Chapter 4
Free Water Content in Concrete

4.1 General

Various researchers (Neville, 1995; Schutter and Tawrwe, 1995; Rilem Commiision 42-CEA, 1981) reported the change of thermal properties such as specific heat, thermal conductivity and coefficient of thermal expansion with the change of free water content in concrete. During hydration process, free water content reduces with respect to the concrete age. The amount of free water in paste decreases with an increase in the degree of hydration and pozzolanic reaction. As a result, thermal properties of concrete change with the degree of hydration reaction and pozzolanic reaction. Therefore, the free water content is an important factor in the evaluation of thermal properties and it must be predictable. In this study, the model proposed by Saengsoy. (2002) for predicting the free water content in concrete was used in thermal properties prediction models. In her study, the free water was defined by weight loss upon drying of saturated pastes and mortars at 105 ºC. The tests were conducted at various test ages (1, 3, 7 and 28 days). The mix proportion of all samples are shown in Table 4.1. Free water in her study is defined as water that was reactable with cementitious materials and excluding gel water. Water restricted by powder materials and water retained on the surface of aggregates was also regarded as free water. Absorbed water in aggregate is not considered as free water and was subtracted from the test results of mortars.

Pastes were prepared with water to binder ratios (w/b) of 0.25 and 0.40. Mortars with water to binder ratios of 0.50 and 0.60 were designed with fine aggregate to binder ratio by weight equal to 3. The influence of fly ash content was studied by varying the replacement ratios of cement by fly ash in the mixtures to be 0, 0.3 and 0.5 for each set of water to binder ratio. An example of description of the mixture designation is as follow; "w25r3" means the sample which has water to binder ratio of 0.25 and fly ash replacement ratio of 0.3.

From her study, it can be concluded from the experimental results that free water content of pastes decreased with respect to time due to water consumption in hydration and pozzolanic reaction. The replacement of cement by fly ash causes relatively higher free water content at early age but tends to decrease in longer age due to pozzolanic reaction. The test results were used to formulate a mathematical model to predict free water content in concrete. The details of free water model are mentioned in this chapter.

4.2 Model for Simulating Free Water Content of Concrete

4.2.1 Free water content

In the study of Saengsoy. (2002), free water in paste was defined as the evaporable water when the paste was subjected to drying at 105 ^{o}C. The evaporable water means the part of water which has not been used in hydration and pozzolanic reaction and has not been trapped as gel water. The gel water is not defined as free water since it is entrapped in the products of hydration and pozzolanic reaction. The free water content reduces with time due to water consumption in hydration and pozzolanic reaction process.

Table 4.1 Mix proportion of the tested paste and mortars

Mixture Designation	w/b	r	s/b
w25r0	0.25	0	0
w25r3	0.25	0.3	0
w25r5	0.25	0.5	0
w40r0	0.40	0	0
w40r3	0.40	0.3	0
w40r5	0.40	0.5	0
w50r0	0.50	0	3
w50r3	0.50	0.3	3
w50r5	0.50	0.5	3
w60r0	0.60	0	3
w60r3	0.60	0.3	3
w60r5	0.60	0.5	3

Remarks: w/b: water to binder ratio, r: fly ash replacement ratio and s/b: natural river sand to binder ratio.

The free water content at a certain age can be estimated as in Eq. (4.1).

$$W_{fw}(t) = W_{fw0} - W_{whp}(t) - W_{wgel}(t) \tag{4.1}$$

where $W_{fw}(t)$ and $W_{wgel}(t)$ are the weight of free water and gel water in the mixture at age t, respectively (kg/m^3). W_{fwo} is the unit water content of the mixture (kg/m^3). $W_{whp}(t)$ is the weight of water consumed by hydration and pozzolanic reactions (kg/m^3).

4.2.2 Chemically bound water content

During the process of reactions, water is consumed by cement hydration and pozzolanic reaction of fly ash as in Eq. (4.2). The minimum water to binder ratio required to complete hydration of cement paste (θ_{hpc}) is considered in this study to be approximately equal to 0.21 as in Eq. (4.3) (Powers 1960, Neville 1995, Lam et al. 2000). In fly ash-cement paste, the water content required for completing reactions will be reduced with the increase of fly ash replacement. The minimum ratio of water to binders for completing reactions is assumed to be equal to 0.20 for paste with 30% of fly ash replacement, and 0.18 for paste with 50% of fly ash replacement. As a result, the minimum ratio of water to pozzolanic material required to obtain the maximum pozzolanic reaction (θ_{hpf}) can be subsequently derived as in Eq. (4.4). It is noted here that the state of complete reactions represents the state of complete hydration reaction and attaining maximum pozzolanic reaction.

$$W_{whp}(t) = \theta_{hpc} \cdot W_{uc0} \cdot \frac{\alpha_{hy}(t)}{100} + \theta_{hpf} \cdot W_{ufa0} \cdot \frac{\alpha_{poz}(t)}{100} \tag{4.2}$$

$$\theta_{hpc} = 0.21 \tag{4.3}$$

$$\theta_{hpf} = \frac{0.984}{3.688 + \exp(2.112 \cdot r)} \tag{4.4}$$

where θ_{hpc} is the minimum ratio of water to binder for completing hydration reaction. θ_{hpf} is the minimum ratio of water to pozzolanic material for attaining the maximum pozzolanic reaction (it is not possible to achieve 100 % degree of pozzolanic reaction since no fly ash is 100 % reactive). W_{uc0} and W_{ufa0} are the weight of cement and fly ash in the mixture at the time of mixing (at t = 0), respectively (kg/m^3). r is the replacement ratio by weight of fly ash in total binder and t is the age of paste (days).

4.2.3 Gel water content

Gel water content increases with age following hydration and pozzolanic reactions since it is entrapped in the products of those reactions. The gel water content is affected by the water to binder ratio in the mixture and replacement ratio of cement by fly ash. Gel water content at a time considered was formulated by using data back analysis obtained from the test results of free water content and Eq. (4.1) as in Eq. (4.5).

$$W_{wgel}(t) = \left(0.0126 + \frac{0.0026}{-1.009 + \exp(0.1414 \cdot w/b)} \right) \cdot W_{uc0} \cdot \frac{\alpha_{hy}(t)}{100} + (6.177 \cdot r^2 + 9.681 \cdot r) \cdot (8.87 \cdot w/b^{8.44} + 0.1156) \cdot W_{ufa0} \cdot \frac{\alpha_{poz}(t)}{100}, \quad r \le 0.5 \qquad (4.5)$$

where $W_{wgel}(t)$ is the weight of gel water in the mixture at time t (kg/m^3 of concrete). W_{uc0} and W_{ufa0} are the weight of cement and fly ash in the mixture at the time of mixing (at t = 0), respectively (kg/m^3 of concrete). r is the replacement ratio by weight of fly ash in total binder, and w/b is the water to binder ratio. α_{hy} (t) is the average degree of hydration of cement in the paste (%), α_{poz} (t) is the degree of pozzolanic reaction of fly ash in the paste (%), and t is the age of paste (days).

For cement paste with water to binder ratio less than 0.21, the minimum water to binder ratio required to complete hydration, there is no gel water exists at the state of complete hydration because the water content was all consumed in hydration process. However, complete reaction is only possible at water to binder ratios above 0.4. Consequently, gel water exists even though at water to binder ratios lower than 0.4. Maximum gel water to binder ratio is assumed equal to 0.19 (Powers 1960, Neville 1995). At water to binder ratios greater than 0.4, an excess of water from that being used for completing reaction and adsorbed on gel solid become free water in capillary pores.

Replacement ratio of cement by fly ash also has an effect on gel water content of paste. Appropriately higher fly ash replacement ratio usually gives higher hydrated and pozzolanic products in long term. Since gel water is a part of hydrated and pozzolanic products, paste with higher replacement ratio of cement by fly ash gives higher gel water content. It is noted that only up to 50% of fly ash replacement was considered, it is expected that gel water will reduce if too much fly ash is incorporated.

Fig.4.1 shows the distribution of ratio to cement weight of free water, gel water, and hydrated water in paste with various water to binder ratio at different degree of hydration.

4.3 Verification of Free Water Content Prediction

The free water content at various ages of the tested pastes and mortars were computed by using Eq. (4.1). The comparison between the analytical results and the test results are shown in Figs. 4.2 to 4.8. Figs. 4.2 to 4.4 show the effect of water to binder ratio. Figs. 4.5 to 4.8 show the effect of replacement ratio of fly ash. It is shown in the figures that the models are satisfactory to predict the free water content of the tested samples. The model obviously shows, in Figs. 4.2 to 4.4, that the mixtures with higher w/b have higher free water content than those with lower w/b. The model also shows, in Figs. 4.5 to 4.8, that the free water of pastes and mortars with fly ash tend to continue decreasing in long term when compared to that of the cement pastes and cement mortars due to pozzolanic reaction.

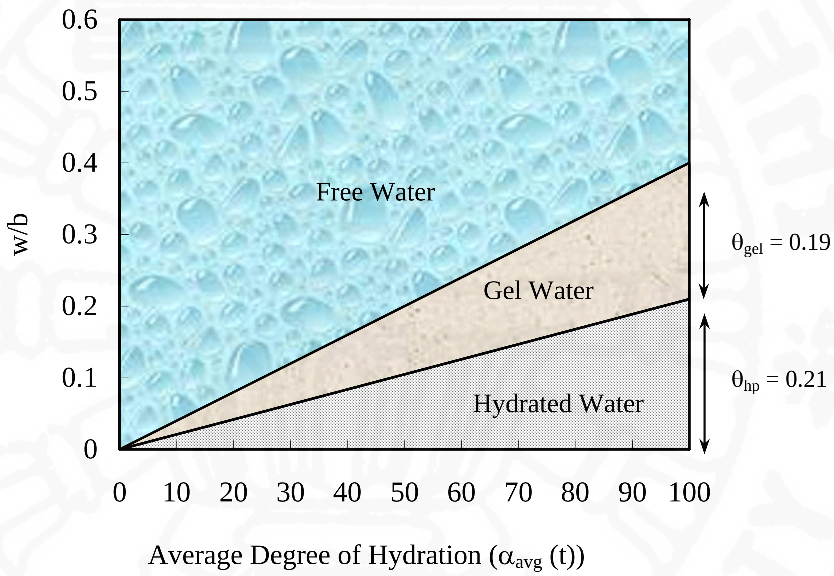

Fig. 4.1 Distribution of ratio to cement weight of free water, gel water, and hydrated water in paste with various water to binder ratio at different degree of hydration

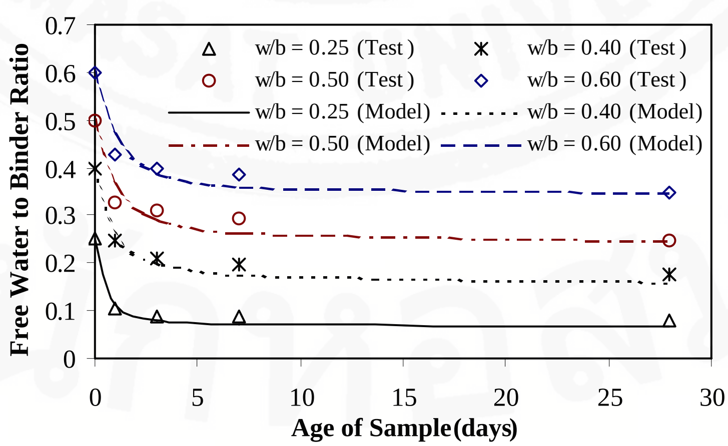

Fig. 4.2 Comparisons between test results and model of weight ratio of free water to total binder of mixtures with no fly ash, and w/b = 0.25, 0.40, 0.50, and 0.60

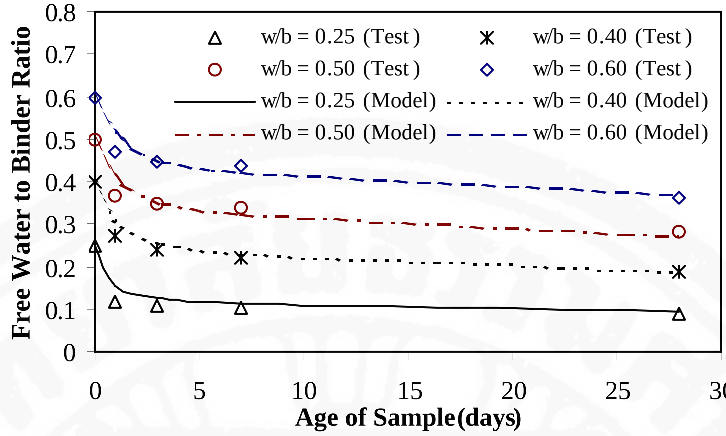

Fig. 4.3 Comparisons between test results and model of weight ratio of free water to total binder of mixtures with fly ash replacement ratio of 0.3, and w/b = 0.25, 0.40, 0.50, and 0.60

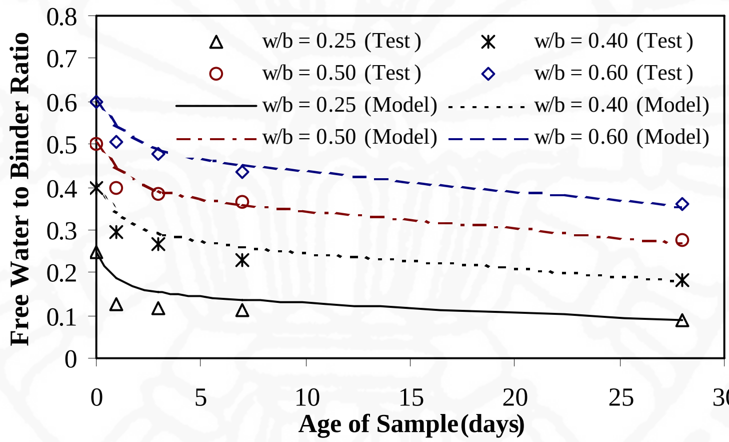

Fig. 4.4 Comparisons between test results and model of weight ratio of free water to total binder of mixtures with fly ash replacement ratio of 0.5, and w/b = 0.25, 0.40, 0.50, and 0.60

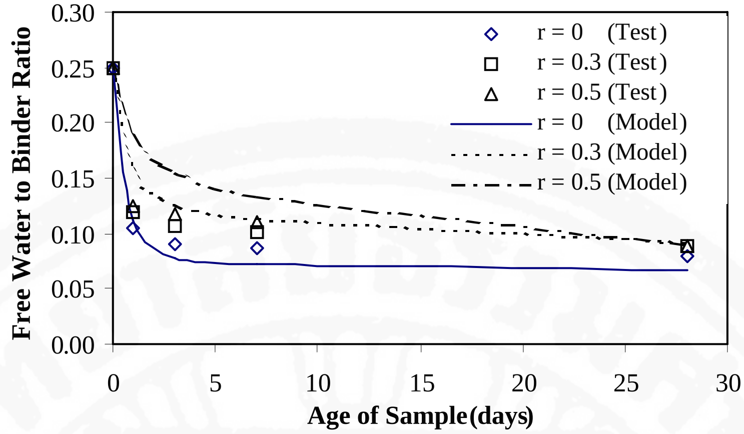

Fig. 4.5 Comparisons between test results and model of weight ratio of free water to total binder of mixtures with fly ash replacement ratio of 0, 0.3 and 0.5, and w/b = 0.25

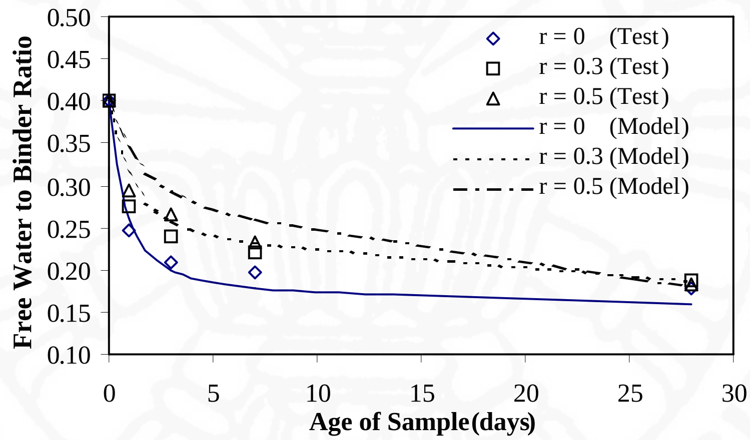

Fig. 4.6 Comparisons between test results and model of weight ratio of free water to total binder of mixtures with fly ash replacement ratio of 0, 0.3 and 0.5, and w/b = 0.40

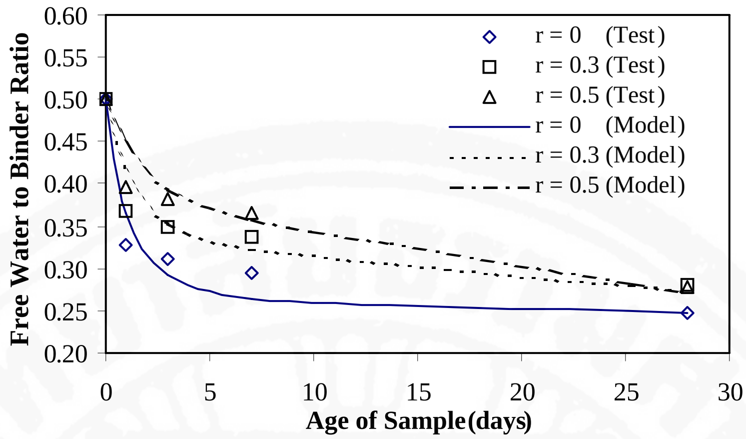

Fig. 4.7 Comparisons between test results and model of weight ratio of free water to total binder of mixtures with fly ash replacement ratio of 0, 0.3 and 0.5, and w/b = 0.50

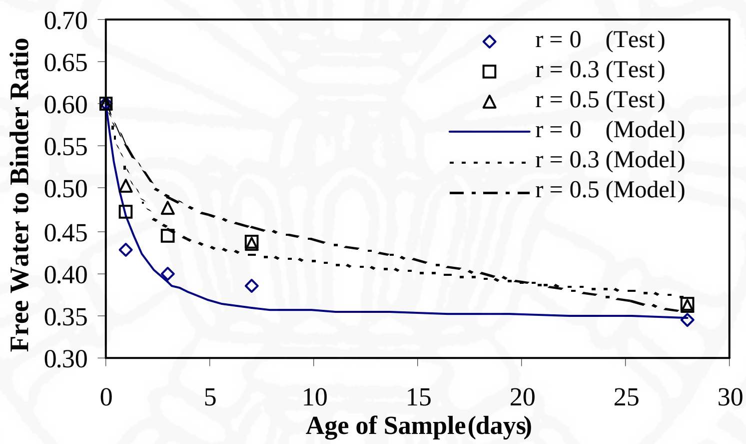

Fig. 4.8 Comparisons between test results and model of weight ratio of free water to total binder of mixtures with fly ash replacement ratio of 0, 0.3 and 0.5, and w/b = 0.60