論 文 の 内 容 の 要 旨

論文題目　　Prediction of strength development of surface layer concrete in structure
（構造体コンクリート表層部の強度発現予測）

氏　　名　　孫　博超

The initial maintenance of fresh concrete is of great significance to the quality of the constructions. The curing quality of initial concrete directly affects the strength and durability of concrete from surface to interior. To understand the curing of concrete, it is necessary to understand the hydration process of cement and its influence. The hydration process of cement is generally considered dependent on the main components of cement clinker, temperature and time. In the actual construction process, in order to ensure the continuity of the construction process of the building, when the hydration reaction is processing in the early curing stage, the demolding treatment is conducted. Water evaporates from the surface of the concrete, causing a difference in water pressure from the surface to the inside, and thus causing the moisture diffusion from the inside to the outside. This directly results from the outside of the cement hydration is not comprehensive, and lead to the strength and durability of low. For reinforced concrete structures, the poor quality of the concrete cover can lead to more carbon dioxide, salt and corrosion of the steel. Therefore, the early quality management of concrete surface layer plays a crucial role in the durability of concrete strength.

For the prediction models of concrete related to time-effect, the equivalent age function

proposed in this thesis considering the influence of temperature and relative humidity also can be applicable, so as to get more accurate evaluation results.

This thesis based on the purpose of strength prediction of surface layer concrete, firstly proposed an equivalent age function that influenced by both temperature and relative humidity which could estimate the strength development at different curing temperatures and relative humidity conditions in chapter 3. Nevertheless, some drawbacks have been found of this proposed model, such as the proposed relative humidity modified function is obtained based on a constant condition of curing relative humidity, the applicability of such function in a changing environment needs more discussed. In addition, the application of the range of humidity also needs to be further discussed in the future. On the other hand, the propose of the thesis is for predicting the strength change in surface layer concrete, the humidity condition inside concrete is also different from the environment.

In order to well and reasonable estimate the strength development of surface layer concrete, a new humidity influence factor is proposed in chapter 4 based on the hydration rate of cement powder. This factor is proposed by referring the cement hydration rate and empirical function of other researchers' and proposed by considering the safety of application to practical construction. After verification, the proposed model can thoroughly evaluate the strength growth of different humidity conditions. Such relative humidity modified model is also verified to the concrete slab based on the simulation result of humidity distribution with time. The internal strength of concrete in the outdoor environment was also predicted.

The detailed results of each chapter are included as follows.

Chapter 1 explains the background, purpose, and innovation of the research. And the overall structure of the doctoral thesis is also summarized.

Chapter 2 mainly aimed at the research content of the research of the thesis and summarized the previous research results which concern with. The aspects of the influence of relative humidity on hydration and strength, maturity method, strength prediction model and internal moisture transfer of concrete are mainly reviewed.

Chapter 3 based on the hydration degree of cement powder at different temperature and relative humidity, the hydration rate was calculated. Then the relationship between hydration degree and hydration rate can be illustrated. A hydration model was applied to obtain the rate constant at different relative humidity and temperature by regression analysis with the experiment result. Taking 20°C-100%RH as the standard condition, the change of rate constant under different temperature and humidity can be expressed by an exponential function, then the equivalent age equation under the action of temperature and humidity can be obtained. The hydration reaction of cement powder is evident under the curing condition of more than 80%RH by the experimental results. The hydration model can basically describe the nonlinear relationship between hydration degree and hydration rate under different temperature and relative humidity. The proposed exponential function can well fit the value of rate constant under different temperature and relative humidity, and then the modified equivalent age function can be proposed based on it.

In chapter 4, the compressive strength of specimens of different sizes was measured under different temperature and relative humidity curing conditions. Moreover, according to the 1-D and 2-D diffusion model, relative humidity distribution on the cross-section of each specimen is simulated. Based on the simulated relative humidity results on the cross-section, the equivalent age and strength of each cross-section are calculated by means of the equivalent age function proposed in Chapter 3 and the strength prediction model of fib model code 2010. The compressive strength of cement mortar is not only significantly influenced by temperature but also by relative humidity. A higher early-age strength is obtained when curing temperature is high, while a low relative humidity reduces the compressive strength of the mortars. Such a phenomenon is more evident at the later stage of curing. With the curing time goes on, the humidity distribution of the internal section gradually decreases. Moreover, due to the small size of the specimens of $1\mathrm{cm}^3$, the environmental humidity will soon affect the central position of the section. On the contrary, the humidity in the cross-section of Ø 10cm is less affected by the environment relative humidity and relatively evenly distributed. At a low curing relative humidity of 70%, the gradient distribution of equivalent age caused by curing relative humidity becomes evident from the 3rd day of curing. As the hydration reaction of all the cross-section of specimens under 90%RH will continue, so the equivalent age is significantly higher than that under other conditions. The equivalent age of the central area of Ø5cm and Ø10cm specimens at different curing humidity is basically equal to it at 100%RH curing.
The prediction accuracy under saturated relative humidity(100%RH) is significantly higher than that under unsaturated relative humidity (70%RH, 80%RH, 90%RH). Moreover, the proposed model slightly underestimates the experimental strength at temperatures of 18°C and 40°C. The prediction strength results can well reflect the compressive strength results obtained in the experiment, and the accuracy of prediction is more evident in larger size specimens.

Chapter 5 mainly focus on the estimation of relative humidity development of surface layer of concrete. The finite difference method (FDM) introduced in Chapter 4 is used to solve the partial differential equation of moisture diffusion theory. The humidity change of different depths of the surface concrete was also measured by the temperature/humidity sensor to verify the simulation result. According to the relative humidity simulation results at different depths under three curing conditions, the relative humidity influence factors g_h and compressive strength at different depths are simulated with the development of time. The experiment is conducted by inserting the temperature/humidity sensors into different depth of the surface layer of concrete. Different curing treatments show different law of humidity development, both surface heating, and wind blowing can accelerate the loss of water in concrete. Which is more evident in the near-surface layer of concrete.

By comparing the simulated relative humidity reduction regarding moisture diffusion to the experimental results, it can be clearly found that the simulation of the model can accurately reflect the relative humidity development of the surface layer of concrete. In the initial stage of curing, the value of g_h is close to 1. The faster the internal humidity decreases, the faster the g_h decreases, and the decreasing speed will be the fastest at 1cm and the slowest at 4cm depth. The simulated equivalent age development with time of each depth and curing conditions grows with a reasonable tendency. High relative humidity leads to a high equivalent age at same curing condition. Not only temperature but also relative humidity has a significant effect on the equivalent age. Under three simulated conditions maintained in the laboratory, strength at a depth of 1cm would soon cease to grow and would be less than 10% of 100%RH strength. The strength at a depth of 2cm under each curing conditions can be found at nearly the same level for each typical age. But even so, due to sufficient water in the early ages, 2cm can still reach a tolerable strength value. At depth of 4cm, relative high strength can reach a considerable high level than that of the other two depths due to the sufficient relative humidity content during the whole curing period. For the outdooring curing specimens, even though the moisture value at the depth of 4cm is close to 100%RH, the strength evaluation results obtained by the model are still significantly lower than the strength of water-curing specimens. And relatively low strength values s can be found at 1cm and 2cm depth. The strength values of 1cm, 2cm and 4cm depth on the 28th day were 1.85MPa, 6.66MPa and 32.49MPa, respectively, which were 4.2%, 15.3% and 74.9% of the experimental strength of water curing at the 28 days.

Although this thesis presented a method to predict the development of internal strength, the result is carried out by the internal temperature and humidity changes obtained through the sensors pre-embedded inside concrete. For the purposes of engineering, this is obviously time and effort consuming. Therefore, it would be the right research direction to deduce the internal temperature and humidity development by placing the sensor on the concrete surface. And sensors placed on the surface can be reused so that both economic efficiency and work efficiency will be greatly improved.

In addition, the influence of humidity on concrete strength in this study was carried out under the condition of specified water-binder ratio mortar under the specified environmental relative humidity, and whether the influence of environmental humidity on strength can replace the influence of real humidity inside concrete on strength remains to be verified. In addition, this experiment is conducted based on the experimental results of cement mortar. The results of strength development and humidity change are different from the results of concrete in practical construction. Therefore, in order to make the results closer to the practical construction, the same research on concrete needs to be done. In the case of low water-cement ratio, the change of internal humidity caused by self-desiccation of cement hydration should be considered.