International Proceedings of Chemical, Biological and Environmental Engineering, Vol. 89 (2015)
DOI: 10.7763/IPCBEE. 2015. V89. 1

Pre-construction Durability Index for Reinforced Concrete Structure

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Abstract. RC structures are designed to satisfy the requirements of safety, serviceability, durability and esthetics. The design procedures followed throughout the world are based on the strength principles and limit state formulation. The durability of structures is judged through the performance that must be delivered during its service life and is examined by several destructive and non-destructive tests. The concept of periodic maintenance is inherently assumed but in realistic terms, periodic maintenance is not guaranteed. This is especially true for rapidly developing countries and for areas of other countries where the periodic maintenance is not ascertained. A detailed investigation has been conducted about the importance of pre and post-construction durability indicators. From the investigation it is found that the pre-construction durability indicators are highly overshadowed in research by post-construction indicators, hence a new pre-construction durability indicator index is proposed based on the principles of performance, life cycle, factor of safety and eco-environment conditions. The proposed index gives practicing engineers' measurable tool to quantify the challenges involved for attaining a long-lasting durable structure and using the proposed index can lead to a minimum maintenance design life, reduction in factor of safety and reduced overall cost of the project.

Keywords: Concrete structures, Durability, Factor of safety, Pre-construction, Post-construction, Eco-environment condition.

1. Introduction

Reinforced concrete structures make up the majority of all construction in the world. A vast number of reinforced concrete structures are built in a severe environment. The interaction of the structure and environment is both at micro and macro-level [1]. Environmental actions can be quantified as surface temperature, humidity and chloride attack. The response of concrete can be examined in terms of permeability, carbonation, chloride penetration resulting in steel corrosion as shown in Fig. 1. It is important to understand and quantify the environmental actions and response of reinforced concrete. However, engineering structures are complex systems, whose components differ in durability and since these concrete structures make up the backbone of any economy, so there performance is a natural concern for all parties involved. Although majority of the design for reinforced concrete structures is governed by the strength criteria but in the recent year much importance has been focused on durability. The design procedures followed throughout the world (FIB, ACI, RILEM and PBC [2]-[5]) for designing RC structures is based on the strength principles and limit state formulation. A structure is considered durable as long as it is able to serve the purpose of its construction, in the environment where it is built with reasonable esthetics and functionality [6], [7]. Durability is mainly quantified in the construction industry by the quality of the built product such as its appearance, permeability index, resistance to carbonation, chloride ion ingress and freeze and thaw resistance [8]. The factors that influence durability can be categorized into two major classes and are referred herein as pre-construction durability indicators and post-construction durability indicators. Pre-construction durability indicators are the factors that are related to the site geology, its location, locally available materials and resources, since they are preferred over the materials that require transportation to the

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site, and economic importance given to periodic maintenance at the design stage of the project, referred to as eco-environment condition of the area where the structure is intended to be built. These indicators serve as key challenge indices that need to be addressed in order to achieve a well-constructed durable structure. The second set of indicators, post-construction, is related to workmanship, onsite investigation, quality assurance, detailing and final finishing. These indicators serve as the final durability checks which are measured using destructive and non-destructive testing.

However, much research in the past has been focused solely on post-construction evaluation of the structures either by improving the methods to measure durability [9] or by developing models that predict the serviceability life of the concrete structures [10] but very little attention has been focused on developing a pre-construction durability indicator index which would give the engineers quantitative tool, regarding the challenges to develop a long-lasting minimum maintenance structure. The fundamental reason for such negligence can be attributed to the fact that all the design codes and guidelines used for designing reinforced concrete structures inherently assume that the periodic maintenance is carried out without disruption. Although this assumption is reasonably true but in real world situations it becomes invalid. In rapidly developing countries like the Kingdom of Saudi Arabia, where owing to the immense economic growth and construction boom many of the infrastructure facilities are constructed without paying due attention to pre-construction durability which lead to a much shorter design life (see Fig. 2-Fig. 4). Furthermore in developing countries the decision of periodic maintenance is based economic considerations and many important structures suffer deterioration without periodic maintenance.

Hence the proposed study aims to develop a measureable engineering tool for pre-construction indicators which affect the overall durability of the structure. The focus of the research is to shed light on the importance of these indicators especially in the areas of rapid construction and where periodic maintenance cannot be fully guaranteed. This will not only be beneficial from the view point of improving the durability and performance of the structures but will also prove fruitful in setting an appropriate factor of safety their by reducing the overall cost of the project and will result in a long-lasting, minimum maintenance infrastructure.

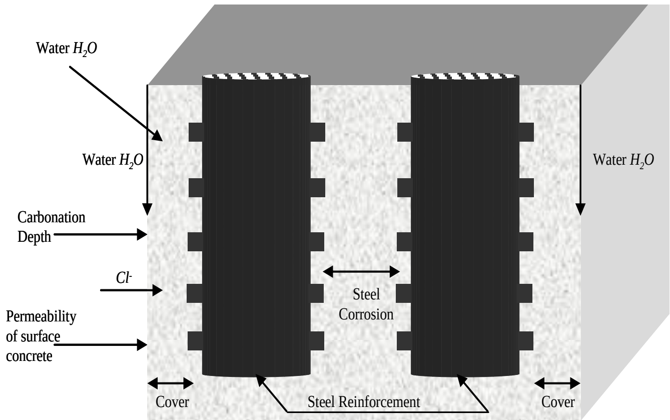

Fig. 1: Factors influencing durability of concrete

Fig. 2: Bridge girder having sewer deterioration

Fig. 3: Slab having spalling

Fig. 4: Girder with exposed reinforcement

2. Detailed Analysis

2.1. Structural Evaluation

Fig. 2-Fig. 4 show the sewer deterioration of different parts of a reinforced concrete structures which suffered sewer deteriorations and durability problems. It can be the seen that although the strength of the structure is sufficient to withstand the applied loads but the lack of periodic maintenance and ignorance of site specific conditions had resulted in sewer durability problems. Since every institution has a limited budget to be spent for periodic maintenance of the structures so many times some of the structures are left without proper maintenance. In such circumstances the importance of pre-construction indicators increases quite significantly, as by paying attention to these indicators at the design and construction stage can incorporate changes that will extend the maintenance free life of the structure. Fig. 5 depicts the service life distribution of a reinforced concrete structure. The vertical axis represents damage suffered by the structure while the horizontal axis represents the age of the structure after its completion. It can be seen that durability of the structure can be distinguished clearly into two major portions. Initial portion is the time it takes for the durability problem to first occurs, referred to as the time in which the structure suffers no visible durability problems. This time is identified as an initiation period and is the same for a structure having regular maintenance and a structure without proper maintenance built of same quality. The second portion of this life-cycle is distinguished as the propagation period. This is the period when the structure starts to deteriorate. It can be seen from Fig. 5 that during this time if the periodic maintenance is carried out than the original state of the structure can be restored but on the other hand for the structure without proper maintenance these durability problems keep aggravating till they finally reach to the maximum state of damage where the structure cannot be deemed usable anymore. t_{cr} represents the critical time period after which the structure cannot fulfill its serviceability requirements. It can be seen clearly that there is a major difference in acceptable service life of a structure with proper maintenance and the one without maintenance. Although much attention in the past has been focused on post-construction durability indicators but if a measureable tool for pre-construction durability indicators is developed the initiation period can be prolonged, thus resulting in a longer, minimum maintenance free durable life of the structure.

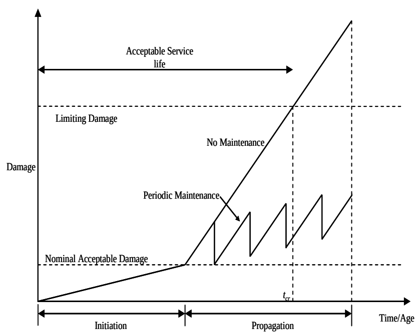

Fig. 5: Comparison of service life cycle of a well maintained and poorly maintained structure

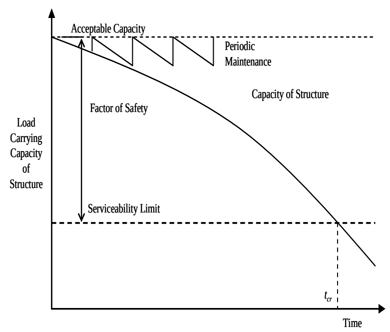

Fig. 6: Relationship between the service life and load carrying capacity

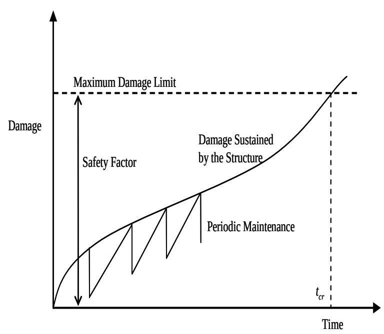

Fig. 7: Relationship between the service life and damage

2.2. Factor of Safety

Factor of safety is the difference between the maximum load carrying capacity and the actual allowed applicable load. This can be represented in terms of damage as the difference between the allowable damage that a structure can bear without compromising its serviceability to the maximum critical damage at which the structure can no longer perform its function effectively. The damage can be quantified as below;

$$Current\ status = Original\ built\ status - Damage \quad (1)$$

It can be seen that if the original built quality is poor and the pre-construction indicators are not taken into consideration than the limiting damage value can reduce drastically leading to much shorter service life of a structure. Fig. 6 depicts the relationship between the service life and load carrying capacity of a well maintained and poorly maintained structure. It can be seen that as the service life of a structure progresses the maximum load carrying capacity of a structure reduces, this can be mainly attributed to the deterioration suffered by the structure on its interaction with the environment and also based on its usage. However during this period the structural durability problems change from initiation phase to propagation phase where the problems can be identified by the help of non-destructive testing such as Rebound Hammer Test. The main difference between the two types of structures comes into action at the time of periodic maintenance. It can

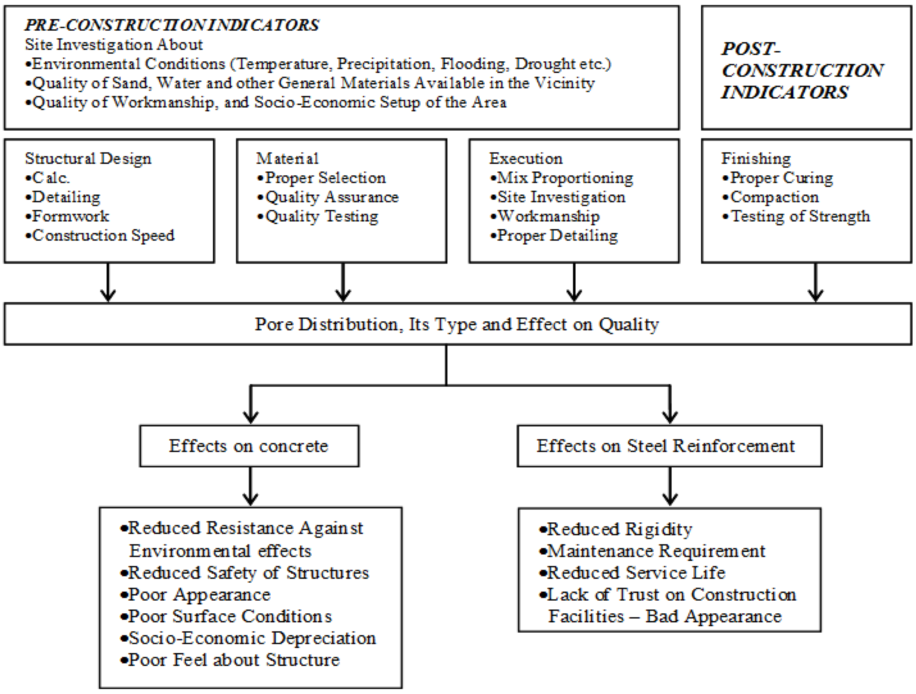

Fig. 8: Proposed flow chart showing improved importance of pre and post construction durability indicators

be seen that as these durability problems initiate, the periodic maintenance is started, which restores the structure back into its original state as compared to a structure without periodic maintenance where these problems keep aggregating till they reach a point where the structure is not able to fulfill its serviceability condition and hence it can no longer be acceptable for safety reasons. The explanation is also true for Fig. 7 where the relationship between service life and maximum sustainable damage of well-maintained structure and a poorly maintained structure is presented. t_{cr} in both the cases represents the critical time it takes for the structure to reach its serviceability limit state. t_{cr} is of critical importance when predicting the durable service life of a concrete structure. Recent studies [11], [12] have shown that non-destructive test such as Schmidt Rebound Hammer test is an effective way of predicting the strength loss of the structure owing to durability problems. Hence a combination of inspection with non-destructive testing can reveal the true age of the structure in absence of periodic maintenance.

2.3. Eco-Environment Condition

Eco-environment condition of a locality represents the current economic and environmental state of area where the proposed structure is to be built. This condition is a crucial indicator of durability challenges that structure will have to face during its life time. In rapidly developing countries with immense construction boom and in areas of the world where periodic maintenance cannot be guaranteed this aspect of the durability indicator has a key role. As the designer of the structure, engineers should be aware of the post-construction maintenance factor and should incorporate this factor in the design. So that proper factor of safety and quality standards could be selected which would lead to minimum maintenance life of the structure. Fig. 8 represents the modification on the design guide [8]. This gives the engineers quantifiable guidelines where a proper representation to pre-construction and post-construction durability indicators is given and the importance of pre-construction indicators is shown. It can be seen that for areas where the periodic maintenance cannot be guaranteed the pre-construction durability indicators hold the key to a

Table 1: Pre-construction durability indicator index

Pre-construction durability indices	Categorization				
Site Importance	Terrorism Threat	Location sea	plane	hills	0~5
Natural Hazards	Earthquakes		Tornado	Snow	0~5
Temperature	Low	Mild	High	Sewer	0~3
Precipitation	Low	Mild	High	Sewer	0~3
Flooding	Not Possible - 0			Possible – 1	
Drought/Fires	Not Possible - 0			Possible – 1	
Soil & Rock Type	Poor	Good		Excellent	0~4
Water Quality	Poor	Good		Excellent	0~4
Workmanship	Poor	Good		Excellent	0~4
Quality Assurance	Poor	Good		Excellent	0~10
Post-construction maintenance	Poor	Good		Excellent	0~10
Pre-Construction Durability Index					0 ~ 50

durable structure. Combining the periodic visual inspections with non-destructive tests the true age of the structure can be ascertained leading to a reduced maintenance requirement.

The construction process is divided into four main categories namely design, material selection, construction and finishing. Three of the main categories are recognized as pre-construction durability indicators. Hence incorporation of these at the design stage would lead to durable structure. A pre-construction durability indicator index is proposed in the proceeding section which gives the practicing engineers a quantitative index which can be used to fix the challenges involved in achieving a durable structure prior to its construction.

3. Pre-construction Durability Indicator Index

Table 1 represents the pre-construction durability indicator index. These indicators are selected based on the site conditions and the climatic information of the region where the structure is proposed to be built, the risk associated to the structure after its completion, chance of natural disasters, geology of the site, quality of workmanship of the area, possibility of quality assurance for the construction and the importance given to long-term periodic maintenance. These information's can be collected form the local authorities, client interview, survey of the site, information gathered from localities, importance factor associated to the structure and geotechnical investigation reports. The table presents a quantitative measure for the pre-construction durability indicators. Each indicator has been given a logical numbering value based on its importance, difficulty associated with its assessment and its impact on the overall long-term durability of the structure. The purpose of the proposed durability index is to give practicing engineers a measurable scale which can used in assessing the difficulty associated with achieving a durable structure. Using the index will help engineers in making smart rational judgment about the factor of safety is associated with different types of structures. This will lead to lower overall costs of the project thus making the structures more economical. Higher the indicator value, more are the challenges associated to long-term durability.

4. Conclusions

It is evident that much research in the past has been focused on the post-construction durability indicators while little attention has been paid to pre-construction durability indicators. In areas of rapid construction growth and in areas where the periodic maintenance of the structures cannot be guaranteed the importance of pre-construction indicators increases, Hence a detailed analysis regarding the pre and post durability indicators is presented, based on the analysis and discussion a pre-construction durability indicator index is presented. The index can be used by the practicing engineers as a quantitative scale for assessing the difficulty associated with achieving long-term durability in reinforced concrete structures. From the analysis the following conclusions can be drawn;

1) Pre-construction durability indicators play a vital role in the overall performance of the structure and need to be considered rigorously before designing.
2) The presented index can be used to ascertain the difficulties associated with developing a long-term durable structure, higher the value larger are the number of challenges and strict attention needs to be paid to each factor and its corresponding importance to attain a durable structure.
3) Use of the index can lead to better visualization of the problematic areas and can help engineers with choosing an appropriate factor of safety.

The use of index can lead to an economic structure with reduced construction cost and minimum maintenance requirements

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