strength required and the maximum nominal size of aggregates. For the design of mixes, there is a provision of minimum cement content in Table 17-2, with consideration of three exposure conditions - moderate, intermediate and severe exposure. The purpose of provision of a minimum cement content is to achieve impermeability and durability.

The provisions in the standard specifications are prescriptive and have several limitations such as:

i. The exposure conditions provided are ambiguous and can be subjective. There is need for a clear definition of exposure conditions such as those provided in Table 1 of EN 206-1 (2013) (similar to KS EAS 131-1, 2008) where a comprehensive description of exposure conditions is given.

ii. It is difficult to measure and verify whether the minimum cement content in a built structure complies with the provisions for a minimum cement content (Neville, 2001; Bentur and Mitchell, 2008). There have been various studies on the subject of minimum cement content and its effects on durability such as provided in Buenfeld and Okundi (1998), Dhir et al.(2004), Wasserman et al. (2009) and Yurdakul (2010). From these studies, it was observed that the cement content can be reduced from the minimum cement content provisions without having an adverse effect on durability. Therefore, to ensure sustainable construction of RC structures in Kenya, this approach should be practically implemented.

iii. The Standard Specifications developed in 1987 fails to consider the changes in cement -both the physical properties (fineness) and chemical properties (Aitcin, 2000; Neville, 2001; Hooton, 2008). A major change in cement is use of supplementary cementitious materials (SCMs) such as slag and pozzolana in production of blended cements e.g. in Bamburi (2020). Due to such changes in cements, the minimum cement content as provided for in the specification may no longer be valid.

iv. The quality control measure for RC structures is a measure of compressive strength on 150 mm cubes. This approach of quality control assumes that on attaining the specified strength, the durability of a RC structure is also achieved. This, however, is false as has been observed in Hooton and Bickley (2014). For RC structures, the aspect that has the highest impact on durability is the properties of the concrete cover - its penetrability and depth (Beushausen et al., 2019).

1.2 From Prescriptive to a Performance-based approach

Due to the limitations in the current provisions for the design of concrete mixes, as mentioned above, there is a need to shift from a prescriptive to a performance-based approach. This has been undertaken in some countries such as Canada(Hooton and Bickley, 2014), Switzerland(Torrent, 2019), Norway (Gjorv, 2013) and South Africa (Beushausen et al., 2019).

A concise overview of the performance-based approach to design for durability is outlined below:

i. Determination of exposures conditions and the predominant deterioration mechanism in a given environment. The use of exposure conditions provided in Table 1 of the BS EN 206-1 (2013) provides a comprehensive guide for this.

ii. On determining the exposure conditions, a suitable Service Life Model (henceforth, SLM) is used depending on the predominant transport mechanisms in a given environment. For example, in marine environments, corrosion is mainly due to penetration of chloride ions and the model used is based on Fick's 2^{nd} law of diffusion (Richardson, 2002). The input parameters required are the surface chloride content, service life and the cover depth obtained from EN 1992.1-1 (2004).

iii. From the SLM, measurable parameters, e.g. diffusion coefficient and cover depth, are obtained which are then be used as performance-based specifications (Richardson, 2002). These specifications are used in quality control of the concrete cover (Beushausen et al., 2019, Gjorv, 2013, Hooton and Bickley, 2014). The main challenge encountered in this approach is development of a suitable test that can be used globally, as the different countries where this approach is used have different tests(RILEM, 2016).

1.3 Research objectives

This paper is based on an ongoing research study where the main objective is to propose a shift from the current prescriptive approach used in Kenya to a performance-based approach. An overview of the three phases that are to be undertaken in the study are provided below:

Phase I: Data collection with the use of a research questionnaire to obtain information from the different parties involved in construction of RC structureson their considerations on design for durability.

Phase II: Fabrication of Oxygen Permeability Index (OPI) test developed by (Ballim, 1991) which will be adopted and used to provide a measure of permeability of concrete mixes.

Phase III: Experimental work aimed at determining the effects of a reduction of clinker (effectively cement content) on the properties of concrete mixes – its workability, compressive strength and durability.

2 Methodology

Phase I, which involved undertaking interviews using a research questionnaire, was undertaken from March to October of this year. The data collection consists of information from consultants involved in structural design, ready mix concrete suppliers, concrete technologists, and academics/researchers. The target number of respondents was 30, but to date, only 21 respondents have been consulted.

The research questionnaire comprised of five questions which are summarized below:

i. The first two questions aimed at obtaining information on the respondent – their occupation and number of years in this position;

ii. The subsequent question sought to determine the approach used in mix design, that is, whether they used the British approach (BRE, 1997) or the American approach (ACI 211.1-91, 2002);

iii. The fourth question asked respondents if the lack of durability of RC structures has been a concern and if so, whether this concern is due to poor structural design, poor workmanship or quality of materials;

iv. The final question sought to determine if the respondents have made changes in their design of concrete mixes for RC structures due to new materials in the industry such as chemical admixtures and blended cements.

3 Results

From responses to the research questionnaire, the following aspects were observed:

i. *Design approach*: For the interviewees who implemented concrete mix design, the common approach was the BRE (1997) method with two respondents using the American approach as is given in (ACI 211.1-91, 2002).

ii. *Lack of durability in RC structure*: Seventeen of the respondents indicated that they found the lack of durability of these structures to be concerning. Of these respondents, majority attributed this to poor workmanship, and a few attributed this to quality of materials used in concrete mixes and structural design.

iii. *Changes in mix designs with new materials e.g. blended cements and admixtures*:

   a. With blended cements, the consultants indicated that they made provisions for higher cement content so as to obtain the required strength. They also observed that with the use of these cements, there is slow strength development and this is suitable for structures where early strength development is not required. These blended cements also have a low heat of hydration which makes them suitable for mass concrete structures.

   b. A concrete technologist highlighted his concern with the use of pozzolanic cements that are being introduced into the construction industry where there is no proper control on quality of pozzolans used in these blended cements.

   c. A consultant indicated that his main concern with concrete mixes was the high variability with compressive strength, and sometimes the lack of it which has resulted in collapse of structures in some cases. He indicated that it may be difficult to introduce a new test for durability as they were already having complaints from contractors who are now required to always test for compressive strength of RC structures.

d. One consultant indicated that blended cements are beneficial where durability concerns are encountered, e.g. in marine areas where sulphate resistant cement was used in design of concrete mixes for a jetty.

e. The use of admixtures has been adopted by some consultants in concrete mix design to increase workability for concrete mixes that is to be pumped up to high levels for high-rise structures and also use of admixtures to accelerate strength gain.

f. One respondent indicated that the older cements resulted in high strength and less cracking in comparison to the newly introduced cements.

g. Most of the respondents indicated that where strength was attained, the durability requirements were also met.

4 Discussion

An overall observation from the responses of the different parties is that the lack of durability of RC structures is a growing concern. There is also an appreciation of the benefits of using blended cements in severe environment such as marine areas instead of Portland cement (CEM I). The construction industry has also embraced the use of chemical admixtures to modify different properties of concrete. The concern with lack of durability in RC structures was mainly attributed to poor workmanship. Therefore, an approach is required to assess the workmanship. This is possible with the use of a performance-based approach where assessment of the concrete cover, its depth and penetrability, are checked regularly using appropriate methods.

5 Conclusion

The investment in infrastructural projects in Kenya is substantial. A majority of structures such as bridges and interchanges are constructed using RC. Therefore, we as Engineers in a post covid future will need to ensure sustainable construction which considers impacts of a structure on the environment and in efficient use of resources. A key aspect in ensuring efficient use of resources is the construction of durable RC structures. This aspect of durability should be considered from the design stage, construction and in maintenance of RC structures. In this future, we shall not only require attainment of the specified compressive strength but also the durability of our structures.

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REFERENCES

ACI 211.1-91. (2002). *Standard Practice for selecting proportions for normal, heavy weight and mass concrete*. American Concrete Institute.

Aitcin, P. (2000). Cements of yesterday and today: Concrete of tomorrow. *Cement and Concrete Research*, *30*(9), 1349–1359.

Ballim, Y. (1991). A low cost, falling head permeameter for measuring concrete gas permeability. *Concrete Beton*, *61*, 13–18.

Bentur, A. and Mitchell, D. (2008). Material performance lessons. *Cement and Concrete Research*, *38*(2), 259–272.

Bentur.A, Diamond, S. and Berke, N. S. (1997). *Steel corrosion in concrete : Fundamentals and civil engineering practice* (1st ed.). E&FN Spon.

Beushausen, H., Torrent, R., & Alexander, M. G. (2019). Performance-based approaches for concrete durability: State of the art and future research needs. *Cement and Concrete Research*, *119*(January), 11–20. https://doi.org/10.1016/j.cemconres.2019.01.003

BRE. (1997). *Design of normal concrete mixes*. British Research Establishment.

BS EN 206-1, (2013). *Concrete – Part 1: Specification, performance, production and conformity*. British Standard Institute.

Buenfeld, N.R. and Okundi, N. (1998). Effect of cement content on transport in concrete. *Magazine of*

Concrete Research, *50*(4), 339–351.
Douglas Hooton, R. (2019). Future directions for design, specification, testing, and construction of durable concrete structures. *Cement and Concrete Research*, *124*(July), 105827. https://doi.org/10.1016/j.cemconres.2019.105827
EN 1992.1-1. (2004). *Eurocode 2: Design of Concrete Structures - Part 1-1: General rules and and rules for buildings*. European Committee for standardization.
Gjorv, O. E. (2013). Durability design and quality assurance of major concrete infrastructure. *Advances in Concrete Construction*, *1*(1), 45–63. https://doi.org/10.12989/acc.2013.1.1.045
Gjørv, O. E. (2011). Durability of concrete structures. *Arabian Journal for Science and Engineering*, *36*(2), 151–172. https://doi.org/10.1007/s13369-010-0033-5
Hooton, R. D. (2008). Bridging the gap between research and standards. *Cement and Concrete Research*, *38*(2), 247–258. https://doi.org/10.1016/j.cemconres.2007.09.012
Hooton, R.D. and Bickley, J. A. (2014). Design for durability: The key to improving concrete sustainability. *Construction and Building Materials*, *67*(PART C), 422–430. https://doi.org/10.1016/j.conbuildmat.2013.12.016
KS EAS 131-1 (2008). *Concrete - Part 1: Specification, performance, production and conformity*. Kenya Bureau of Standards.
Mehta, K. and Burrows, R. W. (2001). Building durable structures in the 21st Century. *Concrete International*, *23*(3), 57–63.
Ministry of Road and Public work (MoR&PW). (1987). *Standard specification for road and bridge construction*.
Neville, A. (2001). Consideration of durability of concrete structures: Past, present and future. *Materials and Structures*, *34*(2), 114–118.
Richardson, M. G. (2002). *Fundamentals of durable reinforced concrete* (1st ed.). Spon Press.
RILEM. (2016). *RILEM TC 230-PSC Performance-Based Specifications and Control of Concrete Durability* (Issue September). http://www.springer.com/978-94-017-7308-9.
Torrent, R. J. (2019). Bridge durability design after EN standards: present and future. *Structure and Infrastructure Engineering*, *15*(7), 886–898. https://doi.org/10.1080/15732479.2017.1414859
Wasserman, R., Katz, A. and Bentur, A. (2009). Minimum cement content - a must or a myth. *Materials and Structures*, *42*, 973–982.
Yurdakul, E. (2010). Optimizing concrete mixtures with minimum cement content for performance and sustainability. In *Optimizing concrete mixtures with minimum cement content for performance and sustainability*.