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Performance Based Durability Design and Specification for Concrete Structures: A Paradigm Shift towards Sustainable Concrete Research and Production in Nigeria

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Abstract

The growing demand for and investment in infrastructure and housing being witnessed in Nigeria implies an intensified use of cement and invariably concrete which is the most widely used construction material. The massive investment in concrete structures demands that these structures are durable and functional over their designed service life. Properties of concrete determines to a large extent the strength and durability performance of concrete which further depends on the properties and interaction of the constituent materials. This article presents a need for integrating performance-based requirements in concrete design and production with a focus on the interdependence between concrete microstructure, exposure environment and durability towards ensuring sustainability. A framework for research and development towards incorporating performance-based specification in concrete research, development and production is presented as a way of strengthening the weak link between researchers and the industry. The framework is developed based on the South African context presented by Ballim and Alexander. This is to enhance quality control and assurance with respect to concrete research and production to achieve design requirement and service life of concrete structures.

Keywords: Durability, performance-based specification, prescriptive specification, concrete, research and development

Introduction

Designing and constructing durable concrete structures to achieve the designed service life is crucial to prevent premature deterioration and maintenance of such structures. Premature deterioration of concrete structures has put the perceived durability of concrete owing to chemical and dimensional stability in most exposure environment in question (Alexander *et al.*, 1999). The recent policy on road construction in Nigeria with focus on the use of concrete pavement as opposed to asphalt-based pavement calls for the consideration of concrete durability performance. The policy stems from the perceived durability and lesser maintenance requirement of concrete compared to asphalt pavement. However, concrete being a porous material is subjected to deterioration with time depending on the severity of the exposure environment and the quality of the concrete. The quality of concrete with respect to durability requirement of structures is more often indicated by the quality of the cover concrete with respect to its susceptibility to ingress of aggressive agents. This implies that the quality of the cover concrete should be dictated by the severity of its envisaged service condition/environment, which should be an important consideration at the design phase of a project. It is also imperative to understand the impact of material properties and design parameters on the quality of concrete vis-à-vis its ability to withstand its exposure condition without premature deterioration and hence unplanned maintenance. Understanding the deterioration process, mechanism and resilience of concrete in a given exposure environment is required to specify the right quality of concrete suitable for a given environment to satisfy serviceability requirements, which to a large extent is dependent on the mix design approach employed.

Concrete mix design as a way of proportioning concrete materials to produce concrete which satisfies the desired specification, is shifting away from being prescriptive to performance-based design globally. However, a cursory look at the Nigerian construction industry shows that to a large extent, prescriptive approach is still largely in use. No doubt, prescriptive approach has its advantage in that it is simpler, easily

understood and can be specified without ambiguity. For instance, it is a common practice on site to specify nominal mix 1:2:4 for a typical reinforced concrete member which often has given room to quackery in concrete practice. A good number of concrete casting team do not have the technical understanding nor background on best practices with respect to concrete production. They more often than not place emphasis on the workability at the expense of performance requirement of concrete. Often, the focus is on completing the task to time, while the quality of concrete produced falls short of the specified 28-day strength leading often times to doctoring of laboratory test results. The consequences of this, is that you have structures that satisfies the strength requirement on paper while failing to meet durability requirements resulting in premature maintenance issues and in severe cases have shorter service life than envisaged.
Concrete quality is influenced by a whole number of factors including materials properties (e.g. cement type and strength class, cement quantity, w/c or w/b ratio, type and quality of aggregates etc.), production and placing processes and quality of workmanship. Adequate knowledge of the interplay between these factors and concrete properties and its response to a given exposure condition is still lacking in the Nigerian construction industry. Till date, emphasis is mostly placed on compressive strength as a performance indicator with little consideration of the impact of exposure conditions influenced by the microstructure of concrete on durability. Microstructure of concrete plays a critical role in ensuring its durability in a given environment. This requires a thorough understanding of the performance of a given concrete mix in a given exposure environment informed by the material response to prevailing environmental conditions. This suggests that a thorough laboratory investigation should precede actual construction while samples should also be obtained from in-situ concrete to ascertain any variation (discrepancy) in properties which can inform necessary quality control action(s) to be taken to enhance quality assurance.
The incorporation of the influence of exposure condition into design requires a strengthening of the link between the industry and research entities across the different climatic zones in the country. The focus of durability performance evaluation is to put into consideration the contribution of pore structure of concrete and service conditions as integral part of both the design and construction phases. This requires development of appropriate testing methods which simulate identified transportation mechanism(s) in a given environment, which can be standardised as durability indicators for quality control and assurance, which can further drive policy formulation and implementation and development of local standards. This article presents the imperatives of adopting and implementing performance-based design to enhance best practices in sustainable concrete production and utilisation.

Current State of Materials and Research on Concrete Durability

In recent times, the Nigerian construction industry is dominated by the presence of Portland limestone cement (PLC) in lieu of ordinary Portland cement (OPC), a development that a good number of practitioners may not be fully aware of. In cases where they are aware, they often lack the technical knowledge of the properties, behaviour and performance of PLC compared to OPC, The PLC in circulation comes in different strength classes which is different from the specification of the known OPC. The differences in strength class suggest a limitation on the use and appropriateness of each strength class for specific concrete works. However, the strength class of PLC being used in construction activities in most cases is dictated by the supply chain and not the technical requirement(s) of the job. For instance, the study by Fapohunda *et al*. (2020) on PLC is limited to only 32.5R and 42.5R citing availability in the market as a constraint. Although, the information on the strength class and cement type is often written on the cement bag, the challenge lies in the awareness, understanding, interpretation and application of the information by users to suit specific performance requirement. The differences in strength class depicts differences in the compressive strength that can be achieved and likely variation/modification in some properties (possibly fineness and some chemical oxides) between each class, but PLC is largely sold at the same price in the open market irrespective of the strength class. This brings to the fore questions about the quality and/or transparency in the supply chain of cement which is taking advantage of the ignorance of end-users.
Study have shown that the influence of limestone powder on the strength of concrete is subject to the fineness of its particle and content (Tsivilis *et al.*, 2002). The concept of intergrinding limestone with

Portland cement clinker leading to the production of PLC has an inherent dilution effect associated with it. Although, it is a recognised strategy in most cement standards globally aimed at reducing the negative impact of CO_2 on the environment, there is the need to clearly understand the local context of this in comparison with plain OPC. This is because the dilution effect has an implication on the w/c ratio as well as the cement content and consequently, on the microstructural development of concrete which needs to be factored into the design and production of concrete. Aside the dilution effect, the filler effect of limestone consequential of its particle sizes and distribution is equally important to minimise the dilution effect and likely consequence on hardened concrete properties. The non-availability of and non-accessibility to plain Portland cement (i.e. OPC) in the open market makes it difficult to establish requisite performance benchmarks and understand the limitation of PLC compared to plain Portland cement and adaptability to Nigerian environment, as most practitioners still treat PLC same as OPC with respect to mix proportioning and concrete production.

Specification of concrete for construction is still largely based on the 28th-day compressive strength with little if at all consideration for durability requirements, while investigation on durability is often with respect to sulphate attack (Abdulazeez *et al.*, 2022; Ata, 2020; Olusola and Ata, 2014). Sulphate attack needs to be contextualised in terms of severity and prevalence as a crucial deterioration mechanism and/or essential measure of concrete durability subjected to both laboratory and field investigation. This is crucial to standardising the testing procedure, development of benchmark (and/or acceptance criteria) for requisite performance indicators in a given exposure environment and for quality control with respect to concrete production and utilisation on construction sites. This will require concerted efforts toward achieving repeatable results and reproducibility of results first in laboratory-based investigations which can be subsequently used to establish acceptable limits of variation for site-produced samples for quality control.

Besides sulphate attack, there are other prevalent deterioration mechanisms which need to be identified, contextualised and thoroughly investigated to understand the condition(s) and mechanism of attack beyond using the effect on compressive strength as an indicator. For instance, the study of Folagbade and Aluko (2019) assessed the permeation characteristics of sawdust ash blended laterised concrete using initial surface absorption as an indicator. The results presented showed the sensitivity of the test to variations in materials characteristics such as w/c ratio and binder type. The test measures the surface properties of concrete which is a crucial indicator of durability with respect to the influence of exposure environment. Although, the test procedure is standardised in BS and ASTM, the test can be adopted and modified to suit local conditions. This can help to describe key performance indicators for local service conditions and define acceptance criteria for quality control towards service life design and prediction for concrete structures.

Furthermore, there is the need for locally developed testing methods based on scientific principles defining requisite concrete performance in given exposure environments to ensure quality assurance and developments of guidelines or standards. The essence of such tests is to develop locally relevant tests that are tailored to prevailing deterioration mechanisms across the different geographical zones in the country putting into consideration material properties and interaction with prevailing environmental conditions. The goal is to have measurable quantities and quantitative values which can be used to adjudge the quality of concrete in service with reference to transport-related properties of concrete.

The weak link between the industry, academics, research institutes and regulatory organisations having direct link with construction materials research and development (R and D) and utilisation in the country needs to be strengthened to curtail quackery, prevalence of sub-standard materials, poor quality control, lack of innovation and poor implementation of research findings. Application of research findings to solve real problems in practice is still largely absent. A good number of researchers lack adequate knowledge and access to local standards while citation of international standards are largely cross references without adequate information of the content of such standards. This creates a wide gap between what is available, what is obtainable and what is the desired expectation which further widens the gap between knowledge and its application to solving real problems.

Paradigm Shift: Prescriptive to Performance-Based Specification

Alexander *et al.* (2008) identified three crucial rate-controlling factors critical to deterioration of concrete structures as the quality of the near-surface concrete of as-built structures, constituent materials used in concrete production and aggressiveness of the exposure environment. Prescriptive specification places much emphasis on constituent materials of concrete by prescribing limiting values for mix design parameters such as cement content, water/binder ratio and compressive strength (Beushausen and Luco, 2015). Durability requirements are specified as material requirements in terms of minimum cement content, maximum w/c ratio, minimum concrete grade etc., which are envisaged to yield durable concrete (Alexander *et al.*, 2010). Prescriptive specification is hinged on the assumption that concrete possessing adequate strength is deemed to be durable, without proactive consideration of the interplay between the physico-chemical characteristic of concrete and its exposure condition which significantly affects the functional requirements and hence the service life of concrete structures.

Performance-based design, on the other hand, integrates material properties, exposure condition and construction process in mix design and testing as essential considerations to achieve durable concrete. It requires the measurement of material properties associated with deterioration mechanism under actual exposure environment which is often simulated in the laboratory (Beushausen and Luco, 2015). The measured material properties under the prevailing exposure conditions are those associated with the transport properties of the concrete cover which can be used for the prediction of durability or service life of concrete structures. Durability of reinforced concrete structures is largely influenced by the quality of the cover zone in terms of the actual depth achieved, chemical composition of the binder phase and its microstructural characteristics which influence its resistance or otherwise to the aggressiveness of the exposure environment (Alexander *et al.*, 2010).

Performance-based design allows the use of innovative materials and techniques while giving room to establish acceptance criteria for requisite durability indicators which can be used to assess the performance of as-built concrete structures besides in-situ concrete tests on site (Beushausen *et al.*, 2019). It is a crucial requirement in performance-based design to subject the as-built structure to durability test. Testing for durability of concrete should focus more on the characteristics of the cover concrete and not the bulk concrete especially for reinforced concrete structures. This is because the quality of the cover concrete with respect to its penetrability, depth and the type of aggressive ion determines the time to initiation of corrosion of reinforcement bar (Alexander *et al.*, 2023) which is crucial to predicting the service life of structures in aggressive environment.

The use of concrete in pavement construction will intensify the demand for and use of concrete as a construction material, hence factors surrounding its durability and sustainability are essential consideration. Performance based design is focused on integrating durability indices into the design of concrete structures without compromise on the strength and stability.

South African Durability Indicators

South Africa seems to be the only known African country that have successfully implemented performance based design and specification approach. The South African context requires the measurement of certain durability indices on concrete that are related to transport properties of aggressive ions in concrete both in situ and in the laboratory (Alexander et al., 2008). These indices are measurable quantities used to represent concrete quality and penetrability of the cover concrete and are sensitive to variation in material properties, concrete production process and environmental factors. Also, these indices have been incorporated into some service life models, for instance, Salvoldi *et al.* (2015) incorporated oxygen permeability index into the development of carbonation model for the prediction of time-dependent carbonation depths of concrete. One advantage of this approach is that it enables relating durability of concrete to known transport mechanisms affecting the cover concrete, as it is the properties of the cover concrete that is germane to durability than the bulk concrete. The South African durability index approach incorporates three indices namely, oxygen permeability index, water sorptivity index and chloride conductivity index. The indices are related to transport mechanism of gaseous, water and ionic species through the cover concrete.

Durability Index Tests

Measurable parameters related to the transport properties of concrete have often been used to relate durability of concrete with the microstructure of the cover concrete. Durability of concrete is a long-term process hence short-term tests have been developed to measure the penetrability of concrete cover with respect to water, ions and gaseous ingress. In Africa, South Africa seems the only country that have fully integrated performance-based design approach with the development of three durability index tests namely oxygen permeability test, water sorptivity and porosity test and chloride conductivity test. Oxygen permeability test is based on the falling head permeability method measuring the pressure decay of oxygen gas permeating concrete disc with time.

Framework for Durability Research and Development

Ballim and Alexander (2018) gave an insight to the guiding principles and framework for the South African durability research and development. In the South African context, the first step in durability research and development involves the indexing of concrete especially the cover concrete in relation to its response to the deteriorating effect of the environment. The durability indexes are then correlated with the result of direct durability testing. Direct durability testing requires both short term (carried out under accelerated conditions which mimicked the aggressiveness of the envisaged environment in the laboratory) and long term testing (carried out in natural aggressive environment) to be done and correlated with each other. This facilitates the development of durability index performance scale and subsequently, the development of quality assurance and performance specification of concrete then follows.

However, durability consideration requires an understanding of the prevailing environmental actions and impact on concrete element based on exposure conditions along with prevalent deterioration mechanisms as given in BS EN 206 for Europe which was modified for South African environment. The Nigerian climatic conditions are a bit different from that of Europe and as such there is a need for modification to reflect the prevailing environmental conditions that have significant influence on concrete durability across the different climatic zones in Nigeria. Also, it is pertinent to identify the different deterioration agents and mechanism of attack on concrete structures which is influenced by concrete response to service conditions or condition of use or a combination of the two. This will invariably guide the development of acceptance criteria for concrete suitability to its exposure condition which is informed by intensive laboratory and site investigation in both short and long term using appropriate test methods. A framework that can be adopted is presented in Figure 1 which can further be reviewed to guide stakeholders in the research, development and production of concrete to meet serviceability requirements in addition to structural requirements of concrete structures.

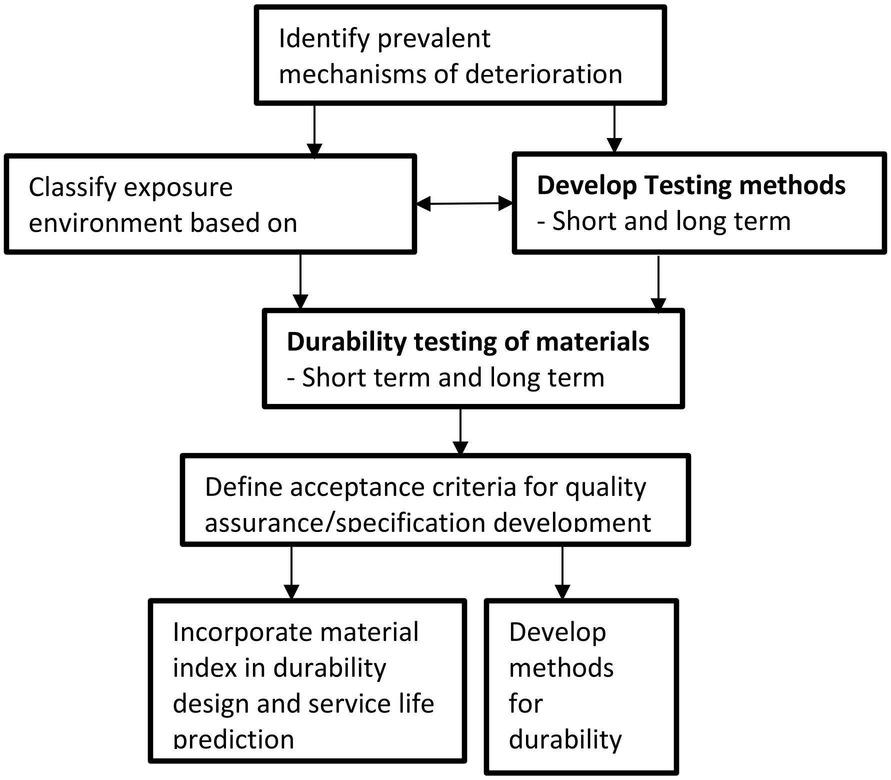

Figure 1: Framework for incorporating durability in concrete research and development

The framework is adapted from the South Africa model presented by Ballim and Alexander (2018) with modification to incorporate the Nigerian scenario with a focus on understanding concrete mix response to prevailing exposure environment and its variation across different climatic conditions. This requires collection of data on variation in concrete properties with changes in environmental conditions both in the short term (accelerated testing) and long term (natural/onsite testing). Also, it is essential to identify the prevailing deterioration mechanisms and the factors (and/or conditions) necessary for their initiation and propagation with respect to reinforced concrete structures. The information obtained will serve as guide for the development of quality control measures and regulatory guidelines for the industry.

Conclusion

The article presented a state-of-art assessment with respect to concrete research and development as well as production in Nigeria. The article identified gaps relating to durability consideration in concrete design and production. A framework on incorporating serviceability requirements in concrete research, development and production in Nigeria has been presented to enhance quality control and assurance with respect to sustainable concrete production and usage. This is to strengthen the link between the industry and researchers as it concerns concrete as a durable construction material. This requires concerted efforts between researchers and practitioners in the construction industry to develop acceptance criteria for concrete relative to performance requirements in given exposure condition.

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