Nuclear Engineering and Design 275 (2014) 23–29

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Prediction of concrete compressive strength considering humidity and temperature in the construction of nuclear power plants

Seung Hee Kwon[a], Kyung Pil Jang[a], Jin-Wook Bang[b], Jang Hwa Lee[c], Yun Yong Kim[c,*]

[a] Department of Civil and Environmental Engineering, Myongji University, Yongin, Republic of Korea
[b] Department of Civil Engineering, Chungnam National University, Daejeon, Republic of Korea
[c] Structural Engineering Research Division, Korea Institute of Construction Technology, Republic of Korea

HIGHLIGHTS

- Compressive strength tests for three concrete mixes were performed.
- The parameters of the humidity-adjusted maturity function were determined.
- Strength can be predicted considering temperature and relative humidity.

ARTICLE INFO

Article history:
Received 20 October 2013
Received in revised form 31 March 2014
Accepted 14 April 2014

ABSTRACT

This study proposes a method for predicting compressive strength developments in the early ages of concretes used in the construction of nuclear power plants. Three representative mixes with strengths of 6000 psi (41.4 MPa), 4500 psi (31.0 MPa), and 4000 psi (27.6 MPa) were selected and tested under various curing conditions; the temperature ranged from 10 to 40 °C, and the relative humidity from 40 to 100%. In order to consider not only the effect of the temperature but also that of humidity, an existing model, i.e. the humidity-adjusted maturity function, was adopted and the parameters used in the function were determined from the test results. A series of tests were also performed in the curing condition of a variable temperature and constant humidity, and a comparison between the measured and predicted strengths were made for the verification.

1. Introduction

Concrete hardens through the chemical reaction of cement and water, i.e. hydration, which is significantly influenced by the external conditions. In order to construct a nuclear power plant in cold or hot weather conditions, close attention must be paid to the concrete works such as quality control of the fresh concrete, strength development of concrete at early ages, cracking due to hydration heat, and so on. The present study is part of a project to develop technologies that will overcome the barriers associated with extremely hot or cold weather conditions in the construction of nuclear power plants. The area of the project to which this study belongs focuses on the prediction of the early age strength development of concretes used in the containment vessels and secondary structures of the nuclear power plant.

As is well known, temperature is a significant factor that influences the strength development of concrete over time, and a lot of research has been undertaken thus far. Approximately sixty years ago, the temperature versus time curve, i.e. the maturity function, was first introduced to predict the strength development (Nurse, 1949; McIntosh, 1949); the maturity concept has been modified and improved by many researchers (Saul, 1951; McIntosh, 1956; Alexander and Taplin, 1962; Malhotra and Carino, 1991; Hansen and Pedersen, 1977; Kim et al., 2001; Carino, 1984; Knudsen, 1980; Tank and Carino, 1991).

There is another important influencing factor that has been scarcely investigated compared with the effect of temperature. Most maturity models have been developed under the assumption that concrete is cured at 100% relative humidity. In reality, concrete is exposed to air with a lower relative humidity, and the internal moisture emerges from inside the concrete through moisture diffusion (Kwon and Shah, 2008). An insufficient water supply due to this diffusion and the evaporation of the internal moisture hinder the hydration of cement. The existing maturity models usually overestimate the strength development of concrete cured in real sites

* Corresponding author. Tel.: +82 42 821 7004; fax: +82 31 825 0318.
E-mail address: yunkim@cnu.ac.kr (Y.Y. Kim).

http://dx.doi.org/10.1016/j.nucengdes.2014.04.025
0029-5493/

(Liao et al., 2008). In order to more accurately predict the strength gain over the concrete ages in realistic circumstances, the effect of humidity must be considered as well as temperature.

In a thick concrete member such as the wall of a containment vessel, the effect of humidity differs to that of temperature: the effect of humidity may be limited in the region near the member surface because the moisture near the surface evaporates quickly and the inner part of the member remains wet for a long time or for the service life of the member. Although the effect of the humidity is limited to the outer region of the member, it remains important to accurately estimate the tensile cracking due to the hydration heat and drying shrinkage, as well as to determine the construction schedule or casting sequence.

Recently, a model capable of simultaneously considering both effects of humidity and temperature in predicting the strength development of concrete, which is called the humidity-adjusted maturity function, was proposed and experimentally verified (Liao et al., 2008). The mix proportions of concretes used in nuclear power plants are almost fixed. In this study, three representative mixes with specified compressive strengths of 6000 psi (41.4 MPa), 4500 psi (31.0 MPa), and 4000 psi (27.6 MPa) were selected, and the compressive strength tests were performed in various curing conditions for a constant temperature and relative humidity. Temperature ranges from 10 to 40 °C and a relative humidity from 40 to 100% were used to investigate the effects of humidity and temperature. From the test results, the parameters used in the humidity-adjusted maturity function were determined. Through the determined parameters, the compressive strength of concrete cured at arbitrary temperature and humidity conditions can be predicted. A series of tests were also performed in the curing condition with variable temperatures and a constant humidity, and a comparison between the measured and predicted strengths was conducted for verification.

2. Humidity-adjusted maturity function

The compressive strength of concrete at an arbitrary age can be described using the following equation, which was proposed by Carino (1984) and Knudsen (1980):

$$S = S_u \frac{k_T(t-t_0)}{1+k_T(t-t_0)}, \tag{1}$$

where S is the compressive strength, S_u is the limiting compressive strength at an infinite age, t is the actual curing age (days), and t_0 is the age (days) when the strength development begins. The parameter k_T is the rate constant (day^{-1}) and was originally assumed to be a function of temperature. Several formulae representing the rate constant have been proposed, and the following equation was proposed by Carino (1982):

$$k_T = A \cdot e^{(BT)}, \tag{2}$$

where A is a constant (day^{-1}), B is the temperature sensitivity factor (1/°C), and T is the curing temperature (°C). In the recent study conducted by Liao et al. (2008), it was assumed that the constant A was a function of the temperature and humidity in order to consider the effect of humidity as well as temperature in the prediction of compressive strength. However, it was found that parameter A depends significantly on the humidity, irrespective of temperature. Therefore, in this study, the rate constant is assumed as follows:

$$k_{T,h} = A(h) \cdot e^{(BT)}, \tag{3}$$

where h is the relative humidity of the air to which the concrete is exposed and $k_{T,h}$ is defined as the humidity-adjusted rate constant. When h is 100%, Eq. (2) becomes equal to Eq. (1). The new parameter defined as the humidity factor was introduced in the existing study, as follows:

$$J_h = \frac{k_{T_c,h}}{k_{T_c,h_r}}, \tag{4}$$

where $k_{T_c,h}$ is the rate constant for the curing condition of a fixed temperature (T_c) and an arbitrary relative humidity (h), and k_{T_c,h_r} is the rate constant at the same temperature (T_c) and reference relative humidity (h_r) (=100%). In a previous study (Liao et al., 2008), it was revealed that the humidity factor has a reverse hyperbolic shape over the relative humidity and can be expressed using the following equation:

$$J_h = J_u \frac{r_h(h^*-h_0)}{1+r_h(h^*-h_0)}, \quad h^* = 100-h, \tag{5}$$

where J_u is the non-dimensional regression limiting humidity factor, r_h is the humidity rate constant (%$^{-1}$), and h_0 is the regression initial humidity constant (%). It was previously observed that h_0 is almost constant irrespective of the curing temperature. When h is identical to h_r, J_h is equal to unity. Therefore, r_h can be expressed as follows:

$$r_h = \frac{1}{h_0(1-J_u)}. \tag{6}$$

The humidity-adjusted rate constant at the specific temperature T_c can be expressed as follows:

$$k_{T_c,h} = k_{T_c,100} \cdot J_u \frac{r_h(h^*-h_0)}{1+r_h(h^*-h_0)} = A(100) \cdot e^{(BT_c)} \frac{r_h(h^*-h_0)}{1+r_h(h^*-h_0)}. \tag{7}$$

The humidity-adjusted affinity ratio (γ'), which is the ratio of the rate constant of concrete cured at an arbitrary temperature and a relative humidity during a time interval (Δt) to the rate constant for curing at the reference temperature and reference relative humidity, is expressed as follows (Liao et al., 2008):

$$\gamma' = \frac{k_{T,h}}{k_{T_c,h_r}} = e^{B(T-T_r)} \frac{h_0-h^*}{h_0-h^*/J_u}. \tag{8}$$

The equivalent age (t'_e) can be derived as follows:

$$t'_e = \sum \gamma' \Delta t. \tag{9}$$

The compressive strength of concrete cured at an arbitrary temperature and humidity can be calculated as follows:

$$S = S_u \frac{k_{T_r,h_r}(t'_e - t'_{0r})}{1+k_{T_r,h_r}(t'_e - t'_{0r})}, \quad k_{T_r,h_r} = A(100)e^{(BT_r)}, \tag{10}$$

where S_u is a function of the temperature and relative humidity, and it can be obtained from curve fitting Eq. (11) to the experimental data.

$$\begin{aligned} S_u(T,h) &= a_0 + a_1 T + a_2\left(\frac{h}{10}\right) + a_3T^2 + a_4T\cdot\left(\frac{h}{10}\right) \\ &+ a_5\left(\frac{h}{10}\right)^2 + a_6T^2\cdot\left(\frac{h}{10}\right) + a_7T\cdot\left(\frac{h}{10}\right)^2 + a_8T^2\cdot\left(\frac{h}{10}\right)^2, \end{aligned} \tag{11}$$

where the parameters a_0–a_8 are empirical constants. For curing with an arbitrary variation of the temperature and humidity over time, the strength can be calculated using the strength difference between two consecutive time steps in Eq. (10), as follows:

$$S = \sum dS = \sum \frac{S_u k_{T_r,h_r} \Delta t'_e}{[1+k_{T_r,h_r}(t'_e+\Delta t'_e - t'_{0r})][1+k_{T_r,h_r}(t'_e - t'_{0r})]}, \tag{12}$$