Chapter 7
Model of Coefficient of Thermal Expansion of Concrete

7.1 General

One of the significant thermal properties is coefficient of thermal expansion **(***CTE*) which is used to compute strain due to temperature variation in mass concrete (Klieger and Lamond, 1994). *CTE* of concrete depends on the *CTE*s of ingredients in concrete, which are cementitious materials, water, hydration products and aggregates. *CTE* can be defined as the length change per unit length of a material when subjecting to a unit temperature change. The unit of *CTE* is expressed in micron per degree Celsius. Examples of the *CTE* of each ingredient in concrete are shown in Table 7.1. The *CTE* of concrete is mainly affected by the *CTE*s of paste and aggregate phases since both are main constituents of the concrete. In this study, *CTE*s at early age of paste, mortar and concrete were studied. A model for predicting *CTE*s was proposed as time, material and mix proportion dependent functions.

7.2. Experimental Investigation

7.2.1 Materials and mix proportions

Cement-fly ash paste and mortars with two different types of fine aggregate (natural river sand and crushed limestone sand) were produced and tested at various ages (1, 3, 7, and 28 days). Chemical compositions and physical properties of the cement and fly ash used in the tests are given in Appendix C (Table C1). Physical properties of aggregates are shown in Appendix C (Table C2). Cement-fly ash pastes were tested to observe the effect of water and fly ash content. *w/b* was varied at 0.25, 0.35 and 0.4 and fly ash replacement ratio, r, was varied at 0, 0.3 and 0.5. Mortars were tested to observe the effect of type and content of aggregate. Fine aggregate to binder ratio by weight was varied at 1 and 3. A description of the mixture designation is as follows; “w25r3” means paste which has *w/b* of 0.25 and fly ash replacement ratio of 0.30. Four mixtures of concrete were produced and tested. For concrete, limestone was used as coarse aggregate whereas natural river sand was used as fine aggregate. The mix proportions of the tested pastes, mortars and concrete are shown in Table 7.2 and Table 7.3. The *CTE* was tested at 1, 3, 7 and 28 days of age. Only two mixtures of cement-fly ash paste (mixtures number 1 and 3 in Table 7.2) were also tested at 12 hours in order to investigate the *CTE* at the age before 1 day. The final objective is to apply the proposed model to calculate restrained strain in mass concrete. The modulus of elasticity of concrete at the age before setting is small then the stress induced by the rise in temperature is insignificant even in zones of full restraint (ACI207.2, 1996). Thermal cracking usually occurs at the age after concrete gain enough stiffness to generate restraint then *CTE* of concrete before hardening is not considered in this study.

Table 7.1 *CTE* and modulus of elasticity of ingredients of concrete

Ingredients	*CTE*, micron/°C	Modulus of Elasticity, x 10^4 MPa
Cement	14.4 (www.supercivilcd.com, 2006)	-
Fly Ash	6.45 (Mangutova1 et al., 2004)	-
Quartz Sand	10.4 (Klieger and Lamond, 1994)	8.48 (Neekhra, 2004)
Limestone	4.5 (Klieger and Lamond, 1994)	14.27 (Neekhra, 2004)
Hydrated Products	20 *	-

* The value was obtained from regression analysis in this study.

Table 7.2 Mix proportions of the tested cement-fly ash pastes and mortars

Mix No.	Mixture Code	*w/b*	r	s/b	g/b
1	w25r0	0.25	0	0	0
2	w25r3	0.25	0.3	0	0
3	w25r5	0.25	0.5	0	0
4	w35r0	0.35	0	0	0
5	w35r3	0.35	0.3	0	0
6	w35r5	0.35	0.5	0	0
7	w40r0	0.40	0	0	0
8	w40s1	0.40	0	1	0
9	w40s3	0.40	0	3	0
10	w40g1	0.40	0	0	1
11	w40g3	0.40	0	0	3

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

Table 7.3 Mix proportions of the tested concrete

Mix No.	Mixture Code	γ	w/b	r
1	γ1.2w4	1.2	0.40	0
2	γ1.4w4	1.4	0.40	0
3	γ1.2w5	1.2	0.50	0
4	γ1.4w5	1.4	0.50	0

Remarks: γ: the ratio of the volume of paste to volume of void in densely compacted aggregate phase.

7.2.2 Specimen preparation and test procedure

It is known that autogeneous shrinkage strain during measurement is one of the important parameters which affects the results of *CTE*. From some previous studies, the effect of autogeneous strain during the measurement of the *CTE* was considered and some measuring methods were developed to separate the effect of autogeneous shrinkage strain from the thermal strain, especially for low *w/b* concrete at early age. Yang and Sato (2002) avoided autogeneous shrinkage strain during the measurement of thermal strain by reducing the hydration that occurred during the test period. The rate of hydration reaction was reduced by reducing of concrete temperature to very low level. The *CTE* excluding autogeneous shrinkage could be obtained by the use of temperature change in the very low temperature region and the measuring temperature changes used in their study were between -1 ^oC to 5 ^oC. However, the method requires sophisticated equipment. In the method proposed by

Bjontegaard and Sellevold (2001), the *CTE* was measured by using varied temperature histories. The specimens were heated up by 7 ^{o}C to 10 ^{o}C per step until reaching the required temperature history. Thermal deformation was measured in each temperature step and autogeneous deformation was measured directly between each temperature step. The method is reasonable for measurement of the *CTE* by automatically deleting the effect of autogeneous shrinkage, but it requires relatively complicated facilities. Kada et al. (2002) proposed a test method by applying temperature shock with the tested temperature range between 10 ^{o}C to 50 ^{o}C and the test duration of less than one hour. The effect of autogeneous shrinkage was neglected in his study because the test duration was short. However, the tested temperature up to 50 ^{o}C was a little bit high and may cause moisture movement to the surface inside the plastic wrap during the test. In this study, the *CTE* test method was designed to minimize the effect of autogeneous shrinkage deformation by controlling the measuring duration to be as short as possible. The temperature range must be controlled to prevent the moisture transfer during testing. The measuring method of Kada et al. (2002) and standard test method ASTM C531 (2000) were adopted and modified to be used in this study due to simplicity. Even though the test duration was short and autogeneous shrinkage strain can be minimized, autogeneous shrinkage strain was calculated and deducted from the measured strain by applying the two-phase model for computing concrete autogeneous shrinkage strain which was proposed by Tangtermsirikul and Tatong (2001). The details of the measuring method used in this study are described as follows.

Prism specimens with dimensions of 25x25x285 mm were used for cement-fly ash pastes and mortars and those with dimensions of 75x75x285 mm were used for concrete. It is known that degree of saturation or moisture content of concrete is an important factor that has influence on *CTE*. However, for mass concrete, the moisture condition may be described as sealed or almost sealed conditions due to large dimensions of the structure (Jonasson et al., 1994) then the specimens were firmly wrapped by using aluminum foil immediately after casting in order to prevent the evaporation of water and to simulate the physical condition of the specimens to be similar to that inside the mass concrete (no moisture loss or gain). The seams between aluminum foil were glued by adhesive tape. Fig. 7.1 shows the wrapped specimens for paste and mortar while concrete specimens are shown in Fig. 7.2. Fig. 7.3 shows the measurement of length change of a specimen. The specimens were tested without removing the wrapped aluminum foil to prevent moisture loss. The specimens were kept at room temperature until the test date. To obtain one data, two specimens were tested for their average. A thermocouple was placed at the center of each specimen to measure the specimen temperature. The temperature range used in the experiment was adopted from Kada et al. (2002). The specimens were tested by cooling them down in the refrigerator to reduce temperature of the specimens from room temperature (about 30 $\pm$ 2 ºC) to 10 ºC, then moving them out of the refrigerator to return up to room temperature. The steps of cooling down and heating up are shown in Fig. 7.4. It has been reported that for a given concrete mixture, the magnitude of thermal expansion or contraction of concrete in normal range of temperature, including the range occurred in mass concrete, is the same for each unit temperature change. In other words, the *CTE* is constant in that range(Klieger and Lamond, 1994). For every 5 ºC change of temperature, the length change was measured using the length comparator. The *CTE* is calculated from Eq. (7.1).

$$CTE = \frac{\varepsilon \pm \varepsilon_{AS}}{\Delta T} \tag{7.1}$$

where *CTE* is the tested thermal expansion coefficient (micron/ ºC) , ε is the strain due to temperature change, ε_{AS} is the strain due to autogeneous shrinkage during the period of ΔT change and ΔT is the temperature change (ºC). The plus sign is used for the heating up stage and the minus sign is used for the cooling down stage.

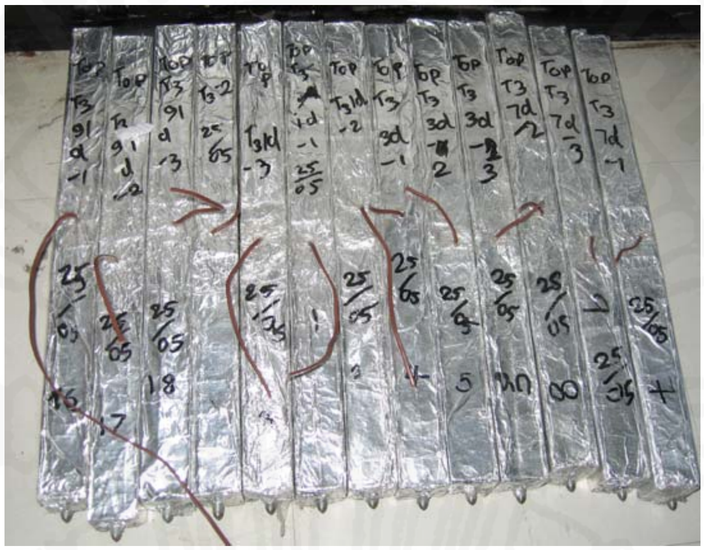

Fig. 7.1 Example of the wrapped cement – fly ash paste and mortar specimens

Fig. 7.2 Example of the wrapped concrete specimens

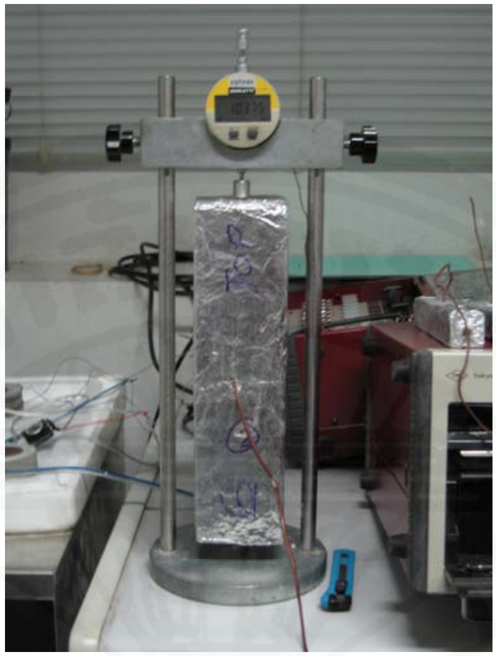

Fig. 7.3 Measurement of length change of a concrete specimen

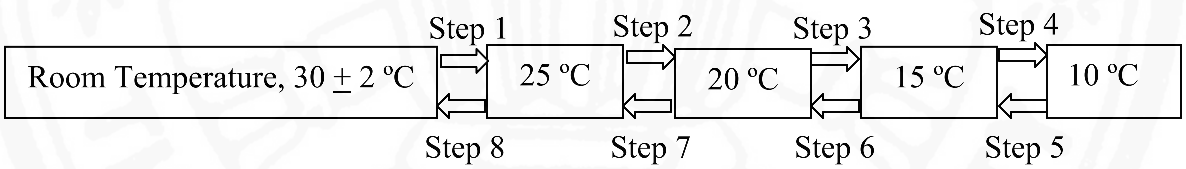

Fig. 7.4. Changes in temperature of the tested specimens.

It must be mentioned here that, the effect of autogeneous shrinkage during testing was also considered in the calculation of the *CTE*. The two-phase model shown in Eq. (7.2) for computing concrete autogeneous shrinkage strain, which was proposed by Tangtermsirikul and Tatong (2001), was used for computing concrete autogeneous shrinkage strain in each step of temperature change (5 ^{o}C for each step). Details of the model can be found in the previous studies (Tangtermsirikul and Tatong, 2001; Tatong, 2001; Tangtermsirikul and Nimityongskul, 1997).

$$\varepsilon_{conc}(t) = \frac{\varepsilon_{po}(t)\cdot E_p(t)\cdot(1-n_a)}{E_p(t)+E_a} \tag{7.2}$$

$$n_a = \frac{V_a}{V_{con}} \tag{7.3}$$

where ε_{conc} is the shrinkage strain of concrete (micron), ε_{po} (t) is the free shrinkage of paste in the concrete at the time considered (micron), n_a is the volumetric ratio of aggregate, E_p (t) is the modulus of elasticity of paste phase at the time considered (MPa), E_a is the modulus of elasticity of aggregate phase (MPa). V_a and V_{con} are the volumes of aggregate and concrete (m^3).

The details on the calculation of modulus of elasticity of aggregate phase are described in the previous study (Tangtermsirikul and Tatong, 2001). Modulus of elasticity of paste was adopted from the study of Yomeyama et al (2002) as is shown in Eq. (7.4).

$$E_p(t) = 3.159 \times 10^3 \times \left(f_{cp}^{'}(t)\right)^{0.474} \quad (7.4)$$

where $f_{cp}'(t)$ is the compressive strength of paste at the time considered (MPa)

Free shrinkage of paste in concrete (ε_{po}) can be obtained from the shrinkage test on paste mixtures or by using a model for predicting free shrinkage of paste proposed by Tatong (2001).

In this study, by using the proposed model together with the free shrinkage of pastes estimated from the test results published in the previous study (Tangtermsirikul, 2003), the autogeneous shrinkage strain in each step of temperature change was considered in the calculation of the *CTE*. The examples of the test results of free shrinkage of cement pastes and cement – fly ash pastes are shown in Figs. 7.5 and 7.6.

From the mixes shown in Table 7.2 and Table 7.3, cement paste with lowest w/b has highest autogeneous shrinkage strain especially at early age then the mix w25r0 was used as an example to explain the effect of autogeneous shrinkage strain. The test duration for one step of temperature variation was 10 minutes. From Fig. 7.5, for cement paste with *w/b* = 0.25 and the test age of 12 hours, the autogeneous shrinkage strain during 12 hours to 1 day was 290 micron (in 12 hours) then in 10 minutes the autogeneous shrinkage strain was about 4 micron. The strain due to temperature change was about 51 micron. In one step, the temperature change was about 5 ^{o}C then the effect of autogeneous shrinkage strain was about 0.8 micron/°C. At 12 hours of age, the tested *CTE* was about 10 micron per ^{o}C. The effect of autogeneous shrinkage strain was only about 8 percent when compared to the tested result of *CTE*. Therefore, autogeneous shrinkage during the test period was not significant.

In this study, most of the tests were conducted at the period about 1 day to 28 days of age then the effect of autogeneous shrinkage is much smaller when compared to the shrinkage at the first 12 hours of age. For example at the test age 1 day, the autogeneous strain of the mix w25r0 is about 2.7 percent when compared to the tested result of *CTE* and it is much lower at later test age. In case of cement-fly ash paste, mortar and concrete, the autogeneous shrinkage is smaller when compared to cement paste then it is not significant too.

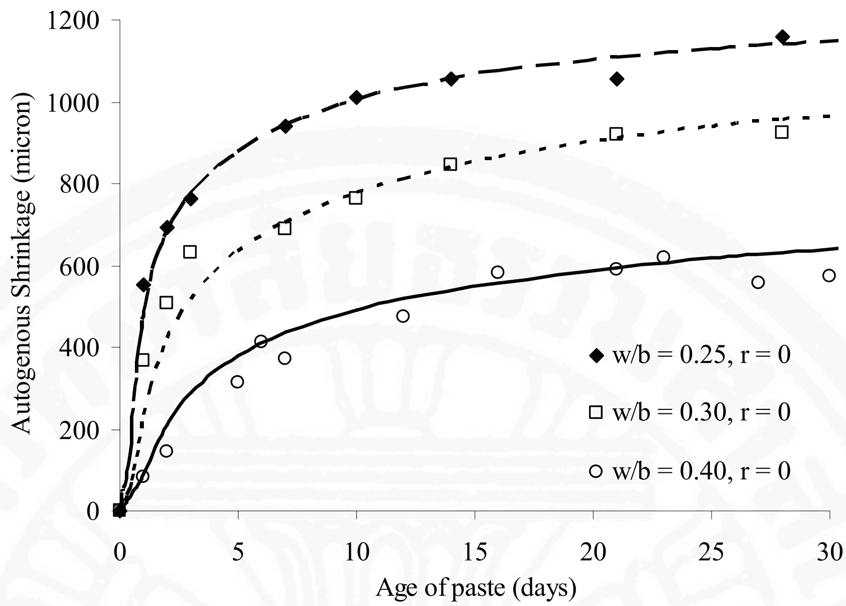

Fig. 7.5 Comparison between test and predicted results of autogenous shrinkage of cement pastes with w/b = 0.25, 0.30 and 0.40, r = 0

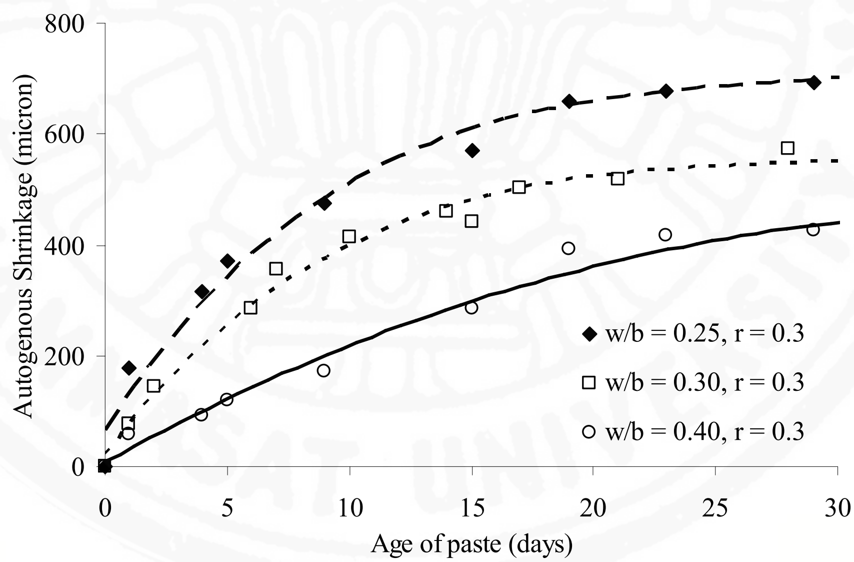

Fig. 7.6 Comparison between test and predicted results of autogenous shrinkage of cement pastes with w/b = 0.25, 0.30 and 0.40, r = 0.3

In conclusion, the amount of autogeneous shrinkage in each step of temperature change was small because the test period in each step was short (about 10 minutes), especially for mortar and concrete. This is in consistent with the study conducted by a group of researchers (Kada et al., 2002) which concluded that the effect of autogeneous shrinkage strain was neglected because the duration for measuring *CTE* was short.

7.3. Experimental Results and Discussion

7.3.1 Thermal expansion coefficient of cement –fly ash paste and mortar

a) Effect of age

From Figs. 7.7, 7.8 and 7.9, it is obvious that *CTE* of paste is a time-dependent property and increases with time. This is because, at longer age, the continuity of paste structure is higher when compared to its structure at early age as a result of increasing hydrated products. Many studies also indicated the similar results. Berwanger and Sarkar (1976) reported that *CTE* decreased with increase in the *w/b* and increased with age. Yang and Sato (2002) reported that *CTE* of high strength concrete decreased rapidly after setting and reached minimum value at about 1 day. Thereafter, *CTE* increased with time up to the age of 7 days depending on the development of self-desiccation.

b) Effect of w/b

The effect of *w/b* is also shown in Fig. 7.7. The effect of *w/b* on *CTE* of paste is not significant. This is because water behaves differently from solid materials. When temperature is increased the volume of water in the capillary pores of paste can also increase. However, unlike solids, water can migrate from one capillary pore to other pores, causing insignificant effect on the thermal expansion of paste.

c) Effect of fly ash

The effect of fly ash content is shown in Figs. 7.8 and 7.9. From the experiments, the *CTE* of cement – fly ash paste increased from the first day and continued to increase in long term. The time-dependent behavior of cement-fly ash paste is different from that of the cement paste in such a way that the *CTE* of the cement paste is almost constant after 7 days. It was also found that the *CTE* of cement – fly ash paste is lower than that of the cement paste with the same *w/b*. Wesche (1997) also found that the use of fly ash reduced the *CTE* of concrete at high replacement percentage. Arshad et al. (1998) found that the *CTE* of concrete is approximately equal to the volumetrically weighted average of the coefficients of its ingredients. Fly ash has a lower *CTE* than cement (see Table 7.1), thus the use of fly ash to replace cement reduces the *CTE* especially at early age when the reaction of fly ash is still not active. The use of fly ash delays the reaction of concrete at early age but continues it long term. Consequently, the *CTE* at early age of cement-fly ash pastes is lower but tends to reach the value of cement-only paste or even higher at long term.

d) Effect of aggregates

Figs. 7.10 and 7.11 show the effect of content of river sand and crushed limestone sand on the *CTE* of mortars. Since the *CTE*s of aggregates are lower than those of the cement-pastes, the *CTE*s of mortars are lower than those of the cement pastes. The mixtures with higher river sand or limestone sand content have lower *CTE*s than those with lower sand content; however, the time-dependent behavior is similar to that shown by paste specimens. Fig. 7.12 shows that mortars with natural river sand show higher *CTE*s than the crushed limestone sand mortars because the *CTE* of natural river sand is higher.

7.3.2 Thermal expansion coefficient of concrete

a) Effect of w/b

The effect of *w/b* on *CTE* of concrete is not significant as shown in Figs. 7.13 and 7.14. The reason is the same as that explained for paste.

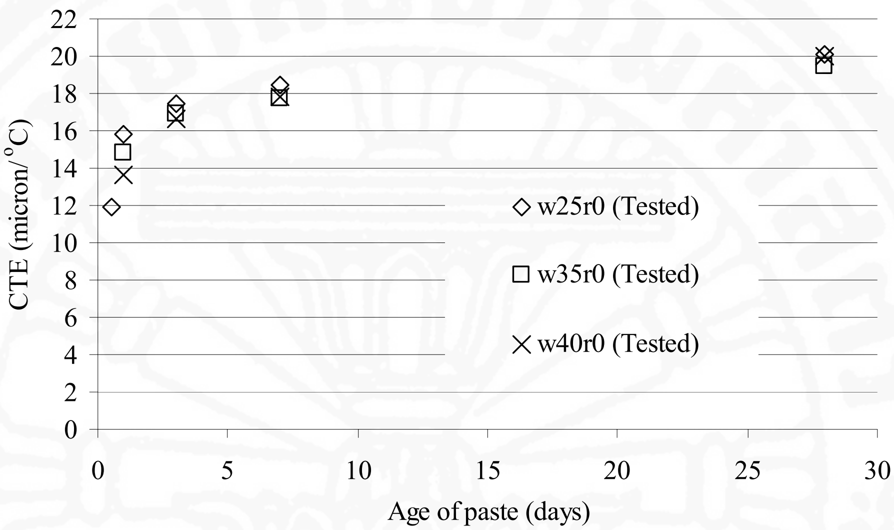

Fig. 7.7. Test results of *CTE* of cement pastes with *w/b* = 0.25, 0.35 and 0.40

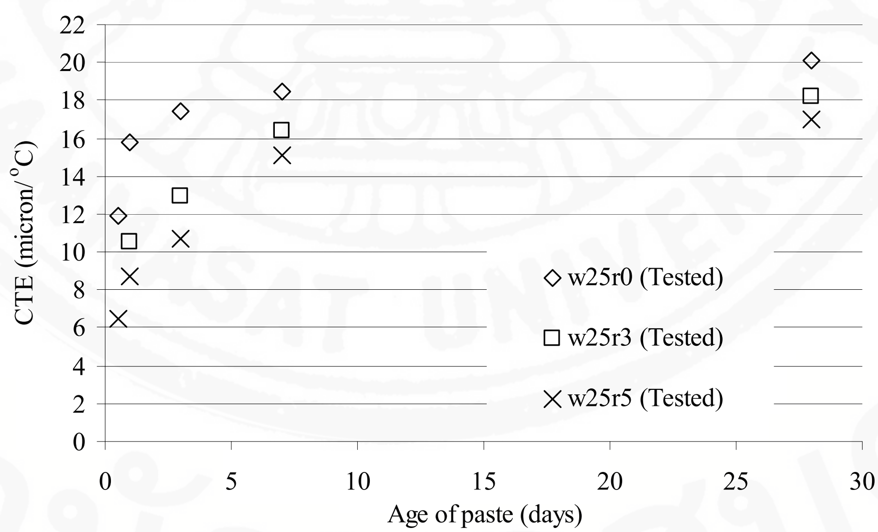

Fig. 7.8. Test results of cement-fly ash pastes with fly ash replacement ratios of 0, 0.3 and 0.5, and *w/b* = 0.25

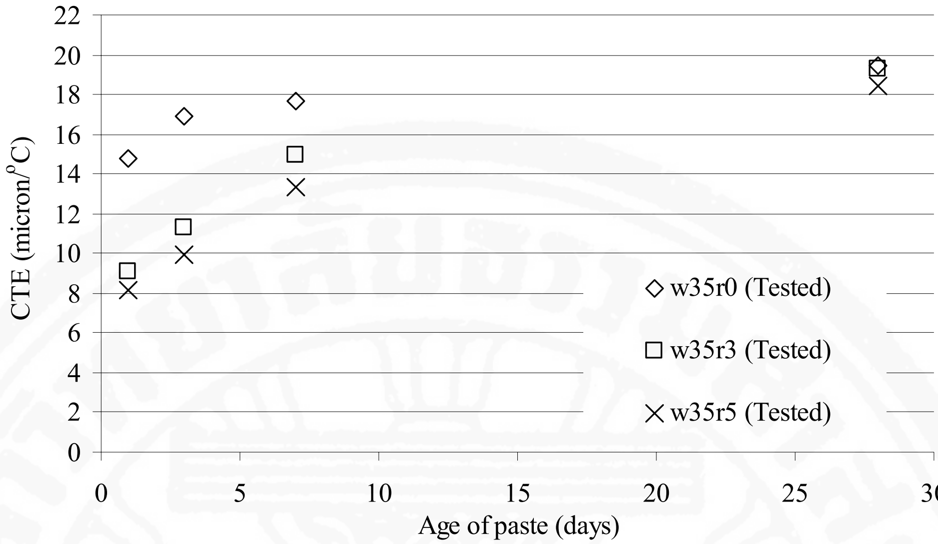

Fig. 7.9. Test results of cement-fly ash pastes with fly ash replacement ratios of 0, 0.3 and 0.5, and *w/b* = 0.35

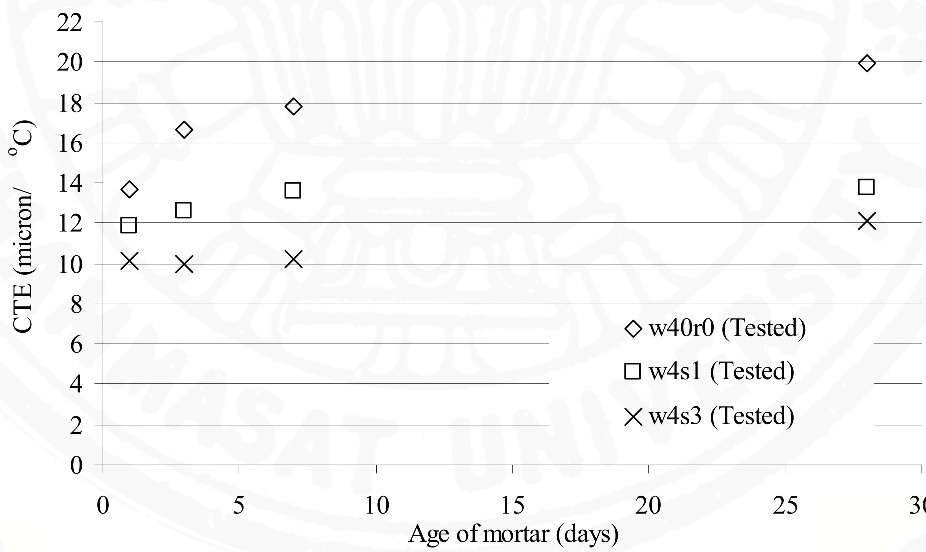

Fig. 7.10. Test results of river sand mortars with sand to binder ratios of 0, 1 and 3, and *w/b* = 0.40

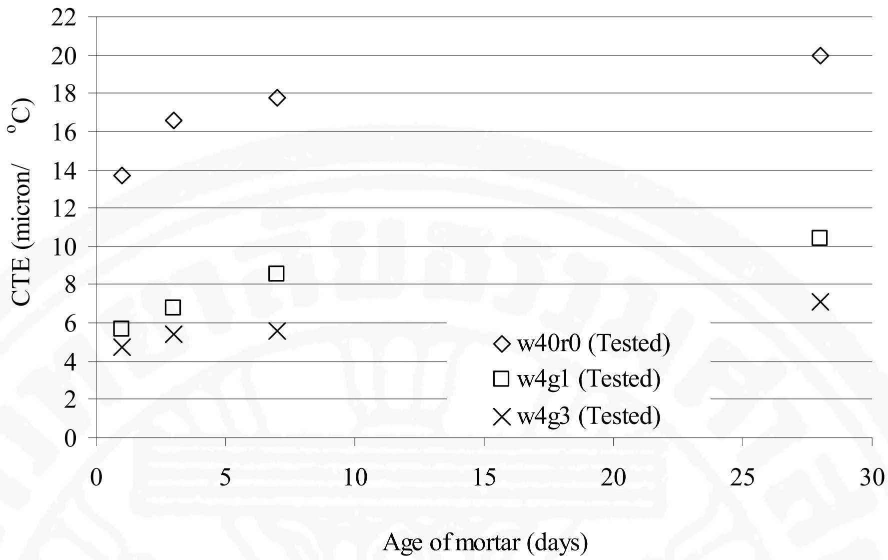

Fig. 7.11. Test results of crushed limestone sand mortars with sand to binder ratios of 0, 1 and 3, and *w/b* = 0.40

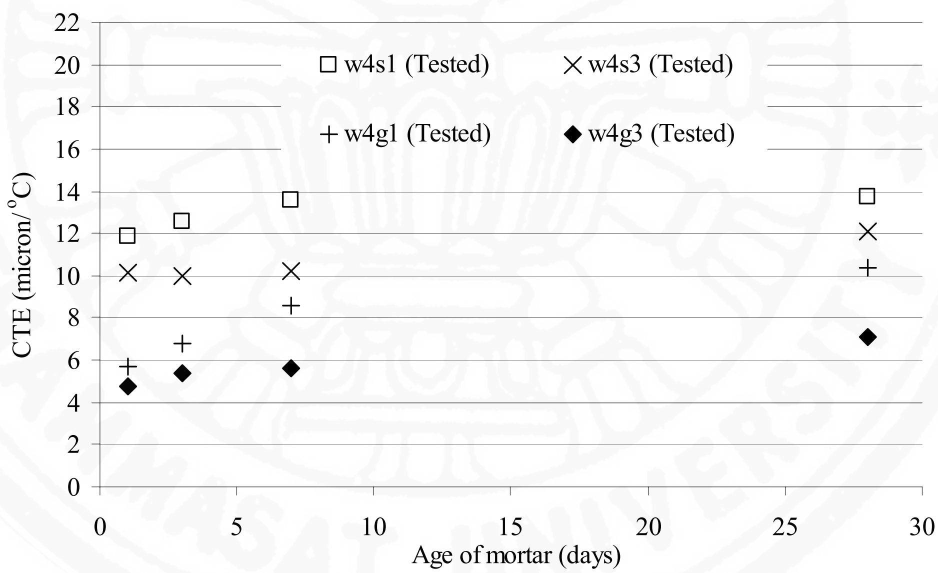

Fig. 7.12. Test results of river sand and crushed limestone sand mortars with sand to binder ratios of 1 and 3, and *w/b* = 0.40

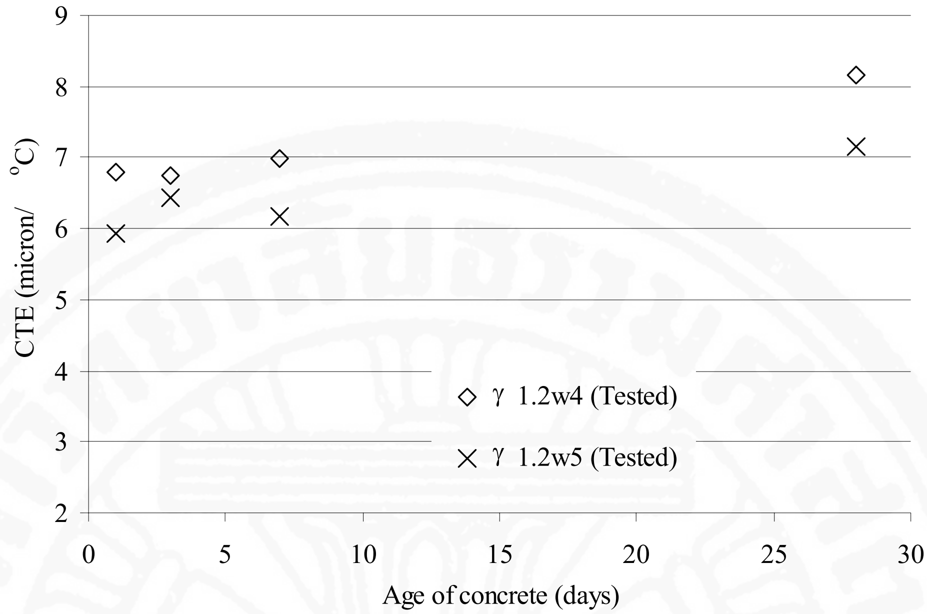

Fig. 7.13. Test results of concrete with γ of 1.2, *w/b* = 0.40 and 0.5

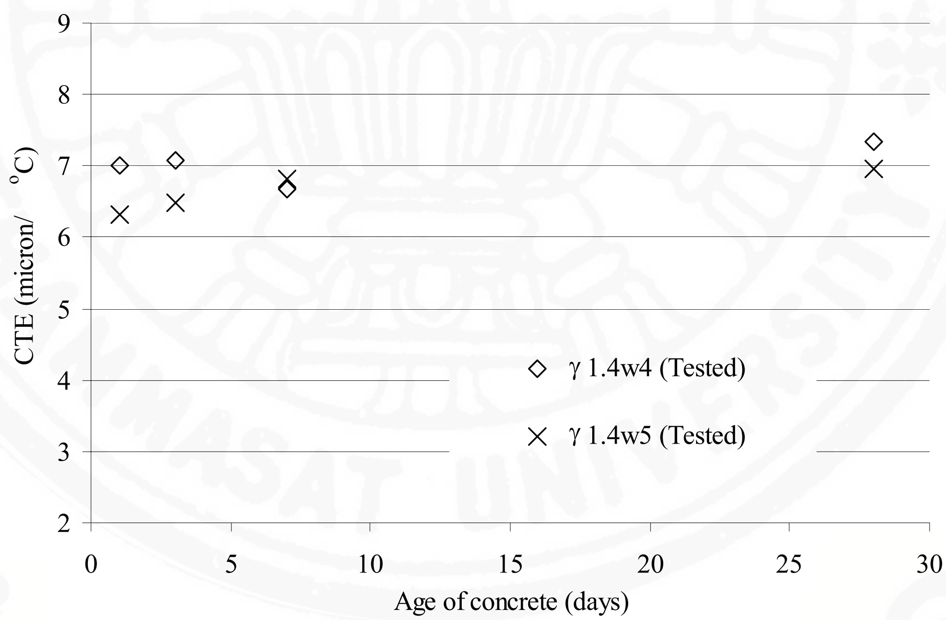

Fig. 7.14. Test results of concrete with γ of 1.4, *w/b* = 0.40 and 0.5

b) Effect of paste content

The effect of paste content on the *CTE* of concrete is shown in Figs. 7.15 and 7.16. It was found that when compared at the same *w/b*, the higher γ gave a slightly higher value of *CTE*. However the effect of paste content is not significant. Aggregate occupies most of concrete volume so a small change in volume of paste does not significantly affect the *CTE* of concrete.

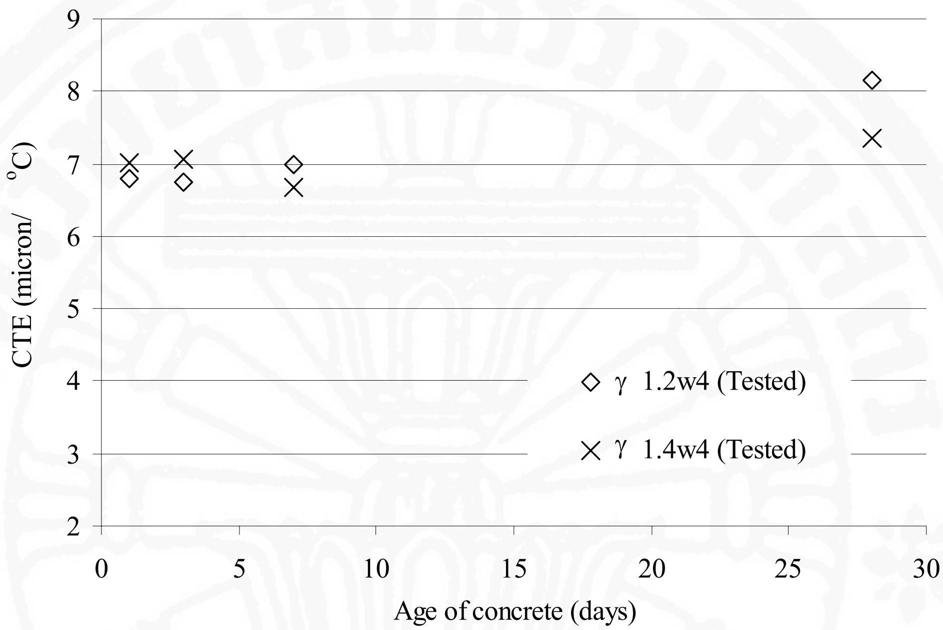

Fig. 7.15. Test results of concrete with γ of 1.2 and 1.4, *w/b* = 0.40

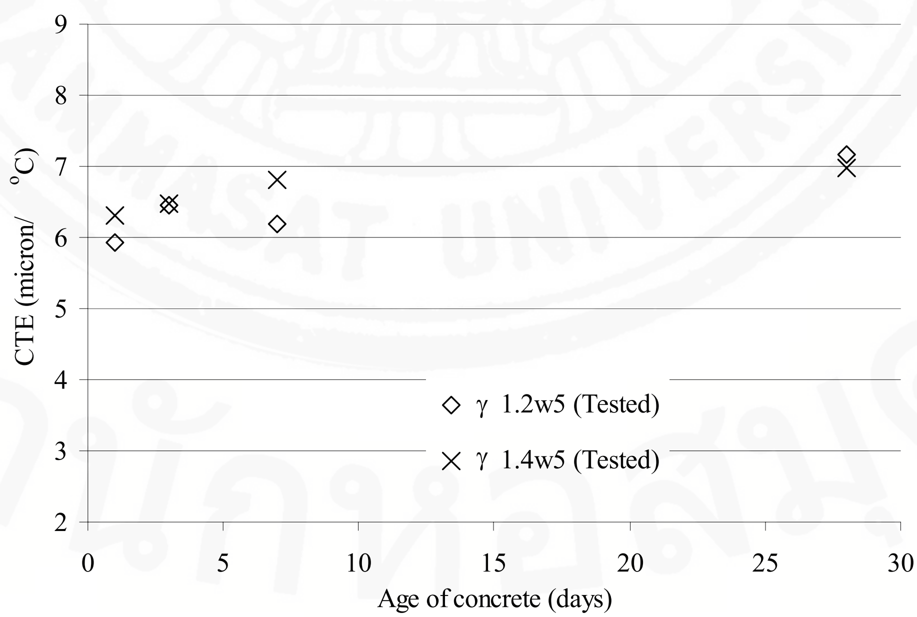

Fig. 7.16. Test results of concrete with γ of 1.2 and 1.4, *w/b* = 0.5

7.4 Thermal Expansion Coefficient Model of Concrete

The *CTE* of concrete is the result of the *CTE*, modulus of elasticity and volume fraction of all ingredients of concrete. However, aggregates seem to be the main factor that affects the *CTE* of concrete because the aggregates occupy most of the concrete volume. The use of higher *CTE* aggregate gives higher *CTE* of concrete. The *CTE* of aggregate varies according to its mineralogical property, for example quartz has a higher *CTE* than calcite (Klieger and Lamond, 1994). In this study, the existing *CTE* model for composite material (Autar, 1997) was adopted to calculate the *CTE*s of mortar and concrete. The model shown in Eq. (7.5) was proposed as a function of the volumetric fraction, modulus of elasticity and *CTE* of each ingredient in concrete.

$$\mathrm{CTE}(t) = \frac{n_p \mathrm{CTE}_p(t) E_p(t) + n_s \mathrm{CTE}_s E_s + n_g \mathrm{CTE}_g E_g}{n_p E_p(t) + n_s E_s + n_g E_g} \tag{7.5}$$

$$n_p = \frac{V_p}{V_{con}} \tag{7.6}$$

$$n_s = \frac{V_s}{V_{con}} \tag{7.7}$$

$$n_g = \frac{V_g}{V_{con}} \tag{7.8}$$

where *CTE*(t) is the coefficient of thermal expansion of mortar or concrete at the considered age (micron/°C). CTE_p (t), CTE_s, and CTE_g are the values of coefficient of thermal expansion of paste, fine aggregate and coarse aggregate, respectively (micron/°C). n_p, n_s, and n_g are the volumetric ratios of paste, fine aggregate, and coarse aggregate, respectively. $E_p(t)$, E_s, and E_g are the modulus of elasticity of paste, fine aggregate, and coarse aggregate, respectively, (MPa), t is the considered age, V_p, V_s, V_g and V_{con} are the volume of paste, fine aggregate, coarse aggregate and concrete, respectively (m^3).

The modulus of elasticity values of fine and coarse aggregates were obtained from a previous study (Neekhra, 2004) as shown in Table 7.1. The stiffness of paste was adopted from the study of Yomeyama et al. (2002) as shown in Eq. (7.4).

The *CTE* of paste varies according to *CTE* and volume fraction of non-reacted cementinious materials and hydrated product. During the reaction, the amount of unhydrated cement and non-reacted fly ash decreases according to time but the amount of hydrated product increases. Due to the differences of the *CTE* of cement, fly ash and hydrated product, when the amount of each ingredient changes with time according to the reactions, the *CTE* of paste also changes time-dependently. The proposed equation for estimating the value of the *CTE* of pastes is shown in Eq. (7.9).

$$\mathrm{CTE}_p(t) = a \times n_{p,uc}(t)\mathrm{CTE}_c + b \times n_{p,ufa}(t)\mathrm{CTE}_{fa} + c \times n_{p,hp}(t)\mathrm{CTE}_{hp} \tag{7.9}$$

where $CTE_p(t)$ is the coefficient of thermal expansion of paste at the considered age (micron/°C). CTE_c, CTE_{fa}, and CTE_{hp} are the values of the coefficient of thermal expansion of cement, fly ash, and the hydration and pozzolanic reaction products, respectively (micron/°C). $n_{p,uc}(t)$, $n_{p,ufa}(t)$, and $n_{p,hp}(t)$ are the volumetric ratio, at the considered age, of unhydrated cement, non-reacted fly ash, and the hydration and pozzolanic reaction products, respectively. The constants a, b and c are derived to be equal to 0.284, 1.230 and 1.499, respectively.

For simplicity at this stage, all hydration and pozzolanic reaction products are assumed to have the same *CTE*. The constants a, b, c and the *CTE* of hydration and pozzolanic products were obtained by using the method of regression analysis from the authors' test results of pastes (with and without fly ash). The *CTE* of hydrated and pozzolanic products were found to be about 20 micron/°C. The effect of air was not considered in this model. The volume of hydrated product can be determined as shown in Eq. (7.10). By using the same principle as mentioned in thermal conductivity model, the volumetric fraction of unhydrated cement, non-reacted fly ash and free water can be obtained by using Eq. (7.11), Eq. (7.12) and Eq. (7.15), respectively.

$$n_{p,hp}(t) = 1 - \left(n_{p,uc}(t) + n_{p,ufa}(t) + n_{p,fw}(t)\right) \tag{7.10}$$

$$n_{p,uc}(t) = n_{p,c0}\left(1 - \frac{\alpha_{hy}(t)}{100}\right) \tag{7.11}$$

$$n_{p,ufa}(t) = n_{p,fa0}\left(1 - \frac{\alpha_{poz}(t)}{100}\right) \tag{7.12}$$

$$n_{p,c0} = \frac{V_{c0}}{V_p} \tag{7.13}$$

$$n_{p,fa0} = \frac{V_{fa0}}{V_p} \tag{7.14}$$

$$n_{p,fw}(t) = \frac{W_{fw}(t)}{\rho_w \cdot V_p} = \frac{W_{fw0} - W_{whp}(t) - W_{wgel}(t)}{\rho_w \cdot V_p} \tag{7.15}$$

where $n_{p,fw}(t)$, $n_{p,uc}(t)$, $n_{p,ufa}(t)$, $n_{p,hp}(t)$ are volumetric ratio of free water, unhydrated cement, unhydrated fly ash and hydrated product, respectively, at the considered age. t is the considered age (day). $n_{p,c0}$ and $n_{p,fa0}$ are volumetric ratio of cement and fly ash at the time of mixing (at t = 0). V_p is the volume of paste (m^3). V_{c0} and V_{fa0} are the volume of cement and fly ash at the time of mixing (at t = 0) (m^3). $W_{fw}(t)$, $W_{whp}(t)$ and $W_{wgel}(t)$ are the weight of free water, water consumed by hydration and pozzolanic reactions and gel water in the mixture at time t, respectively (kg/m^3 of paste). W_{fw0} is the weight of water at the time of mixing (at t = 0) (kg/m^3 of paste) and ρ_w is the specific gravity of water.

7.5 Verification of Thermal Expansion Coefficient Model of Concrete

By using Eq. (7.9) and the *CTE* of the cementitious materials shown in Table 7.1, the verifications with the experimental results of the *CTE* model of paste are shown in Figs. 7.17 to 7.19. It is shown that the proposed *CTE* model is satisfactory for predicting the *CTE* of the tested cement-fly ash pastes. The model shows that pastes with a higher fly ash replacement ratio (r = 0.5) have a lower *CTE* than those with a lower fly ash replacement ratio (r = 0.3) especially at early age. The model also shows that the *CTE* of paste is time-dependent and increases with age. Fig. 7.20 shows the comparison between the test results conducted by the authors and the computed results from the model. It was found that the prediction was satisfactory with the value of R^2 equal to 0.87.

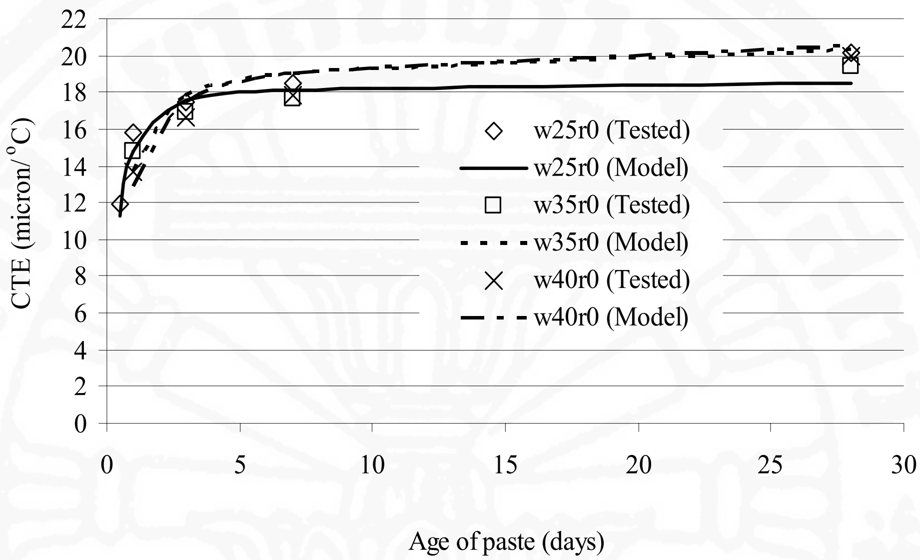

Fig. 7.17 Comparison between test and predicted results of *CTE* of cement pastes with *w/b* = 0.25, 0.35 and 0.40

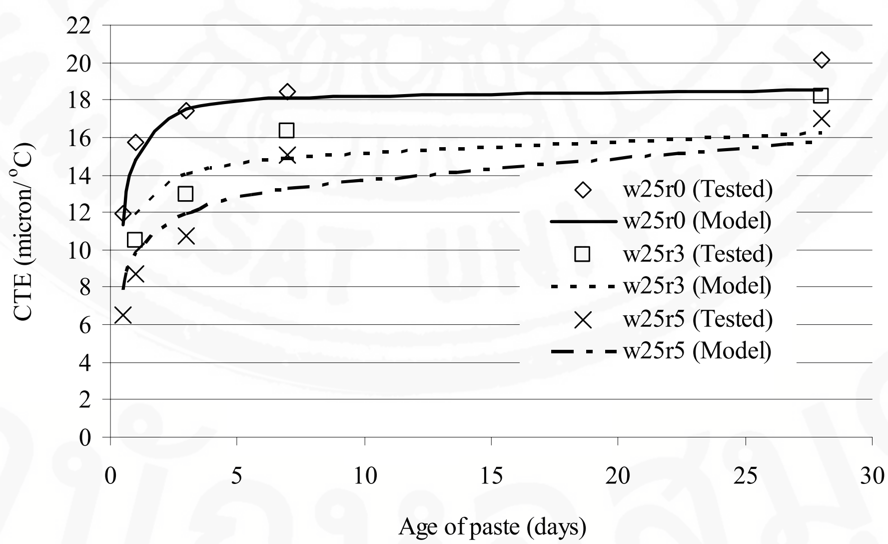

Fig. 7.18 Comparison between test and predicted results of cement-fly ash pastes with fly ash replacement ratios of 0, 0.3 and 0.5, and *w/b* = 0.25

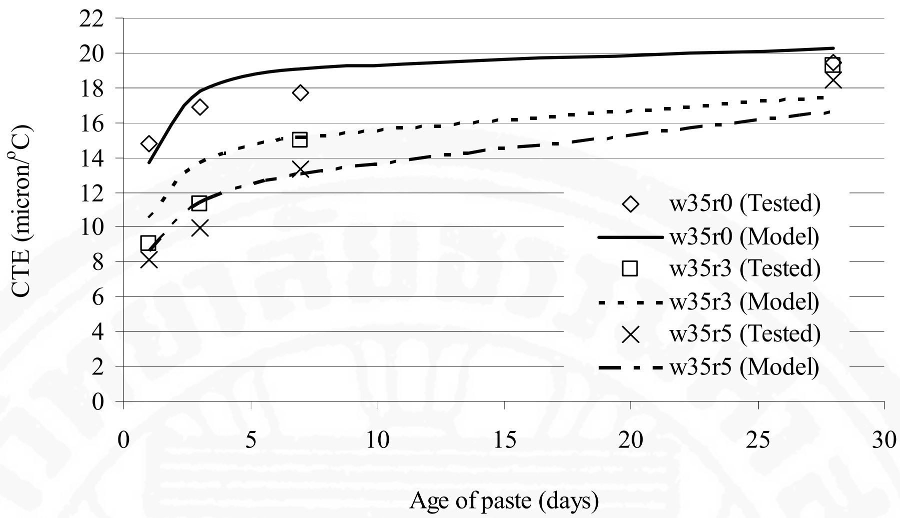

Fig. 7.19 Comparison between test and predicted results of cement-fly ash pastes with fly ash replacement ratios of 0, 0.3 and 0.5, and *w/b* = 0.35

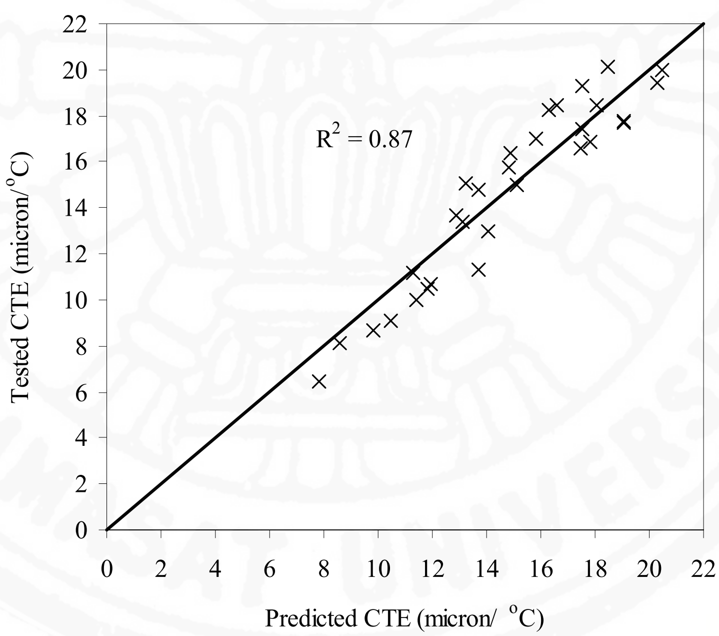

Fig. 7.20 Comparison between predicted and test results of authors' test results of *CTE* of cement – fly ash pastes

By using Eq. (7.5) and the properties shown in Table 7.1, the verifications of the *CTE* model with the test results of mortar and concrete are shown in Figs. 7.21 to 7.26. It is shown in the figures that the proposed *CTE* model is satisfactory to predict the *CTE* of the tested mortar and concrete. The model shows that the *CTE* of concrete depends largely on the *CTE* of aggregate and also slightly increases with time. Fig. 7.27 shows the comparison between the test results of mortar and concrete conducted by the authors and the computed results from the model. It was found that the prediction was satisfactory, with the value of R^2 equal to 0.93. It was found that for concrete the accuracy was within $\pm$1 micron/°C.

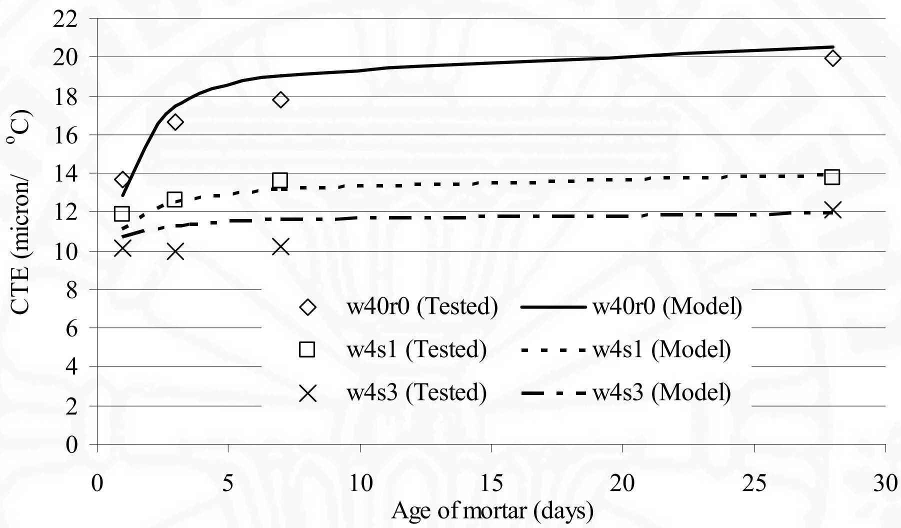

Fig. 7.21 Comparison between test and predicted results of river sand mortars with sand to binder ratios of 0, 1 and 3, and *w/b* = 0.40

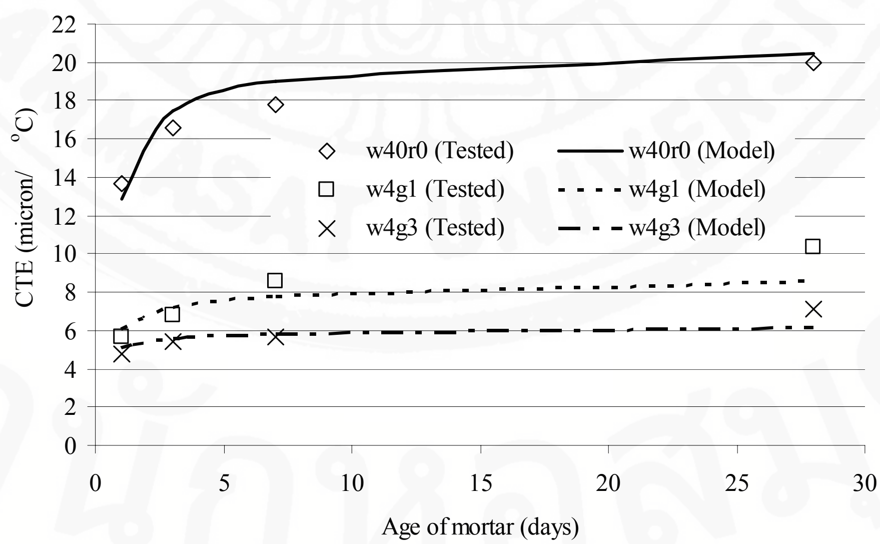

Fig. 7.22 Comparison between test and predicted results of crushed limestone sand mortars with sand to binder ratios of 0, 1 and 3, and *w/b* = 0.40

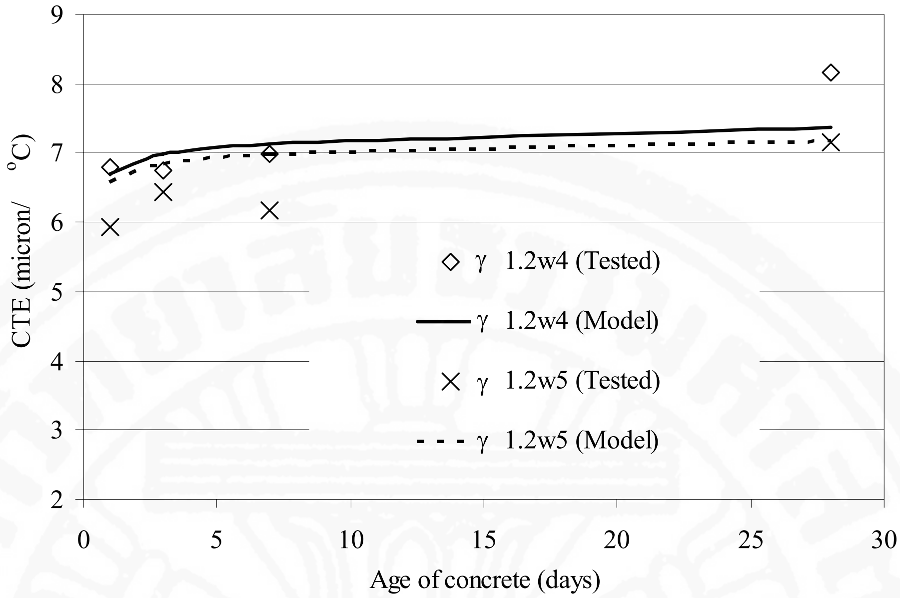

Fig. 7.23 Comparison between test and predicted results of concrete with γ of 1.2, *w/b* = 0.40 and 0.5

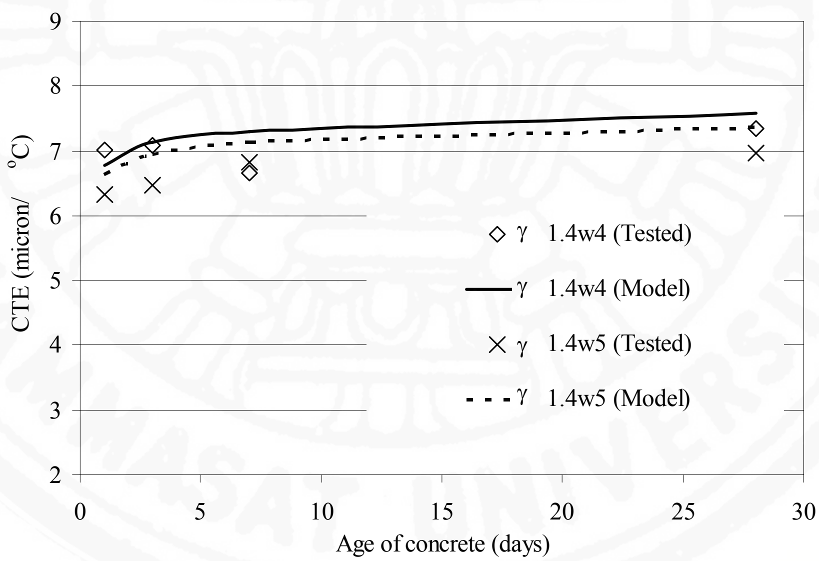

Fig. 7.24 Comparison between test and predicted results of concrete with γ of 1.4, *w/b* = 0.40 and 0.5

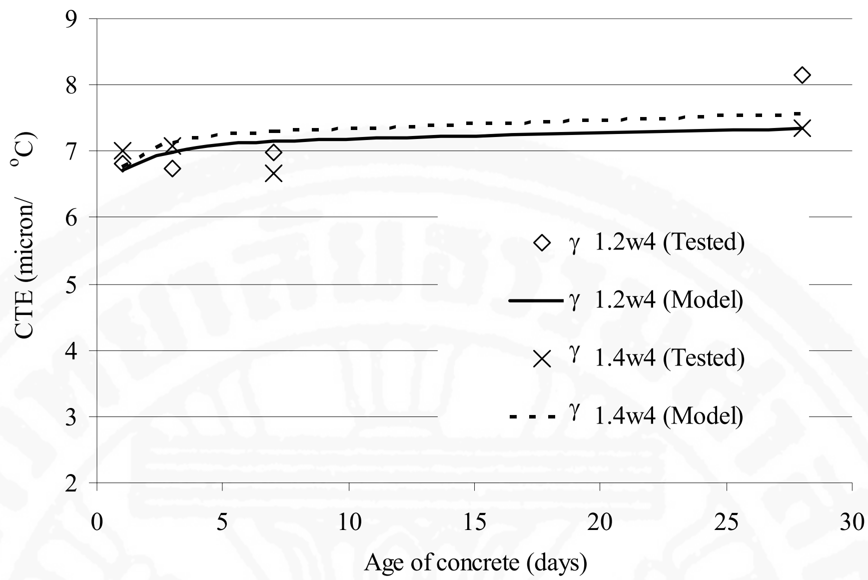

Fig. 7.25 Comparison between test and predicted results of concrete with γ of 1.2 and 1.4, *w/b* = 0.40

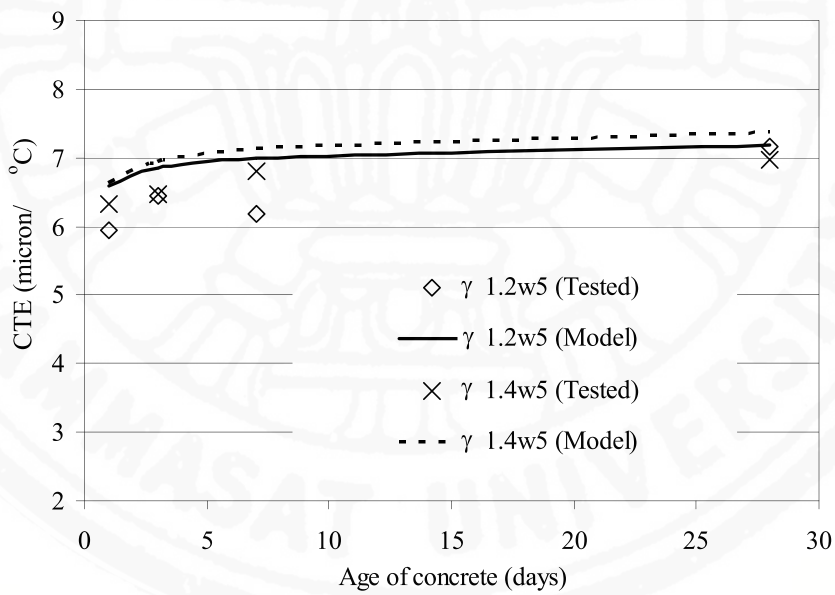

Fig. 7.26 Comparison between test and predicted results of concrete with γ of 1.2 and 1.4, *w/b* = 0.5

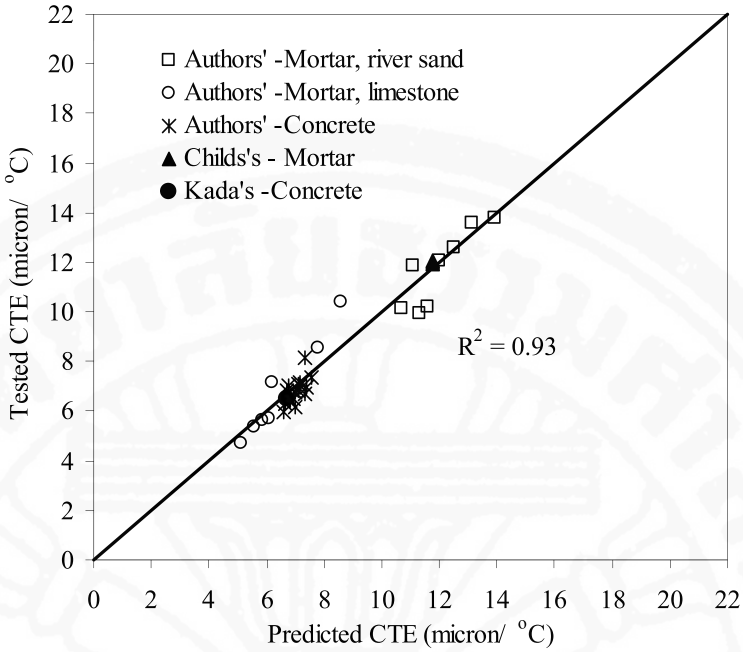

Fig. 7.27 Comparison between predicted and test results of authors' test results of *CTE* of mortars and concrete, Childs's test results of mortar and Kada's test results of *CTE* of concrete.

The model was also verified with the test results conducted by Childs et al. (2007) and Kada et al. (2002) as shown in Fig. 7.27. The mix proportions of mortar tested by Childs et al. and concrete tested by Kada et al. are shown in Appendix C (Table C9 and C10, respectively). Limestone and natural river sand were used as coarse and fine aggregates, respectively. The properties of coarse and fine aggregate in Table 7.1 were used in the *CTE* calculation. It was found that the prediction was satisfactory.

As shown in Fig. 7.28, the model was also compared with the test results conducted by Neekhra (2004) in which concrete prepared with many types of aggregate, such as limestone (LST1, 6 and 9), sandstone (SST-12), siliceous gravel (SRG -1, 2 and 3) and calcareous gravel (CRG-3) were tested at age of 28 days. Mix proportions of the tested concretes and properties of the coarse aggregates used by Neekhra are shown in Appendix C (Table C11). The properties of fine aggregate in Table 7.1 were used in the verification calculation. It was also found that the prediction was satisfactory with the value of R^2 equal to 0.97 or accuracy within $\pm$1 micron/°C.

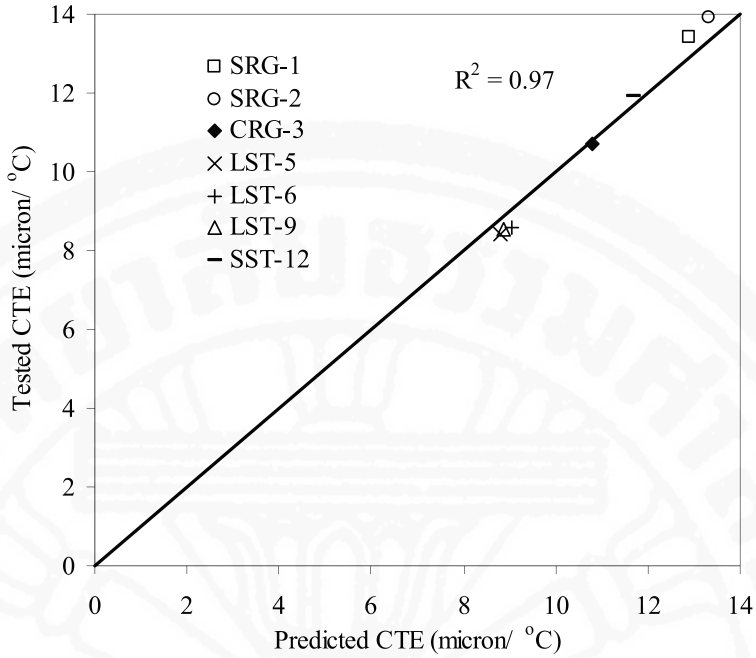

Fig. 7.28 Comparison between predicted and Neekhra's test results of *CTE* of concrete