Chapter 7

Mix Design of Fly Ash Concrete Subjecting to Carbonation

7.1 General

The major application of these models is to simulate the carbonation process of fly ash concrete that requires an essential consideration on its carbonation resistance. However, other important properties of concrete, such as its workability in fresh state and mechanical properties in hardened state, are still required and taken into consideration in the typical 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 the 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. can be estimated from the compressive strength. The relationships between these mechanical properties and the 28-day compressive strength recommended by ACI committee 318 (1995) are generally used in practice in Thailand.

The mix design method proposed in this study is based on three prediction models, i.e. the model for simulating carbonation of fly ash concrete proposed in this study, the workability prediction model proposed by Khunthongkeaw (2001) and Wangchuk et al. (2003a, b), and the compressive strength prediction model proposed by Kaewkhluab (2002), respectively. Simple design charts for mix proportioning of fly ash concrete subjecting to carbonation can be subsequently established. Thus, concrete can be designed based on the performance concept to find optimum mix proportion to reduce the carbonation problem of concrete structures. The adopted models and the design charts are discussed in this chapter.

7.2 Workability Prediction Model

Workability and consistency are important properties of concrete in fresh state, which can also adversely affect the properties of the hardened concrete if they are not practiced suitably. The desired workability in any particular work also depends upon the means of compaction available. Therefore, workability should be defined as an intrinsic property of the concrete without referring to the circumstances. Based on the study of Kitticharoenkiat (1998), Khunthongkeaw (2001) and Wangchuk et al. (2003a, b) proposed a model for predicting slump of concrete as follow.

7.2.1 Model formulation

It was verified that free water content has linear relationship with deformability of ordinary concrete as in Fig. 7.1 and the following equations.

$$SL = \alpha_{SL} (W_{fr} - W_0) \tag{7.1}$$

where SL is the slump value of fresh normal concrete (cm). α_{SL} is the slope of slump-free water content curve (cm/kg/m^3 of concrete). W_{fr} is volume of free water in the fresh concrete mixture (kg/m^3 of concrete) and W_0 is minimum free water content required for initiating slump (kg/m^3 of concrete). It is observed from Fig. 7.1 that the slump increases with an increase of free water content. In addition, when concrete has a larger paste content aggregate, aggregate are will dispersed and have a larger interparticle distance in the paste. These result in a better deformability of the mixture.

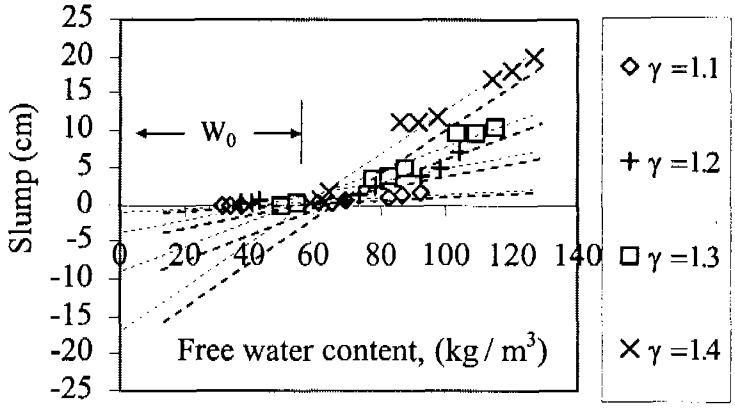

Fig. 7.1 Relationship between slump and free water content of fresh concrete

The slope of slump-free water content curve, α_{SL}, indicates the deformability of concrete due to the gravity force and was formulated to have relationship with the ratio of paste volume to void content of compacted aggregate phase (γ) as shown in the following equation.

$$\alpha_{SL} = 3.57\gamma^4 - 21.34\gamma^3 + 46.74\gamma^2 - 43.92\gamma + 14.94 \quad (7.2)$$

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 particles in the fresh concrete and can be obtained as in the following.

$$W_{fr} = W_u - W_{rp} - W_{ra}' + W_a \quad (7.3)$$

where W_u is the unit water content in the mixture (kg/m^3 of concrete). W_{rp} is the restricted water by powder materials (kg/m^3 of concrete). W_{ra}' is the restricted water on the surface of aggregates (kg/m^3 of concrete). W_a is the additional free water due to the situation that very fine powder particles fill in the voids among cement particles and drive out the free water that is entrapped in the voids (kg/m^3 of concrete). The total amount of restricted water by all solid materials can be derived as follows.

For powder materials: $$W_{rp} = \sum_{i=1}^{n} \beta_{pi} w_{pi} \quad (7.4)$$

For aggregates: $$W_{ra}' = \beta_s' w_s' + \beta_g' w_g' \quad (7.5)$$

where β_{pi} is the water retainability coefficient of powder material type i. w_{pi} is the absolutely dried weight of powder material type i (kg/m^3 of concrete). n is total number of powder materials used in the concrete. β_s' and β_g' are the surface water retainability coefficients (excluding absorption) of fine and coarse aggregates, respectively. w_s' and w_g' are the saturated surface dry weights of fine and coarse aggregates, respectively (kg/m^3 of concrete). The water retainability coefficient of powder materials was formulated in the study by taking into consideration of many physical characteristics of the powder, such as porosity, surface condition, shape, fineness, and size distribution. The influences of admixture and temperature are also considered in this parameter. However, the water retainability coefficient of aggregates was considered as the surface water retainability and was formulated to have relationship with the surface area of aggregates. This is because, in mix design of concrete, unit water content does not include the absorption of aggregates since standard condition of aggregate is considered to be saturated surface dried. So the restricted water in exception of the absorbed water in the aggregate particles is considered.

It can be observed from Fig. 7.1 that the amount of free water of the mixture below the point that the curve intercepts the free water content axis does not produce slumps. This is considered to be because the amount of free water is not enough to overcome the interparticle surface forces, which include friction and cohesion among solid particles. The amount of water required for balancing the interparticle surface forces among the solid particles (W_O) was empirically formulated as follow.

$$W_0 = \frac{9 \times 10^{-2} \, S_{eff}^{\ 0.76}}{L} \tag{7.6}$$

where S_{eff} is effective surface area of solid particles (m^2/m^3 of concrete) and L is lubrication coefficient to account for the spherical effect of particle shape. The effective surface area of solid particles has been defined as the surface area of all solid particles that have the possibility to be in contacts and thus produces resistance to the deformability of the fresh concrete mixture. The effective surface area of solid particles was derived as follow.

$$S_{eff} = S_{ta} + \phi_m \eta_p \sum_{i=1}^{n} s_{pi} w_{pi} \tag{7.7}$$

where S_{ta} is the total surface area of aggregates in the mixture (m^2/m^3 of concrete). w_{pi} is the absolutely dry weight of powder material type i (kg/m^3 of concrete). s_{pi} is the specific surface area of powder material type i (m^2/kg). n is total number of kind of powder materials used in the mixture. ϕ_{rb} is a factor indicating the effect of type and dosage of admixture. η_p is the effective contact area ratio of powder, which indicates the ratio of surface area of powder material that effectively contacts with aggregates to the total surface of powder materials.

The accuracy of the model was verified by comparing the predicted results from the model with the test results. Fig. 7.2 shows that the proposed model could be used to predict the slump of fresh fly ash concrete using various types of aggregate. Fig. 7.3 shows that the proposed could be used to predict the slump of fresh concrete with other types of pozzolans with and without mechanical treatment. The verification tests showed that this model could be used to predict slump of fresh concrete replaced by various type of powder materials, with and without mechanical treatment, with and without application of mineral and chemical admixtures with a satisfactory accuracy.

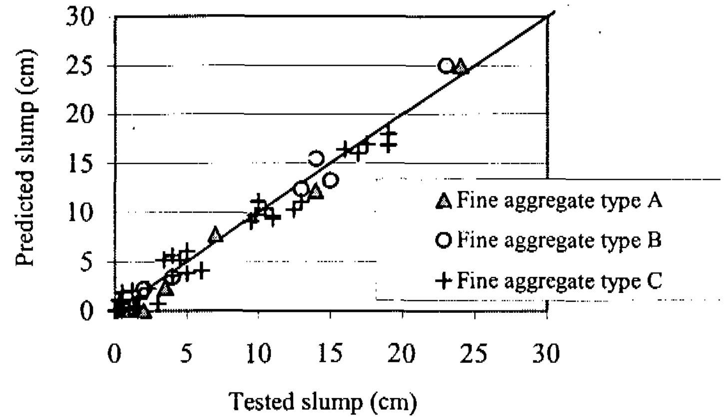

Fig. 7.2 Verification of slump of fly ash concrete

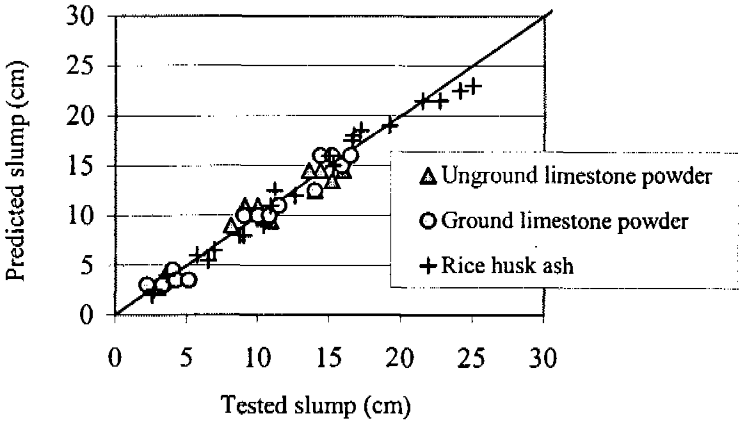

Fig. 7.3 Verification of slump of concrete with various types of powder

7.2.2 Application of the workability prediction model to roller compacted concrete

Roller-compacted concrete (RCC) is a cost-effective material and a construction technique, which is widely used throughout the world for dam construction. The main difference between RCC and conventional concrete is its no-slump consistency, which must be consolidated by vibrating rollers. Usually RCC has low cementitious material content but high content of pozzolans. Fly ash is commonly used in RCC due to benefits from low heat generation at early age and increase of workability. For conventional concrete, the slump test is applied for evaluating workability. However, for very stiff concrete, such as RCC, the slump test is improper. The Vebe consistency test has been introduced and used to evaluate consistency of RCC. This test is appropriate particularly for very dry concrete mixtures and also has the additional advantage that the treatment of concrete during the test is comparatively closely related to the method of placing in practice. (U.S. Army Corps of Engineers 2000 and Neville 1995)

It was mentioned in Khunthongkeaw (2001)'s study that the free water content in concrete mixture also has a unique relationship with other types of workability measurement for special concrete. The relationship between the inverse of Vebe time and free water content is shown in Fig. 7.4. It is observed that increases of free water content and ratio between paste volume and void content of compacted aggregate phase (γ) result in a better deformability of the mixture (higher inverse of Vebe time) and less time for the paste to rise up and fill all cavities under the surface of glass plate rider. It is also found that if the free water content in concrete is less than a particular value, the inverse of Vebe time remains almost constant. This is because the amount of free water is not enough to overcome the interparticle surface forces among solid particles causing very long Vebe time. An equation was derived based on Fig. 7.4 to relate Vebe consistency of RCC with free water content as follows.

$$VB = \frac{200}{\gamma^{8.7}(W_{fr} - W_o)} + 5.0 \tag{7.8}$$

where VB is Vebe time of roller-compacted concrete (second). γ is the ratio of paste volume to void content of the compacted aggregate phase. W_{fr} is volume of free water in the fresh concrete mixture (kg/m^3 of concrete), W_0 is the intercept of W_{fr} axis (kg/m^3 of concrete). In the other words, W_0 is the minimum free water content required for making the RCC workable. It is noted here that the equation is limited for Vebe time between 1-100 second.

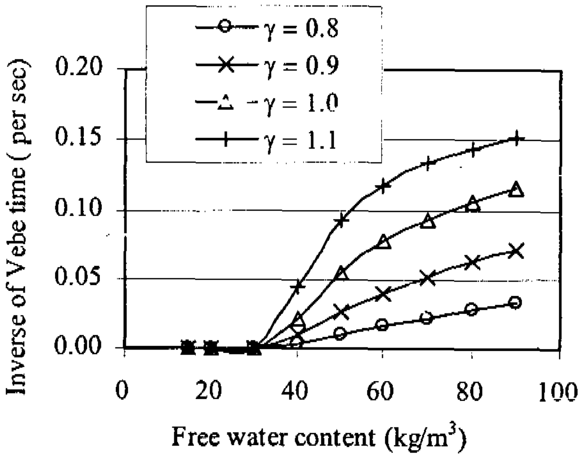

Fig. 7.4 Relationship between inverse of Vebe time and free water content in concrete

The model was verified by using test results of RCC with various contents of powder, water to binder ratio, and types of fly ash and aggregates for RCC tested in laboratory during construction of the Ta Dan Dam (Khunthongkeaw and Tangtermsirikul 2003). Figs. 7.5a to 7.5c show the verification tests that varies the water to binder ratio (between 0.48 to 0.93), replacement ratio (between 0.44 to 0.8), and powder content in RCC (between 120 to 250 kg/m^3 of concrete), respectively. Fig. 7.6 shows the verification of RCC from the construction of Pak Moon Dam (Kokkamhang 1998). The verifications show that the proposed model could be used to predict Vebe time of the tested RCC mixtures with satisfactory accuracy.

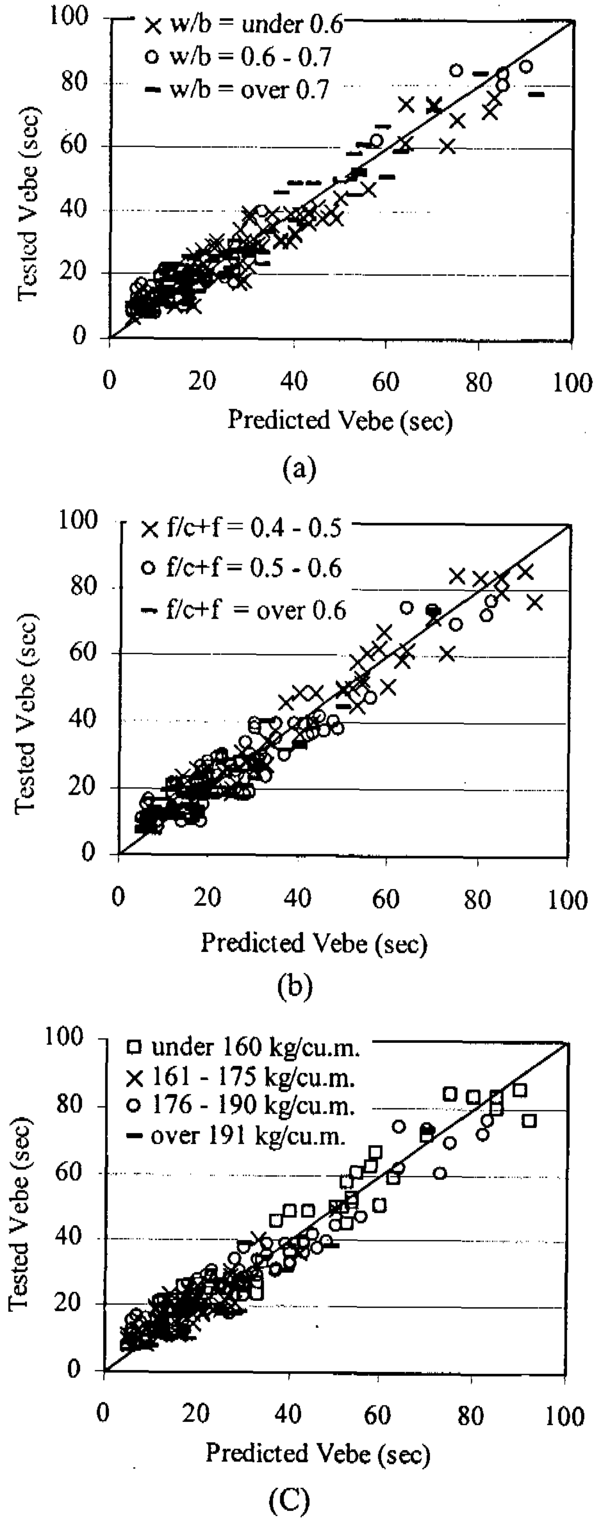

Fig. 7.5 Verification of Vebe time (Ta Dan Dam)

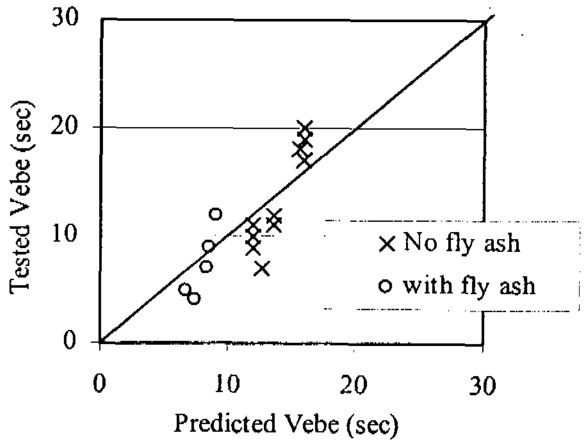

Fig. 7.6 Verification of Vebe time (Pak Moon Dam)

7.3 Compressive Strength Prediction Model

The model for predicting compressive strength of concrete at any age proposed by Kaewkhluab (2002) was adopted in this study. This model was formulated on the basis of the 28-days compressive strength. The term of strength development ratio was proposed as the ratio of compressive strength at any age to its 28-day compressive strength. In this model, two sub-models for predicting the 28-day compressive strength and the strength development ratio were proposed. Thus the compressive strength of concrete at any age can be computed by,

$$f_c'(t) = \phi(t) \cdot f_c'(28\ \text{days}) \tag{7.9}$$

where f_c' (t) and f_c' (28 days) are the compressive strength (Mpa) at concrete age t (days) and 28 days, respectively. $\phi(t)$ is the strength ratio at concrete age t (days).

7.3.1 28-day compressive strength model

It is known that an increase of water to cement 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, some very fine fly ash particles can fill in the voids among cement particles. This leads to dense packing of particles of binder materials and affects concrete strength positively. The ability to fill voids among cement particles increases as the particle size of fly ash reduces. Moreover, spherical particles are likely to have a better ability to fill voids among cement particles than non-spherical particles. In this model, loss on ignition (LOI) in fly ash is regarded as a non-reactive and low strength portion in concrete. Majority of the LOI in fly ash is unburned carbon. It was found that fly ash with higher LOI gives lower 28-day compressive strength than that with lower LOI when the replacement contents are the same. This effect was found smaller if fly ash had a higher CaO content. It was also confirmed in the study that normal concrete with small paste content, in comparison with voids among aggregates, leads to inadequate paste to fill voids and results in a poor aggregate-paste interface bond. Consequently, poor compressive strength concrete is obtained. On the contrary, too much paste content, in comparison with voids content, also results in lower compressive strength since generally paste is more porous than aggregate. Nevertheless, the reduction of the strength while increasing paste content beyond its optimum value becomes less significant in concrete with lower w/b as the result of its higher strength of paste. The use of water-reducers with no retarder was found to affect the compressive strength positively especially at early age since water-reducing admixture contributes to dispersion of the particles of binders in the fresh state, which improves the reactivity within the paste. Concrete with higher w/b has less effect of water-reducing admixture on compressive strength than that with lower w/b because binders are relatively well dispersed. The type of water-reducing admixture also affects its contribution to the compressive strength. The equation for predicting 28-day compressive strength of concrete [f_c' (28 days)] was summarized as follows.

$$f_c'(28\,\text{days}) = \left[\alpha_1 \log(\text{CaO}_{\text{eff}}) + \lambda_f\, \alpha_2\right] \chi_\gamma\, \chi_{\text{LOI}}\, \chi_{\text{wr}}\, \chi_{\text{air}} \tag{7.10}$$

in which,

$$\alpha_1 = 8.5(w/b)^{-1.54} + 27.73 \tag{7.11}$$

$$\alpha_2 = -0.45(w/b)^{-3.80} + 67.97(w/b) - 114.30 \tag{7.12}$$

where 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 water to binder ratio (w/b). λ_F, χ_γ, χ_{LOI} χ_{wr}, Ψ_{air} are the parameters indicating effects of filling effect of fly ash, γ value, loss on ignition of fly ash, water-reducing admixture, and entrained air, respectively on 28-day compressive. (Kaewkhluab 2002)

7.3.2 Strength development model

In the strength development model, strength ratio is defined as the ratio between compressive strength at any age of the concrete and its 28-day compressive strength. Strength at any age and rate of strength development of fly ash concrete are affected by the characteristics of the fly ash. SiO_2 and CaO are regarded as the main chemical compositions influencing hydration and pozzolanic reactions mainly contributing to the strength development of fly ash concrete. CaO mainly affects the hydration reaction and its products. CH reacts mainly with SiO_2 in fly ash during the pozzolanic reaction. The term SiO_2/CaO was proposed as the ratio between SiO_2 content and CaO content in the total binders. It was observed that an increase of SiO_2/CaO causes a lower compressive strength at ages before 28 days. In contrast, at later ages, an increase of SiO_2/CaO increases the compressive strength. Until the ratio reaches the optimum point, compressive strength decreases with an increase of SiO_2/CaO. This is because at early age the pozzolanic is not very reactive. Hydration reactions are the major reactions that generate calcium silicate hydrate and contribute to strength of concrete. At later age, SiO_2 in fly ash reacts with calcium hydroxide released from the hydration reaction and gives calcium silicate hydrate that contributes to strength in addition to calcium silicate hydrate from the hydration reaction. However, it is noted that if the amount of SiO_2 is excessive when compared to calcium hydroxide supplied by hydration, strength development will be lower.

At early ages that the pozzolanic reaction is still not very reactive, concrete with lower w/b gives better strength ratio than that with higher w/b since lower w/b yields denser structure of the paste leading to higher strength ratio and vice versa. At later ages when pozzolanic reaction becomes more active, concrete with lower w/b gives lower strength ratio than that with higher w/b because concrete due to more free water for reactions and better dispersion of the cementitious powders. In addition, the effect of particle filling of fly ash on strength development model was also included in the model since this effect contributes to the improvement of the compressive strength differently at different ages. This improvement is significant at early ages and especially in concrete incorporating spherically fine fly ash like air-classified fly ash. It was evident that the compressive strength of concrete at the early age was improved by water reducer more significantly than at the later age. The equation for predicting strength ratio of concrete was summarized as follows.

$$\phi_t = \left[1 + \ln\left(\frac{t}{28}\right)\Gamma\right] \cdot \omega_f(t) \cdot \omega_{wr}(t) \qquad (7.13)$$

where t is the age of concrete considered (days). Γ is the parameter indicating effect of water to cement ratio and value of SiO_2/CaO. ω_F and ω_{wr} are the time dependent parameters indicating filling effect of fly ash and effect of water reducing admixture, respectively on strength development ratio. (Kaewkhluab 2002)

7.4 Mix Design

In these models, properties of concrete can be forecasted by the process of analysis where the properties of the materials and mixture proportion are presumed. The process of analysis is not convenient in design since trials of the mix proportion are required and must be adjusted based on the experience after the computed results are obtained. In addition, the analysis of these models is rather complex. A mix design computer program will be developed in the future. However, in this study, charts and tables are constructed from the models and proposed to facilitate the mix design process. The mix design method proposed in this chapter considers only slump, compressive strength, and carbonation depth of concrete. In the mix design process, the required properties of concrete are compressive strength at specific age(s), slump, carbonation depth, and replacement ratio of fly ash. In this model, the carbonation depth is specified by the thickness of concrete cover to reinforcing steel bars within and the maintenance free period of concrete against carbonation. Two values of water to binder ratio those give concrete the required compressive strength at specific ages and carbonation resistance are determined from the design charts. The smaller value of water to binder ratio is selected to ensure that concrete satisfies the requirements. The paste content is then determined from the design charts for satisfying the required slump. Therefore, the concrete is designed to satisfy all the requirements.

7.4.1 Limitations

At present, the workability and strength prediction models are applicable to various type and wide range of concrete. However, the carbonation simulation model still has limitation on application and requires future verification for a wider range of concrete types. The proposed durability design method is therefore appropriate for conventional concrete with and without fly ash that has 28-day compressive strength not over 60 MPa and slump value between 1 and 25 cm. This method is not applicable for air-entrained concrete and special types of concrete, i.e. lightweight concrete, high strength concrete, underwater concrete, self-compacting concrete, or roller compacted concrete. It is remarked that the depths of carbonation were verified up to two years. Ingress of carbonation at later ages is forecasted by using the model proposed in this study. For material limitations, the standard Portland cement type I complied with the requirement of TIS-15 (1989) is recommended. The models used as the basis of this design method have taken into account the variations of properties of fly ash and aggregates. However, for the simplicity, the design charts do not fully cover the changes of properties and types of fly ash and aggregates. It is therefore recommended that the method is suitable for unprocessed fly ashes that are classified as type 2a and 2b by EIT-1014 (2003) and have fineness not over than 320 m^2/kg. Details of fly ash in the EIT-1014 (2003) are given in Appendix B. Fine and coarse aggregates must be river sand and limestone coarse aggregate, respectively. The aggregates must satisfy the industrial standard (TIS-566, 1989) and the standard (EIT-1014, 2003). The maximum size of coarse aggregate is not larger than 38 mm.

7.4.2 First step: compressive strength

It was found from the model that various parameters affected the compressive strength of concrete. However, it is very difficult to construct the design charts that consider all parameters. In the design charts, it is considered that the major parameters significantly affecting the compressive strength of concrete are water to binder ratio, paste content, fly ash content, age of concrete, and properties of cement and fly ash. Since the 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. In addition, although engineers usually specify compressive strength at 28 days, for some structures and purposes, strength at other ages are also specified. Thus the design charts for compressive strength are constructed at age of concrete of 3, 7, 14, 28, 91 days and separated into two sets for fly ash type 2a and 2b (EIT-1014, 2003) as shown in Appendix C1.

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), i.e. $\gamma = 1.2$ for normal concrete. Then the value of water to binder ratio is selected from the design charts (Appendix C1) from the required compressive strength. It is noted that if the compressive strengths at more than one specific age is required, the minimum water to binder ratio that satisfies all strength requirements is selected.

7.4.3 Second step: carbonation depth

It was confirmed in this study that the major parameters affecting carbonation resistance of concrete are type and replacement level of fly ash, water to binder ratio, curing period, and environmental condition. Where paste content and aggregate content are considered as insignificant parameters and ignored in this mix design method (see section 5.2.4 for the effect of paste content on carbonation depth). In this design method, the maintenance free period of concrete is specified by the period that carbonation front moves from the exposed surface of concrete 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 of concrete and maintenance free period of concrete with the water to binder ratio and replacement level of fly ash types 2a and 2b (EIT-1014, 2003) as shown in Appendix C2. The environmental conditions were divided into three locations, i.e. city-sheltered area, city-non-sheltered area, and rural (sheltered) area. It is noted that the effect of curing period is not covered in these proposed design charts.

In this step, the water to binder ratio is selected from the design charts (Appendix C2) by the given type and content of fly ash, cover thickness of structure, designed maintenance free period, and environment that the structure will be located in. The smaller value between water to binder ratio selected from the first step (in 7.4.2) and the second step (7.4.3) is used here to ensure that the designed concrete meets the requirement for both compressive strength and carbonation resistance. It is remarked that the concrete is possibly over designed for either compressive strength or carbonation resistance.

7.4.4 Third step: slump

Workability is considered as an important concrete property in fresh state and generally indicated by slump value. This property is influenced mainly by physical properties of the solid ingredients. The chemical properties of ingredients, within the limited ranges, 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 proportion and physical characteristics of binder and aggregates. It was 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 between 90 to 105%. 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-distribution of aggregate give a larger γ value, for a certain paste content, and thus a better workability. For fine aggregate (river sand), the value of γ cannot cover the effect of size effective enough due to much higher fineness when comparing to the coarse aggregate. Thus, FM value of sand is taken into consideration in this method. The design charts are shown in Appendix C3.

In this step, the actual value of γ is determined from the value of water to binder ratio given by the second step, the required slump, and the given FM of river sand. Then the entire process is repeated again with this actual value of γ until all the requirements are satisfied. The mix proportion of concrete is calculated from the selected value of γ and water to binder ratio, the tested value of sand to aggregates ratio and void content, and the given replacement ratio of fly ash and specific gravity of all ingredients. However, in some cases, the value of γ that gives a required slump value may not be possibly achieved from the selected value of water to binder ratio. This is because the required properties of concrete are beyond the performance of conventional fly ash concrete without chemical admixture. Generally, the problem occurs when concrete needs a very low water to binder ratio to satisfy the required high strength and durability. Thus chemical admixture is required. The use of chemical admixture does not affect significantly the compressive strength or carbonation resistance of concrete. However, it significantly affects the slump of concrete. The proposed design charts for slump are not applicable if chemical admixture is used. Dosage of admixture must be estimated from trial mixing or other design methods.

7.4.5 Example of mix design

The required performances of concrete are as follows

1. Required 7, 28, and 91 day compressive strength are 14, 20, and 24 Mpa, respectively.
2. Required slump is 10 cm.
3. Structure is designed to have 3 cm of cover thickness
4. Structure must satisfy 50 years maintenance free period in city location (indoor)
5. Fly ash type 2a is used with the replacement ratio of 0.3 to the total binder

The given properties of solid ingredients are as follows

1. Specific gravities of cement and fly ash are 3.1 and 1.9, respectively.
2. Fine aggregate is river sand with FM and specific gravity of 2.75 and 2.6, respectively
3. Coarse aggregate is limestone with specific gravity of 2.7.
4. Absorptions of fine and coarse aggregates are 1.0 and 0.5%, respectively.
5. It was found that sand to aggregate ratio of 0.4 give a minimum void volume of 24%.

First step

The γ value of 1.2 is assumed. Fly ash type 2a is used with the replacement ratio of 0.3 to the total binder. Therefore, according to the compressive strength requirement at 7, 28, and 91 days, the water to binder ratios of 0.55, 0.60, and 0.58 are derived, respectively, from Figs. C1-2 (r = 30%), C1-3 (r = 30%), and C1-4 (r = 30%), respectively. Therefore, the minimum water to binder ratio of 0.55 is selected ($\gamma = 1.2$).

Second step

The structure is planed to satisfy a 50-year maintenance free period in city-sheltered area with the covering depth of 3 cm. Fly ash type 2a is used with the replacement of 0.3 to the total binder. Therefore, the water to binder ratios of 0.52 is obtained from Figs. C2-3 (city-sheltered). The smaller value of water to binder ratio of 0.52 is selected in this step instead of 0.55 in the first step.

Third step

From the requirement of slump (10 cm), the γ value of 1.37 is obtained from Fig. C3-1 (r = 30%) for the given water to binder ratio of 0.52, FM of sand of 2.75, and fly ash content of 30% of the total binder. The selected γ value of 1.37 and water to binder ratio of 0.52 are found to satisfy the requirement for compressive strength in all ages (see Figs. C1-2, C1-3, and C1-4). Therefore, the mix proportion is derived as follows

1. γ value is 1.37
2. Water to binder ratio (w/b) is 0.52
3. Replacement percentage of fly ash (f/c+f) is 0.3
4. s/a is 0.4, which gives the minimum void of 24%
5 Air content is assumed to be 1% by volume of concrete

7.4.6 Calculation of mix proportion

Volume of paste, V_p can be obtained as,

$$V_p = V_c + V_f + V_w + V_a \qquad (7.14a)$$

and $$V_p = \gamma \times 0.24 \times 1000 = 1.37 \times 0.24 \times 1000$$

$$= 328.8 \quad \text{liter/m}^3 \text{ of concrete} \qquad (7.14b)$$

Volume of fly ash (V_f) can be derived from,

$$0.30 = \frac{1.9 \cdot V_f}{3.1 \cdot V_c + 1.9 \cdot V_f}$$

$$V_f = 0.70\, V_c \qquad (7.14c)$$

Volume of water (V_w) can be derived from,

$$0.52 = \frac{1.0 \cdot V_w}{3.1 \cdot V_c + 1.9 \cdot V_f}$$

$$2.30\, V_c = (7.12d) \qquad (7.14d)$$

Volume of air (V_a) is assumed equal to 1%

$$V_a = 0.01 \times 1000$$

$$= 10 \text{liter/m}^3 \text{ of concrete} \qquad (7.14e)$$

Substitute Eqs. (7.12b, 7.12c, 7.12d, 7.12e) into Eq. (7.12a), then

$$328.8 = V_c - 0.70V_c - 2.30\, V_c - 10$$

$$V_c = 79.7 \quad \text{liter/m}^3 \text{ of concrete} \qquad (7.14f)$$

$$W_c = 79.7 \times 3.1$$

$$= 247.1 \quad \text{kg/m}^3 \text{ of concrete} \qquad (7.14g)$$

Substitute Eq. (7.12f) into Eq. (7.12c), then

$$V_f = 55.8 \quad \text{liter/m}^3 \text{ of concrete} \qquad (7.14h)$$

$$W_f = 55.8 \times 1.9$$

$$= 106.0 \quad \text{kg/m}^3 \text{ of concrete} \qquad (7.14i)$$

Substitute Eq. (7.12f) into Eq. (7.12d), then

$$V_w = 183.3 \quad \text{liter/m}^3 \text{ of concrete} \qquad (7.14j)$$

$$W_w' = 183.3 \quad \text{kg/m}^3 \text{ of concrete} \qquad (7.14k)$$

Volume of aggregates ($V_s + V_g$) can be derived from,

$$V_s + V_g = 1000 - V_p$$

$$= 671.2 \quad \text{liter/m}^3 \text{ of concrete} \tag{7.14m}$$

Weight of aggregates in SSD condition can be derived from,

$$0.40 = \frac{V_s}{V_s + V_g} \tag{7.14n}$$

$$V_s = 268.4 \quad \text{liter/m}^3 \text{ of concrete} \tag{7.14o}$$

$$W_s' = 268.4 \times 2.6$$

$$= 697.8 \quad \text{kg/m}^3 \text{ of concrete} \tag{7.14p}$$

Substitute Eq. (7.12j) into Eq. (7.12m), then

$$V_g = 402.8 \quad \text{liter/m}^3 \text{ of concrete} \tag{7.14q}$$

$$W_g' = 402.8 \times 2.7$$

$$= 1156.0 \quad \text{kg/m}^3 \text{ of concrete} \tag{7.14r}$$

Since, absorptions of fine and coarse aggregate are 1.0 and 0.5%, respectively. Actual weight of aggregate and water can be derived from,

$$W_s = (1 + 0.01) \times 697.8$$

$$= 704.8 \quad \text{kg/m}^3 \text{ of concrete} \tag{7.14s}$$

$$W_g = (1 + 0.005) \times 1156.0$$

$$= 1161.8 \quad \text{kg/m}^3 \text{ of concrete} \tag{7.14t}$$

$$W_w = 183.3 - (704.8 - 697.8) - (1161.8 - 1156.0)$$

$$= 170.5 \quad \text{kg/m}^3 \text{ of concrete} \tag{7.14u}$$

The mix proportion of concrete can be obtained as follows,

Weight of cement = 247.1 kg/m^3 of concrete

Weight of fly ash = 106.0 kg/m^3 of concrete

Weight of water = 170.5 kg/m^3 of concrete

Weight of sand = 704.8 kg/m^3 of concrete

Weight of gravel = 1161.8 kg/m^3 of concrete

where V_p, V_c, V_f, V_w, V_a, V_s, and V_g are the volume of paste, cement, fly ash, water, air, sand, and gravel, respectively (liter/m^3 of concrete). W_c, W_f, W_w, W_s, and W_g are the actual weight of paste, cement, fly ash, water, sand, and gravel, respectively (kg/m^3 of concrete) in mix proportion of concrete. W_s' and W_g' are the weight of sand, and gravel in SSD condition, respectively (kg/m^3 of concrete). W_w' is the weight of water when aggregates are in SSD condition (kg/m^3 of concrete).