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A New Form of Nondestructive Strength-Estimating Statistical Models Accounting for Uncertainty of Model and Aging Effect of Concrete

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Abstract As concrete ages, the surrounding environment is expected to have growing influences on the concrete. As all the impacts of the environment cannot be considered in the strength-estimating model of a nondestructive concrete test, the increase in concrete age leads to growing uncertainty in the strength-estimating model. Therefore, the variation of the model error increases. It is necessary to include those impacts in the probability model of concrete strength attained from the nondestructive tests so as to build a more accurate reliability model for structural performance evaluation. This paper reviews and categorizes the existing strength-estimating statistical models of nondestructive concrete test, and suggests a new form of the strength-estimating statistical models to properly reflect the model uncertainty due to aging of the concrete. This new form of the statistical models will lay foundation for more accurate structural performance evaluation.

Keywords: concrete strength, strength-estimating equation, model error, model uncertainty, concrete age

1. Introduction

It is necessary to assess the safety of structures and predict their remaining lifespan in order to maintain and manage concrete structures. Based on the assessing results, a decision can be made on the repair, reinforcement and removal of the structures. With demand and interest for the structural performance evaluation of existing structures on the rise, the need for an appropriate reliability model for accurate performance assessment is also growing (Kim et al., 2007). It is needed to consider the uncertainty arising from material strength and load condition in order to build a proper reliability model. In an effort to establish a statistical model that can reflect the uncertainty of the strength-estimating model used in conducting nondestructive concrete test, this paper examined the existing strength-estimating statistical models and seeks to find out a new form of the models that can consider the model uncertainty.

There are two widely used nondestructive test methods on concrete such as rebound number method and ultrasonic velocity method. Depending on how to consider the impacts of concrete age in these nondestructive test methods, the strength-estimating statistical models can be categorized into three forms: 1) basic form, 2) form using age compensation coefficient 3) form using age in explanatory functions. The first form takes into account only rebound number or ultrasonic velocity without considering the concrete age. The second form is built to consider the change in concrete strength along the concrete age by multiplying the basic form with the age compensation coefficient. The third

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form uses the concrete age in explanatory functions of the statistical model instead of using multiplication of age compensation coefficient.

With the concrete age rising, the environment is expected to have growing influences on concrete. As it is almost impossible to consider all the impacts of the environment in the strength-estimating models, the increase in concrete age leads to heightened uncertainty in the strength-estimating models. It means that an increase in the concrete age results in increased variation of probability distribution of estimated concrete strength. As the new form of strength-estimating models is suggested to consider the increase in variation of the probability distribution along the concrete age, this new form is expected to help to assess structural performance of concrete structures more accurately.

2. Existing Form of Strength-Estimating Statistical Model in Nondestructive Concrete Tests

Representative nondestructive tests of concrete include rebound number method (Schmidt hammer test method), ultrasonic pulse velocity method and a method combining these two. To find out an improved form of strength-estimating statistical models for nondestructive concrete tests aimed at assessing performance of concrete structures more precisely, this paper seeks to review the existing forms of the models and improve them by dealing with their shortcomings in accounting for the model uncertainty which varies along time. This section explains the existing forms of the statistical models by using only Schmidt hammer test as an example. The statistical models for other nondestructive test methods, such as the ultrasonic pulse velocity method and the combined method, can be explained similarly as Schmidt hammer test method.

2.1 Basic Form

The strength-estimating statistical model of Schmidt hammer test is as follows:

$$f'_c = a_0 + a_1 R + \sigma\varepsilon \tag{1}$$

In this equation, f'_c means the exact concrete strength, R means the rebound number, and a_i are coefficients obtained from regression analysis. If ε is defined as a random error with standard normal distribution, σ becomes a standard error that shows the variation of distribution of statistical data. As the number of statistical data increases, it approaches the standard deviation of the model error. As the basic form does not consider the impacts of concrete age, one of the important factors in estimating the concrete strength, modified forms using age compensation coefficient were suggested by many researchers as introduced in the following.

2.2 Form Using Age Compensation Coefficient

As the basic form is not accurate in estimating concrete strength according to concrete age, the estimated strength is compensated by considering the impacts of concrete age. Estimated strength by the basic form can be compensated according to the concrete age by multiplying the estimated strength with the age compensation coefficient. In the case of Schmidt hammer test, the compensated concrete strength is obtained as following.

$$f'_c = \alpha(t, R) \times (a_0 + a_1 R) + \sigma\varepsilon \tag{2}$$

In this equation, f'_c is the exact concrete strength compensated according to the concrete age, and $\alpha(t, R)$ is the age compensation coefficient. The age compensation coefficient $\alpha(t, R)$ is obtained by comparing the concrete strengths estimated by eqn. (1) and the corresponding real strengths, and conducting regression analysis with a nonlinear regression function of the concrete age t and the rebound number R (Kim et al., 2002).

2.3 Form Using Age as an Explanatory Function

The impacts of concrete age can be considered like in eqn. (3) by adding the concrete age as an explanatory function to a linear statistical model, instead of using the age compensation coefficient (Han and Lee, 2002).

$$f'_c = a_0 + a_1 R + a_2 t + \sigma\varepsilon \tag{3}$$

In eqn. (3), the rebound number R and the concrete age t are used as explanatory functions, but a more accurate statistical model can be built by adding more explanatory functions such as $\log(t)$, $1/t$, $t \times R$ and R/t etc. The previous form using age compensation coefficient such as eqn. (2) can be expressed by the current form when several nonlinear explanatory functions are added to eqn. (3).

3. Improved Form of Strength-Estimating Statistical Model in Nondestructive Concrete Tests

The increase in concrete age leads to a growing influence of the environment on the concrete strength. However, this growing influence of the environment on the concrete strength is not yet considered in the existing strength-estimating models. For instance, as the concrete ages after concrete casting, carbonation and evaporation on the concrete surface greatly affects the rebound number (Kwon, 1998). And increasing concrete age helps to decrease gel water inside the concrete, ultimately reducing the ultrasonic pulse velocity (Oh et al., 1996). Even though these impacts affect the nondestructive tests that use the rebound number and the ultrasonic pulse velocity, these impacts are not closely related with the concrete strength. Therefore, a rise in concrete age helps to increase the error of the existing models that estimates the concrete strength by the rebound number and the ultrasonic pulse velocity. This means that the model error σ in the strength-estimating model like eqns.(2) and (3) increases according to the concrete age.

Since the model error of the strength-estimating statistical model significantly depends on the concrete age, the standard deviation of the model error can be defined as a function of the concrete age such as $\sigma(t)$. It is inevitable to properly consider the change in probability distribution of the model error according to the concrete age in order to predict the remaining lifespan and assess the performance of concrete structures in a more safe and accurate way.

There have been many attempts to more precisely represent the mean value of concrete strength with a statistical model, but there have been no efforts to precisely indicate the probability distribution of the model error in a strength-estimating model, which changes according to the concrete age. This paper suggests the new standard form of a strength-estimating statistical model like eqn. (4) for study aimed at properly defining the probability distribution of the model error, which changes according to the concrete age.

$$f'_c = \sum_i a_i(t) \cdot f_i(R,t) + \sigma(t)\varepsilon \tag{4}$$

In this equation, f'_c is exact concrete strength varying according to the concrete age, f_i is explanatory function of the rebound number R and the concrete age t, $a_i(t)$ is coefficient of each explanatory function obtained from the regression analysis of the test data at a specific concrete age t, $\sigma(t)$ is a standard deviation of the model error that changes according to the concrete age, and ε is a random error with a standard normal distribution assuming that the model error has a normal probability distribution. Enough number of the explanatory functions and their coefficients should be summed to properly estimate the concrete strength. $a_i(t)$ and $\sigma(t)$ can be defined by regression analysis of the statistical data at each concrete age and expressing them by certain fitting functions of the concrete age.

The form shown in eqn. (4) is only for the Schmidt hammer test using rebound numbers. The form can be easily applied to the ultrasonic pulse velocity method simply by replacing the rebound number R with the ultrasonic pulse velocity V_p in the explanatory functions in eqn. (4). In general, the form applied to the combined method using both the Schmidt hammer test and the ultrasonic pulse method is as following

$$f'_c = \sum_i a_i(t) \cdot f_i(R, V_p, t) + \sigma(t)\varepsilon \quad (5)$$

4. Conclusion and Future Study

As concrete ages, the surrounding environment is expected to have growing influences on the concrete. As all the impacts of the environment cannot be considered in the strength-estimating model of a nondestructive concrete test, the increase in concrete age leads to growing uncertainty in the strength-estimating model. Therefore, the variation of the model error increases. It is necessary to include those impacts in the probability model of concrete strength attained from the nondestructive tests so as to build a more accurate reliability model for structural performance evaluation.

The existing concrete strength-estimating models by a nondestructive test have tried to represent the mean value of real concrete strength so far, and there has been a lack of efforts to properly represent the change in probability distribution of real strength along the concrete age. This paper suggested a new form of strength-estimating statistical model like eqns. (4) or (5) to make sure that the probability distribution of real strength according to the concrete age could be properly reflected in the estimation, which lays the foundation for accurate prediction of remaining lifespan of concrete structures and assessing their performance.

In an effort to build strength-estimating models tailored to the suggested form, the authors are collecting the data of tests on concrete structures previously conducted by other researchers, and plan to make use of data accumulated by Korean Infrastructure Safety & Technology Corporation. Since the concrete strength with age is strongly influenced by the concrete mix design parameters such as, water cement ratio, cement aggregate ratio, the authors are also collecting the mix design parameters, as well as nondestructive test data on concrete strength and age. Incorporating mix design parameters in the suggested formulation would increase the applicability of the newly proposed model once all the statistical data analysis is performed.

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