Durability Design of Concrete Subjecting to Carbonation

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Abstract

Problems on durability of existing concrete structures can be caused by ill-conditioned analysis and design, improper concrete proportion and material selection, low construction quality, ignorance of protection and maintenance of the structure, or their combination. In this paper, the performance-based durability design charts for conventional fly ash concrete subjected to carbonation are proposed as an example of solution to the problem of improper concrete proportion and material selection. Concrete structures can be durable for a long time when materials, mixes, covers, and environment are selected properly. The design charts are constructed based on several semi-microscopic performance prediction models, i.e. compressive strength prediction model, workability prediction model, and carbonation simulation model of fly ash concrete. These models are also introduced briefly in this paper.

Keywords: Carbonation, Performance-based design, Fly ash concrete

1. Introduction

Carbonation is one of the durability problems that occurs when carbon dioxide reacts, in the presence of moisture, with calcium hydroxide in concrete. It reduces the alkalinity of the concrete pore water which leads to the corrosion problem of reinforcing steel bars. It is obvious that for reinforced concrete structures, the onset of reinforcement corrosion is considered as one of the important stages for determining the service life of the structure. Moreover, other important properties of concrete, such as its workability in fresh state and its mechanical properties in hardened state are also taken into consideration in the mix proportioning of concrete. Workability is significant only during the period of construction. However this property affects also the other properties in long term. The properties in hardened state decide the serviceability of the structures. One of the most important properties of the hardened concrete is strength. Compressive strength is always specified in the mix design. This is because many other mechanical properties, i.e. tensile strength, flexural strength, modulus of elasticity, etc. are practically estimated from the compressive strength. The mix design method proposed in this study is based on three semi-microscopic models, i.e. workability prediction model [1], compressive strength prediction model [2], and carbonation prediction model [3]. Thus, concrete can be designed based on the performance concept to find the optimum mix proportion to reduce carbonation problem of the concrete structures.

2 Workability Prediction Model

It was verified by Khunthongkeaw [1] that free water content has linear relationship with slump of fresh concrete as,

$$SL = \alpha (W_{fr} - W_0) \qquad (1)$$

where SL is the slump value of fresh normal concrete (cm). α is the slope of slump-free water content curve (cm/kg/m^3 of concrete). This parameter mainly depends on the paste content [1]. W_{fr} and W_0 are the volume of free water in the fresh concrete mixture and the minimum free water content required for initiating slump (kg/m^3 of concrete).

Free water, W_{fr}, is defined in the study as the amount of water that is free, by any means, from being restricted by all solid

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particles in the fresh concrete and can be obtained as,

$$W_{fr} = W_t - W_{rp} - W_{ra} - W_a \quad (2)$$

where W_t is the unit water content in the mixture (kg/m^3 of concrete). W_{rp} and W_{ra} are the restricted water by powder materials and on the surface of aggregates, respectively (kg/m^3 of concrete). W_a is the additional free water due to filling effect (kg/m^3 of concrete). Filling effect is the situation that very fine powder particles fill in the voids among cement particles [1] and thus drives out the free water that is entrapped in the voids. The filling effect increases as the particle size of fly ash reduces. Moreover, spherical particles are likely to have a better ability to fill voids than non-spherical particles.

3. Compressive Strength Prediction Model

It is known that an increase of w/b ratio significantly decreases the concrete strength. In addition, the use of fly ash with high CaO content and high fineness leads to concrete with higher 28-day compressive strength. When incorporating fly ash in concrete, the filling effect leads to dense packing of particles of binder materials and affects concrete strength positively. Fly ash with higher LOI gives lower 28-day compressive strength than that with lower LOI when the contents are the same. Kaewkluab [2] also proposed that concrete with small paste content, in comparison with voids among aggregates, led to inadequate paste to fill voids and resulted in poor aggregate-paste interface bond. Consequently, poor compressive strength concrete was obtained. On the contrary, too much paste content, in comparison with voids content, also resulted in lower compressive strength since generally paste was more porous than aggregate. Nevertheless, the reduction of the strength while increasing paste content beyond its optimum value became less significant in concrete with lower w/b ratio as the result of its higher strength of paste. The equation for predicting 28-day compressive strength of concrete was given by,

$$f_c'(28\text{ days}) = [\alpha_1 \log(CaO_{eff}) + \lambda_f \alpha_2]\, \chi_\gamma\, \chi_L\, \chi_a \quad (3)$$

where f_c'(28 days) is the 28-day compressive strength of concrete (MPa). CaO_{eff} is the effective calcium oxide content in concrete (kg/m^3 of concrete). α_1 and α_2 are the slope and y-intercept of the log (CaO_{eff}) – f_c'(28 days) curve which are dependent on w/b. λ_f, χ_γ, χ_L, and χ_a are the parameters indicating effects of filling effect of fly ash, paste content, loss on ignition of fly ash, and entrained air, respectively on 28-day compressive strength. In this model [2], the term of strength development ratio was proposed as the ratio of compressive strength at any ages to its 28-day compressive strength. The compressive strength of concrete at any age was computed as,

$$f_c'(t) = \phi(t) \cdot f_c'(28\text{ days}) \quad (4)$$

$$\text{in which, } \phi_t = \left[1 + \ln\left(\frac{t}{28}\right)\Gamma\right] \cdot \omega_f(t) \quad (5)$$

where $f_c'(t)$ and $\phi(t)$ is the compressive strength (MPa) and the strength development ratio of concrete at age t (days). Γ is the parameter indicating effect of water to cement ratio and value of SiO_2/CaO. ω_F is the time dependent parameters indicating filling effect of fly ash strength development ratio.

4. Carbonation Simulation Model

The carbonation simulation model [3] includes water migration model, CO_2 diffusion, and calculation of alkalinity and pH in concrete pore water. The model was developed for one-dimensional simulation since carbonation was considered as a near surface problem. According to the analysis of the model, the pH in the concrete element was estimated. In order to estimate the carbonation depth, it was assumed that the carbonation depth was the distance from the concrete surface to the center of the innermost concrete element that had pH value less than 9. Since, the carbonation depths were determined by the phenolphthalein solution. Color of this solution changed into purple when pH was higher than 9 [4].

In this model [3], the rate of gas diffusion was assumed to follow the Fick's law, which was popularly used to describe a motion by the diffusion of a substance in the concrete in the direction of the concentration gradient. The degree of saturation and humidity in the pores greatly influence the diffusion of CO_2. Because in the saturated concrete, the pores are filled with water and gas diffusion is almost impossible. CO_2 starts to diffuse when the water in concrete pores dries out. The water content in concrete was estimated by using the water migration model [3]. The fluxes of gases diffusion were derived in the model as follow.

For vapor,

$$FH(x,t) = -DH(x,t)\frac{\partial RH(x,t)}{\partial x} \quad (6)$$

For CO_2,

$$F_c(x,t) = -D_c(x,t)\frac{\partial C(x,t)}{\partial x} \quad (7)$$

where F_H and F_c are the fluxes of water vapor (kg/m^2/day) and CO_2 (mol/m^2/day) transfer across a unit cross-sectional area of concrete. D_H and D_c are the diffusion coefficients of water vapor (kg/m/day) and CO_2 (m^2/day). RH is the relative humidity in concrete pores (%). C is the gaseous concentration of CO_2 in concrete pores (mol/m^3). x is the distance from the exposed surface (m). t is the considered time (day). The carbonation reaction rate depends on the availability of CH, concentration of CO2, and temperature of the pore solution. Based on the Arrhenious's equation for thermally activated process, the rate of carbonation reaction was simply formulated as follows.

$$r_c(x,t) = k_c \cdot [CH](x,t) \cdot [CO_2](x,t) \quad (8)$$

in which,

$$k_c = \beta\left[-\frac{E_0}{RT}\right] \quad (9)$$

where r_c is the average reaction rate of CO_2 with the dissolved CH during the carbonation reaction (mol/m^3/day). [CH] and [CO_2] are the molar concentrations of CH and CO2 in pore water (mol/m^3). kc is the reaction rate coefficient (m^3/mol/day). R is the gas constant. β and E_0 are the constant and the activation energy of the reaction [3]. The concentration of hydroxyl ion and pH in the pore water were given as follows.

$$[OH^-](x,t) = 2\,[CH'](x,t) \quad (10)$$

$$pH(x,t) = 14 + \log\{[OH^-](x,t)\} \quad (11)$$

where [OH-] and [CH'] are the molar concentrations of OH- and CH, respectively in concrete pore water (mol/m3). pH is the pH value of the pore solution.

5. Design Charts

In those models, properties of concrete can be forecasted by the process of analysis where the properties of the materials and mixture proportion are presumed. However, the analysis of those models is complicated. A mix design computer program will be developed in the future. In this study, charts are constructed from those models to facilitate the mix design. The mix design proposed in this study considers initial slump, compressive strength (at any ages), and carbonation resistance of concrete.

5.1 Limitation

The proposed mix design method is appropriate for conventional concrete with and without fly ash that has 28-day compressive strength less than 60 MPa and initial slump value less than 25 cm. This method is not applicable for air-entrained concrete and special types of concrete, i.e. lightweight concrete, underwater concrete, SCC, or RCC. For material limitations, the standard Portland cement type I is recommended. The models used as the basis of this design method take into account the variations of properties of fly ash and aggregates. However, for the simplicity, the design charts do not cover all the changes in properties of fly ash and aggregates. It is recommended that the method is suitable for unprocessed fly ashes that are classified as type 2a and 2b by EIT-1014 [5] and have fineness not over than 320 m^2/kg. Fine and coarse aggregates must be river sand and limestone coarse aggregate, respectively. The gradation of aggregates must satisfy the standard [5]. The maximum size of coarse aggregate is not larger than 38 mm.

5.2 Design method and charts for compressive strength

It was found from the compressive strength prediction model [1] that various parameters affected the compressive strength of concrete. However, it is very difficult to construct the charts that consider all parameters. In these charts, it is considered that the major parameters significantly affecting the compressive strength of concrete are w/b ratio, paste content, fly ash content, age of concrete, and properties of cement and fly ash. Since a single type of cement is recommended and the model is applicable only for the normal crushed limestone coarse aggregate and river sand, the only ingredient that varies significantly in property is fly ash. Therefore, two types of fly ash (2a and 2b) are included with the replacement percentage of 0 to 50% in the charts. Although, engineers usually specify the compressive strength at 28 days, strength at other ages is specified for some structures and purposes. Thus the charts are also constructed at various ages of concrete, i.e. 3, 7, 28, 91 days. The examples of design charts at the age of 7 and 28 days of fly ash (2a) concrete are shown in Figs. 1 and 2, respectively.

Prior to conducting the mix design, sand to aggregates ratio that gives a minimum void volume is recommended and can be determined from the test (ASTM C29/C29M-91a). Compressive strength is designed by assuming the ratio between paste volume to total void volume of compacted aggregate phase value (γ) equal to 1.2. Then w/b ratio is selected from the charts from the required compressive strength. It is noted that if the compressive strengths at more than one specific age is required, the minimum value of w/b that satisfies the requirements of compressive strength at all specified ages is selected.

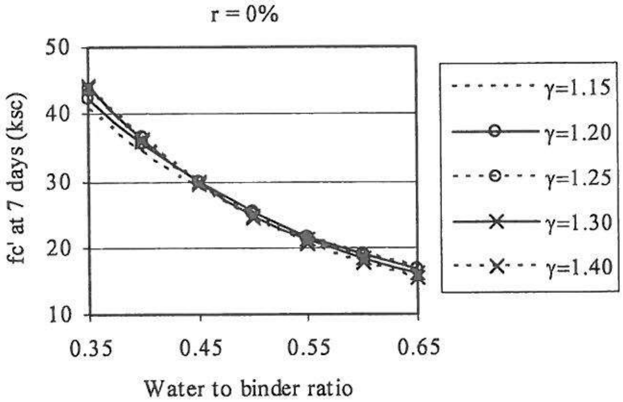

Fig. 1 Design chart for compressive strength (at 7 days)

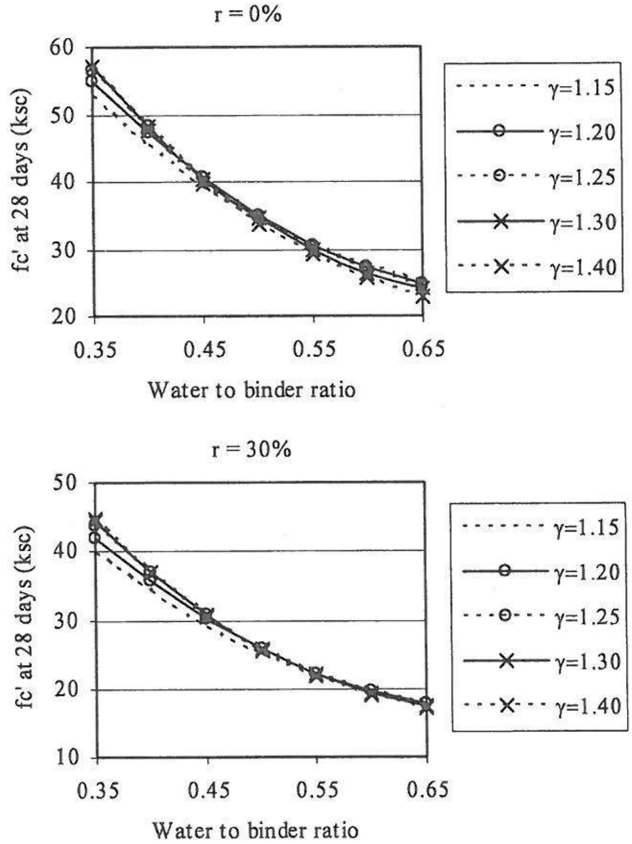

Fig. 2 Design chart for compressive strength (at 28 days)

5.3 Design method and charts for carbonation resistance

It was confirmed in the carbonation simulation model [3] that the major parameters affecting carbonation resistance of concrete were type and replacement level of fly ash, w/b ratio, curing period, and environmental condition. Where paste content and aggregate content were considered as insignificant parameters and were ignored in this design method. The effects of environment were separated based on the model into three cases by relative humidity and CO_2 content as shown in Fig. 3.

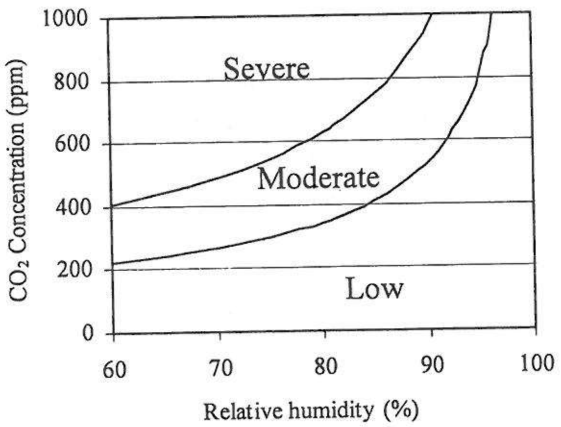

Fig. 3 Classification of carbonation environment

The maintenance free period of concrete from carbonation is specified as the period of carbonation depth traveling from the concrete surface to the reinforcing steel bars. The traveling distance of carbonation depth is equal to the thickness of concrete cover to the reinforcing steel bars. The design charts for carbonation resistance design are constructed to relate the cover thickness and maintenance free period of concrete, w/b ratio, and type and content of fly ash. The examples of design charts of fly ash concrete for carbonation are shown in Figs. 4 and 5.

In this section, w/b ratio is selected from the design charts. The smaller value between w/b ratio selected from section 5.2 and this section is used here to ensure that the designed concrete meets the requirement for both compressive strength (at any specified ages) and carbonation resistance.

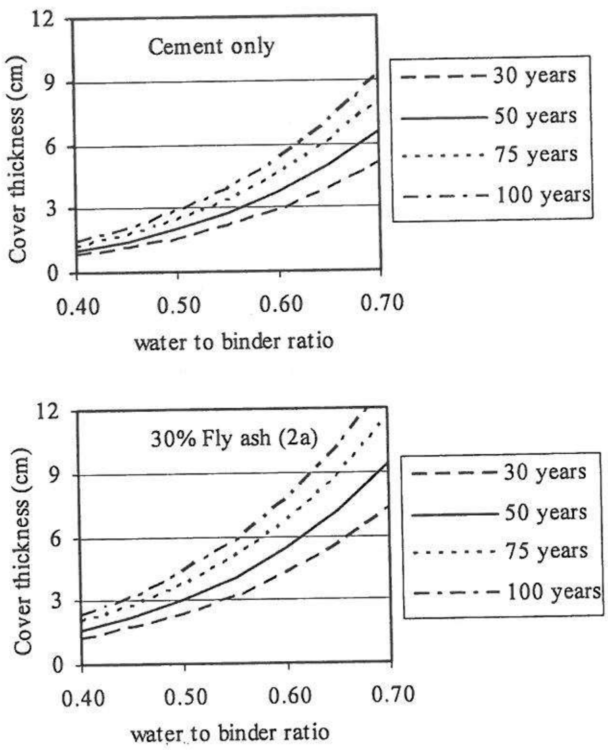

Fig. 4 Design chart of carbonation (severe environment)

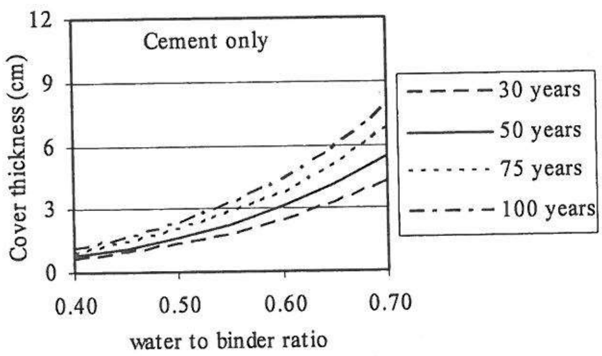

Fig. 5 Design chart of carbonation (moderate environment)

5.4 Design method and charts for slump value of concrete

Slump property is influenced mainly by physical properties of the solid ingredients. The chemical properties do not affect slump significantly because very small amount of reactions takes place in the early fresh state. From the model, the major parameters influencing slump of concrete are mix proportion and physical characteristics of binder and aggregates. It is found that the effect of type of fly ash can be ignored due to its small effect. However it is recommended that this method is suitable for fly ash that has water requirement not less than 90%. For coarse aggregate (limestone), the effects of shape, size and size distribution are indirectly considered by the γ value, i.e. the more spherical shape, larger size, and better size-distributed of aggregate give a larger γ value and thus a better workability. For fine aggregate (river sand), the value of γ cannot cover the effect of size effectively enough due to much higher fineness when comparing to the coarse aggregate. Thus, fineness modulus (FM) value of sand is taken into consideration in the charts. The examples of design charts are shown in Figs. 6 and 7.

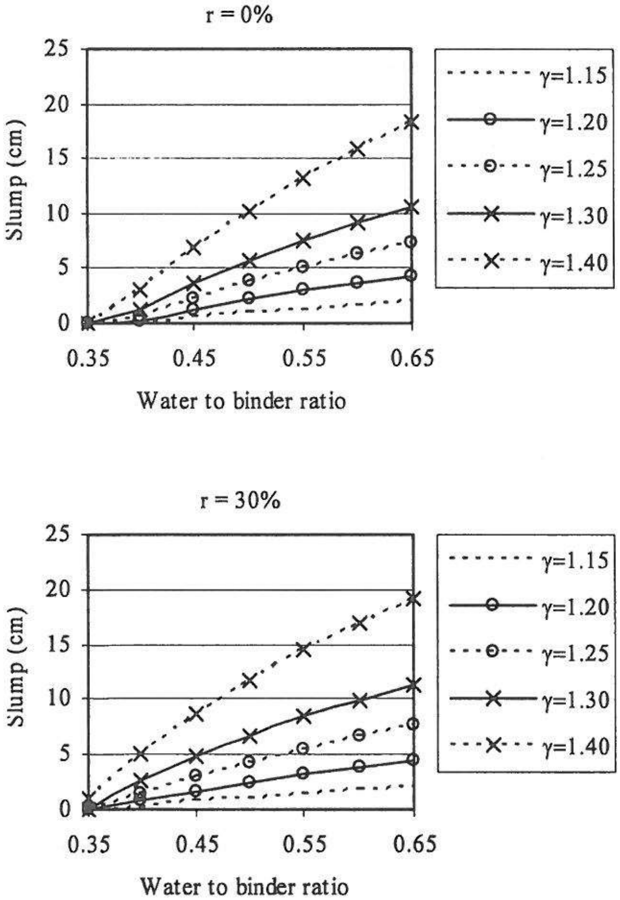

Fig. 6 Design chart for slump of concrete (FM = 2.75)

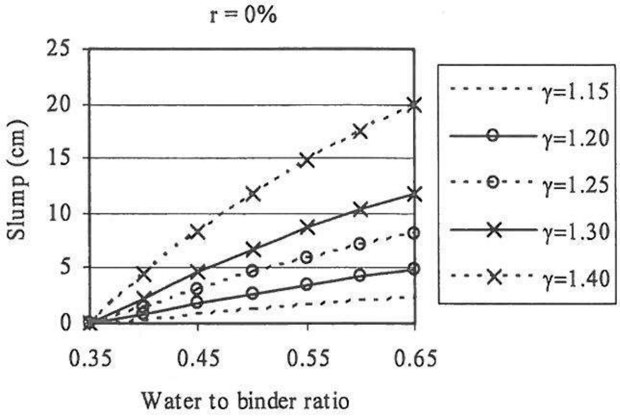

Fig. 7 Design chart for slump of concrete (FM = 3.25)

In this step, the actual value of γ is determined from the value of w/b ratio given from section 5.3. Then the entire process is repeated again with this actual value of γ until all the requirements are satisfied. However, in some cases, the value of γ that give a required slump value may not be possibly achieved from the selected w/b ratio. This is because the required properties are beyond the performance of conventional fly ash concrete without chemical admixture. Generally, the problem occurs when concrete needs a very low w/b ratio to satisfy the required high strength and durability. In this case, the chemical admixture is required. Chemical admixture does not affect on the compressive strength or carbonation resistance of concrete significantly. However, it affects the workability of concrete. It is noted that this proposed design charts for slump are not applicable if chemical admixture is used. Dosage of admixture must be estimated from other design methods.

6. Conclusions

The proposed design charts for mix proportioning of fly ash concrete subjecting to carbonation environment includes three major properties of concrete, i.e. compressive strength, slump, and carbonation resistance. The design charts were based on three models already proposed. In this design method, the value of γ was assumed at the beginning. Two values of w/b ratio were given from the design charts of compressive strength and carbonation resistance. The smaller value of w/b ratio was selected to ensure that the designed concrete meets the requirement for both compressive strength and carbonation resistance. The actual value of γ was given later from the design charts of slump.

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