Chapter 6
Model of Thermal Conductivity of Concrete

6.1 General

Thermal conductivity (k) of mass concrete indicates the rate of heat transfer in the mass concrete. ACI 207.4 (1993) states that the mineralogical characteristics of the aggregate, moisture content and density of concrete influence k of concrete. From the previous researches, as mentioned in Chapter 2, the time dependent properties of k of concrete were not yet clarified. The inconsistent results among each researcher may be because of the different curing condition, moisture content during testing and different test method. The moisture content significantly affects k of concrete so the moisture content must be controlled to simulate the real situation that occurs in the concrete structure. The test method must be able to control the redistribution of moisture in the test sample. It was found from previous study that transient method was able to prevent this effect, so the transient method was used in this study (Brown and Javaid, 1970).

In mass concrete, fly ash is effective for controlling temperature and so reducing the risk of thermal cracking. Some experiments were conducted to investigate the effect of fly ash in paste, mortar and concrete but all were conducted in the oven-dried condition (Demirboğa et al., 2003: Demirboğa, 2003; Demirboğa, 2003; Demirboğa, 2007). Most of the proposed equations for calculating the k of hardened concrete did not cover fly ash concrete. Some of them did not consider the use of different types of aggregate and different concrete mix proportion (Kim, 2003). The constant k values of matured concrete have been traditionally used in analysis of thermal cracking problems. This may not be always realistic especially at very early age when the heat generated from hydration reaction is high. As a result, the model for predicting k considering time, material and mix proportion dependent properties of fly ash concrete was proposed in this study.

6.2 Experimental Program

6.2.1 Mix proportion and materials.

Ordinary Portland cement (OPC) and lignite fly ash were used as cementitious materials. The chemical compositions and physical properties of cement and fly ash are shown in Appendix C (Table C1). Cement-fly ash pastes and mortar were produced and tested at various ages (1, 3, 7, and 28 days) to study the effect of age. Properties of aggregates are shown in Appendix C (Table C2). The cement-fly ash pastes were tested to observe the effects of water and fly ash content. Water to binder ratio (*w/b*) was fixed at 0.25 and fly ash to binder ratios were varied at 0 and 0.5. Mortars were tested to observe the effect of aggregates. For mortar, *w/b* and fine aggregate to binder ratio (*g/b*) by weight were fixed at 0.4 and 2, respectively. The mix proportions of the tested mixtures are shown in Table 6.1.

Table 6.1 Mix proportions of the tested cement-fly ash pastes and mortar

Mix No.	Mixture Code	w/b	r	g/b
1	w25r0	0.25	0	0
2	w25r5	0.25	0.5	0
3	w40g2	0.40	0	2

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

6.2.2 Specimen preparation and test procedure

There are two methods for measuring k of concrete i.e. steady state method and transient method (Brown and Javaid, 1970; Klieger and Lamond , 1994). Steady state method is useful when the material under examination is rigid and dry or conditioned to the ambient condition. The method is not suitable when moisture redistribution can occur during the period of the test. The transient method is convenient to use with rigid and semi-rigid materials and has particular advantages when k of moist materials is to be measured. Transient measurement technique is appropriate for low conductivity porous materials. The rapidity of the determination does not allow sufficient time for any moisture movement to occur within the sample during testing (Toyokazu and Yoshiro, 1976). As mentioned earlier, moisture has great effect on k of concrete then transient method was preferable (Neville, 1995). The apparatus called Hot Disk Thermal Constants Analyzer was used for measuring k in this study (see Fig. 6.1a and 6.1b). The details of the apparatus are shown in the previous study of Bentz (2007).

Prism specimens with dimension of 25x25x25 mm were used for cement-fly ash pastes and mortar. After one day, the formworks were removed and all specimens were immediately wrapped firmly with plastic sheet in order to prevent 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). In order to eliminate the effect of plastic sheet during the measurement, the plastic sheets were removed just before test. The total testing time was about 2 minutes so moisture movement within the sample was negligible. The specimens were kept under the room temperature (28 + 2 °C) in seal-curing condition until the time of measurement. To obtain one data, two samples were tested for their average.

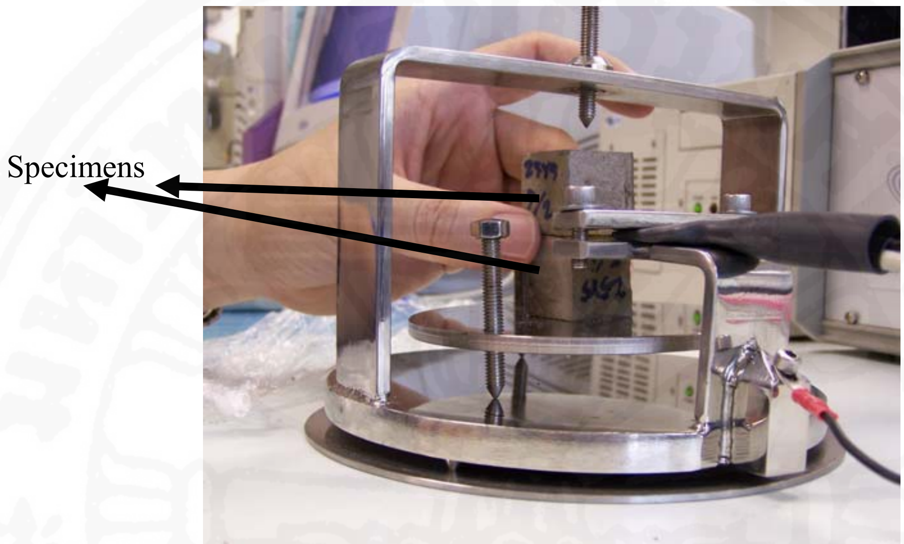
6.3. Experimental Results

6.3.1 Effect of age

The effect of age is shown in Figs 6.2 to 6.4. Comparison between the measured data and the authors' model is also shown in the figures. It was found that k of pastes and mortar increased from 1 to 3 days and slightly decreased after that, however the differences were not significant. It is difficult and complicate to measure k of concrete at a few hours after casting so it is assumed that at the age just after mixing (at t = 0 day), k of concrete can be calculated based on volumetric ratio of the ingredients in concrete and their individual k (Bentz, 2007) so k of concrete at the age just after mixing is the lowest when compared to the values at later ages. From the tests, k of pastes slightly decrease after the age of about 3 days because of self-desiccation. If there is no loss of water due to self-desiccation, k of paste is supposed to increase because of the increase of hydrated product and continuity of paste structure. The same reason can be applied to the case of cement – fly ash paste and mortar.

6.3.2 Effect of *w/b*

The effect of *w/b* is shown in Fig 6.2 It was found from the authors' and other researcher's test results (Bentz, 2007) that *w/b* did not significantly affect *k* of cement paste.



(a)

(b)

Fig. 6.1 Apparatus for Testing Thermal Conductivity (a) setting of specimens, (b) testing of specimens

6.3.3 Effect of fly ash

The effect of fly ash content is shown in Fig 6.3. *k* of pastes with fly ash is lower than that of the cement paste. This is because the use of fly ash decreases density of paste and increase the total porosity of paste. This effect was consistent with the results performed by other researchers (Demirboğa et al., 2003: Demirboğa, 2003; Demirboğa, 2003; Demirboğa, 2007) who found that *k* decreased with the increase of fly ash content.

6.3.4 Effect of aggregates

Fig. 6.4 shows the effect of aggregate content on *k*. The test results of mortar obtained in this study were compared with the test results of paste conducted by other researchers (Kim et al. 2003 and Bentz, 2007). It was found that *k* of cement paste is lower than that of the mortar because aggregate has higher *k* than paste. This is consistent with the experimental results conducted by other researchers. (Khan, 2002; Neville, 1995; Kim et al. 2003; Xu and Chung, 2000)

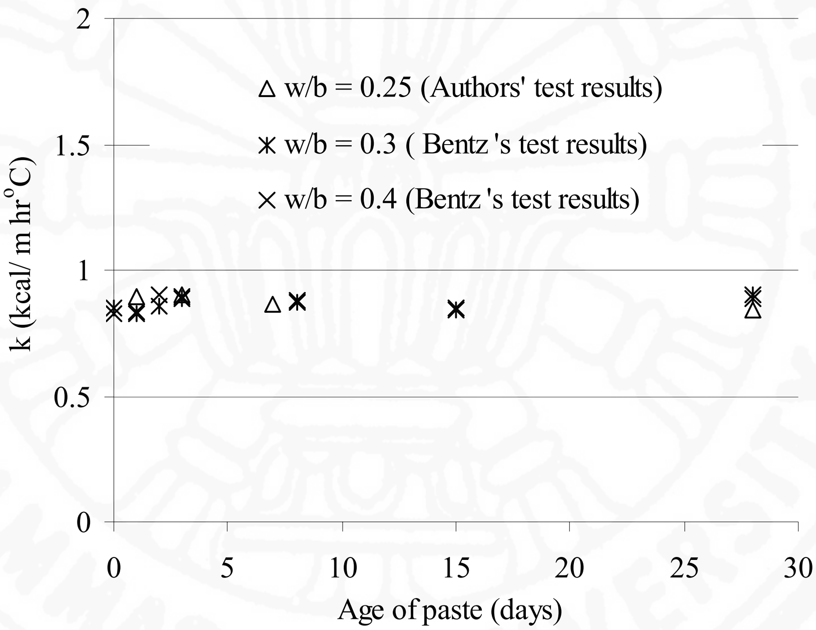


Fig. 6.2 Test results of *k* of pastes with *w/b* = 0.25, 0.3 and 0.4

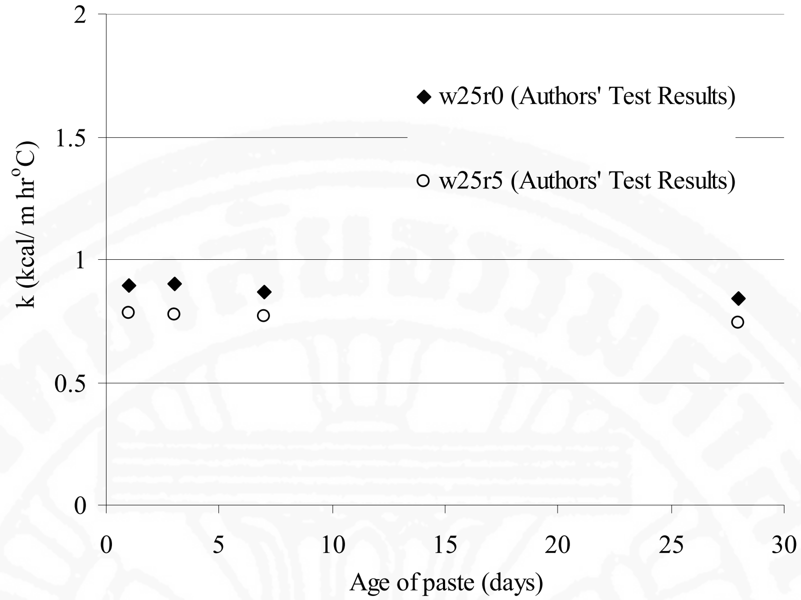


Fig. 6.3 Test results of *k* of pastes with *w/b* = 0.25 and fly ash replacement ratio of 0 and 0.5

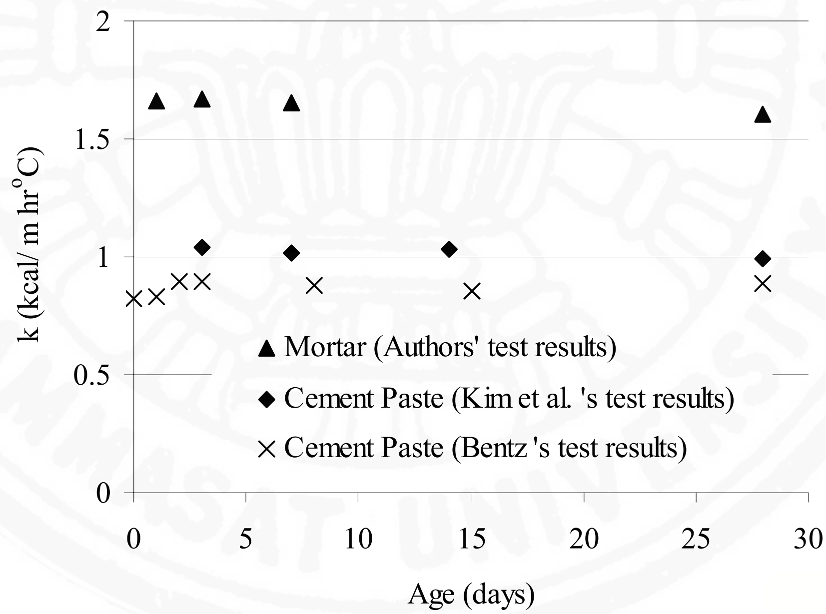


Fig 6.4. Test results of *k* of pastes with *w/b* = 0.4 and mortar with *w/b* = 0.4, g/b = 2

6.4. Thermal Conductivity Model for Fly Ash Concrete

Many existing equations for estimating *k* of concrete can not automatically take into account the effect of mix proportion because the test data of *k* of mortar or *k* of the reference concrete are required (Campbell-Allen and Thorne, 1963; Kim et al., 2003). Furthermore, the effect of fly ash was not included in those equations. In this study, a model for estimating *k* of concrete taking into account the effect of fly ash was proposed. The value of *k* of fly ash concrete can be automatically calculated from the mix proportion and the *k* values of the ingredients in concrete. The details of the model are described as follows.

The *k* of concrete is assumed to be derivable based on the volumetric ratio and *k* of the ingredients and the hydrated product as shown in Eq (6.1). The effect of air was included in this model. The volumetric ratio of hydrated product can be determined from Eq. (6.2). The volumetric ratio of unhydrated cement is calculated based on the average degree of reaction of cement from Eq. (6.6). The volumetric ratio of non-reacted fly ash at age t is calculated from Eq. (6.7). The volumetric ratio of free water can be computed using Eq. (6.10). The details of free water determination are mentioned in Chapter 4. The details of degree of hydration and degree of pozzolanic reaction are described in Chapter 3.

$$k(t) = n_g k_g + n_s k_s + n_{fw}(t) k_w + n_{uc}(t) k_c + n_{ufa}(t) k_{fa} + n_{ra} k_{ra} + n_{hp}(t) k_{hp} \tag{6.1}$$

$$n_{hp}(t) = 1 - \left(n_{uc}(t) + n_{ufa}(t) + n_{fw}(t) + n_g + n_s + n_{ra}\right) \tag{6.2}$$

$$n_s = \frac{V_s}{V_{con}} \tag{6.3}$$

$$n_g = \frac{V_g}{V_{con}} \qquad (6.4$$

$$n_{ra} = \frac{V_{ra}}{V_{con}} \qquad (65)$$

$$n_{uc}(t) = n_{c0}\left(1 - \frac{\alpha_{hy}(t)}{100}\right) \tag{6.6}$$

$$n_{ufa}(t) = n_{fa0}\left(1 - \frac{\alpha_{poz}(t)}{100}\right) \tag{6.7}$$

$$n_{c0} = \frac{V_{c0}}{V_{con}} \tag{6.8}$$

$$n_{fa0} = \frac{V_{fa0}}{V_{con}} \tag{6.9}$$

$$n_{fw}(t) = \frac{W_{fw}(t)}{\rho_w \cdot V_{con}} = \frac{W_{fw0} - W_{whp}(t) - W_{wgel}(t)}{\rho_w \cdot V_{con}} \tag{6.10}$$

where *k*(t) is thermal conductivity of concrete at the considered age (kcal/m hr ^oC), k_g, k_s, k_w, k_c, k_{fa}, k_{ra}, k_{hp}: are thermal conductivities of coarse aggregate, fine aggregate, free water, cement, fly ash, air and hydrated product, respectively (kcal/m hr ^oC). n_{uc}(t), n_{ufa}(t), n_{hp}(t) are volumetric ratios of unhydrated cement, non-reacted fly ash and hydrated product, respectively, at the considered age. n_g, n_s, n_{ra} are volumetric ratios of coarse aggregate, fine aggregate and air, respectively. n_{fw}(t), n_{whp}(t), n_{wgel}(t) are the volumetric ratios at the considered age of free water, water consumed by hydration and pozzolanic reactions and gel water, respectively. n_{c0}, n_{fa0} and n_{fw0} are the volumetric ratios of cement, fly ash and water at the time of mixing (at t = 0). V_s, V_g, V_{ra} and V_{con} are the volumes of fine aggregate, coarse aggregate, air and concrete, respectively (m^3). V_{c0} and V_{fa0} are the volumes 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 weights of free water, water consumed by hydration and pozzolanic reactions and gel water in the mixture at time t, respectively (kg/m^3 of concrete). W_{fw0} is the weight of water at the time of mixing (at t = 0) (kg/m^3 of concrete), $\alpha_{hy}(t)$ and $\alpha_{poz}(t)$ are the average degree of hydration of cement and degree of pozzolanic reaction of fly ash, respectively, in paste at the considered age (%). t is the considered age (day). ρ_w is the specific gravity of water.

Table 6.2 shows the values of k of all ingredients in concrete. All of them are obtained from other studies except for fly ash powder and hydrated products (Klieger Lamond, 1994; Bentz, 2007; ASHRAE, 1993; Roller, 2000). In this study, k of hydrated product was obtained by the use of regression analysis together with the test results of cement paste and k of fly ash powder was derived from the test results of cement-fly ash paste. Thermal conductivity of hydrated product and fly ash powder were found to be 1.00 and 0.65 kcal/m hr ^{o}C, respectively.

6.5 Verification of Thermal Conductivity Model

The comparison between the analytical results obtained from the proposed model and the experimental results are shown in Figs. 6.5 to 6.7. Fig. 6.5 shows the effect of replacement ratio of fly ash and Fig. 6.6 shows the effect of *w/b*. The effect of aggregate content is illustrated in Fig. 6.7. It is shown in the figures that the proposed *k* model is satisfactory to predict *k* of the tested pastes and mortar. The model shows, in Figs. 6.5 and 6.6, that *k* of pastes increase just after mixing until about 3 days and is nearly constant after that. The use of fly ash decreases *k* of paste. In Fig. 6.7, *k* of mortar is higher than that of paste. The effect of self-desiccation was not included in the model but it was found that the prediction was still satisfactory.

Table 6.2 Thermal conductivities of the ingredients in concrete

Thermal Coefficients	Thermal Conductivities (kcal/m hr ^{o}C)
Limestone	2.20 (Klieger and Lamond, 1994)
Quartz Sand	3.00 (ASHRAE, 1993)
Air	0.026 (Roller, 2000)
Water	0.51 (Klieger and Lamond, 1994)
Cement	1.33 (Bentz, 2007)
Fly Ash	0.65*
Hydrated Product	1.00*

* The value was obtained from regression analysis in this study

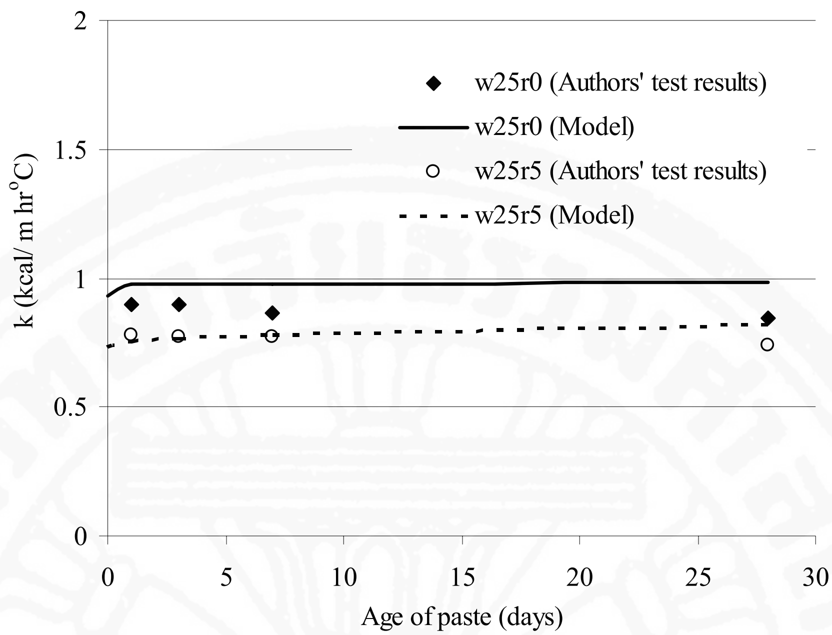


Fig. 6.5 Test and predicted results of *k* of pastes with *w/b* = 0.25 and fly ash replacement ratio of 0 and 0.5

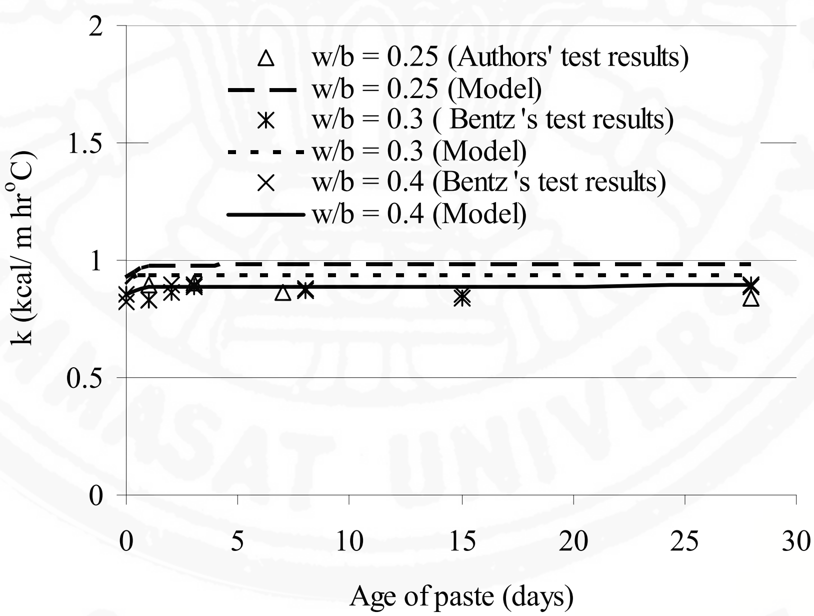


Fig. 6.6 Test and predicted results of *k* of pastes with *w/b* = 0.25, 0.3 and 0.4

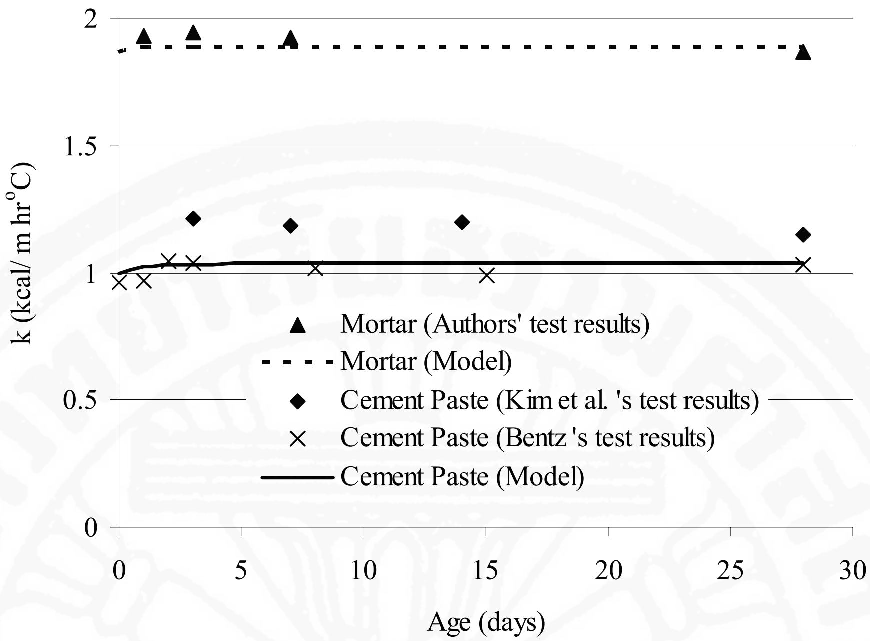


Fig 6.7. Test and predicted results of *k* of pastes with *w/b* = 0.4 and mortar with *w/b* = 0.4, g/b = 2

Figs. 6.8 to 6.14 show that the prediction results were also satisfactory when compared with the test results conducted by other researchers. Figs. 6.8 and 6.9 show the verification of the proposed model with the other researcher's test results of cement pastes with *w/b* = 0.3 and 0.4, respectively (Kim et al., 2003; Toyokazu and Yoshiro, 1976; Bentz, 2007). It was found that at the same *w/b*, the test results obtained from different researchers were a little different especially for cement paste with *w/b* = 0.3 at very early age (before 1 day). It is possibly due to different material especially cement and test method. Nevertheless, the predicted results were closed to those test results except for the results of cement paste with *w/b* = 0.3 at very early age conducted by Toyokazu and Yoshiro (1976). However, this inaccuracy was much less obvious in the case of mortar and concrete (see Fig 6.11).

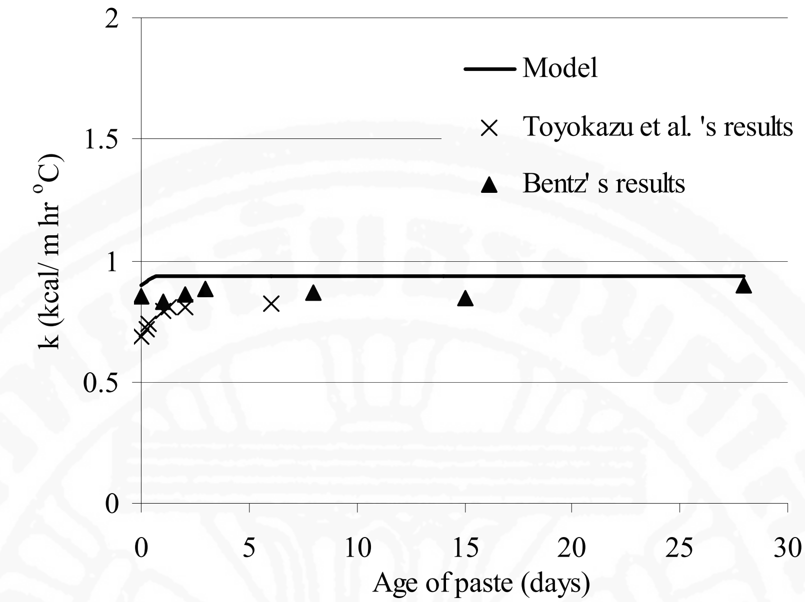


Fig. 6.8 Comparison between Toyokazu and Yoshiro's test results, Bentz's test results and *k* model of cement paste, *w/b* = 0.3

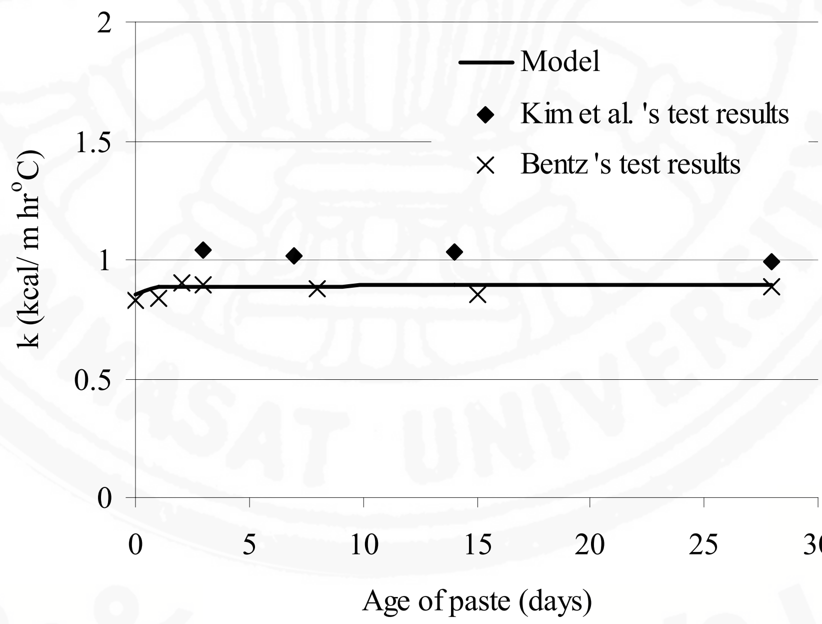


Fig. 6.9 Comparison between Kim et al.'s test results, Bentz's test results and *k* model of cement paste, *w/b* = 0.4

The model was verified with the test results conducted on sealed and saturated pastes by Bentz (2007) as shown in Fig. 6.10. Cement pastes were cast with *w/b* equal to 0.3 and 0.4. The specimens were cured under the sealed and saturated condition. The tests were conducted from fresh state until 28 days. From his study, specimens cured under sealed and saturated condition showed nearly the same values of *k*. The comparison between the test results and the prediction were shown in Fig. 6.10. It was found that the model can predict *k* of cement paste for both sealed and saturated condition with acceptable accuracy.

The model was also verified with the test results conducted by Toyokazu and Yoshiro (1976) in Fig. 6.11. Cement paste, mortar and concrete were cast and tested at the age of 1 - 144 hours. The mix proportion and *k* of aggregate used in the verification are shown in Appendix C (Tables C4 and C5**)**. The comparison between the test results and the predicted values are shown in Fig. 6.11. *k* of coarse and fine aggregates were not directly measured but were obtained from the regression analysis of the test results and it was found that the values agreed well with *k* of aggregates recommended in various handbooks (ACI 207.4, 1993; Klieger and Lamond, 1994; ASHRAE, 1993; ACI 122, 2002). It can be seen from Fig. 6.11 that the model is satisfactory to predict *k* of Toyokazu et al.'s tested mixtures of cement paste, mortar and concrete.

In case of Khan's research (2002), concrete mixtures were prepared with various types of coarse aggregate which were limestone, basalt and siltstone whereas two types of sand were used as fine aggregate. Mortars were cast by using two types of fine aggregate which were sand types I and II. As mentioned in his study, *k* of sand type I was higher than that of sand type II because the main mineral composition of sand type I is quartz but that of sand type II is mica. The specimens were tested at the age of 28 days. The properties of the coarse and fine aggregates and the mix proportions used in his study are shown in Appendix C (Tables C6 and C7). The values of *k* of aggregates were obtained by the same regression method as mentioned in the previous paragraph and it was also found that the values agreed well with *k* of aggregates recommended in various handbooks (ACI 207.4, 1993; Klieger and Lamond, 1994; ASHRAE, 1993; ACI 122, 2002). Fig. 6.12 shows the comparison between the test results and the predicted values. The predictions were satisfactory with R^2 equal to 0.87.

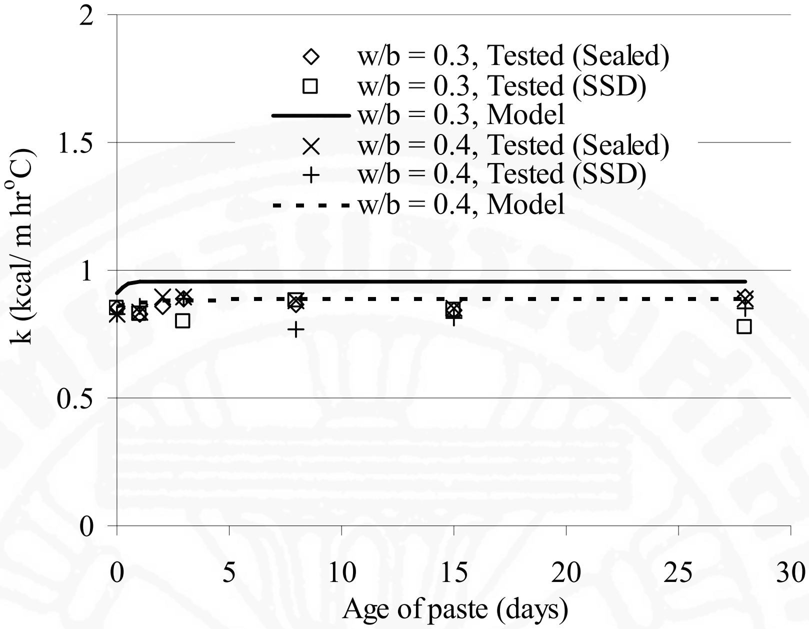


Fig. 6.10 Comparison between Bentz's test results and *k* model of cement paste, *w/b* = 0.3 and 0.4

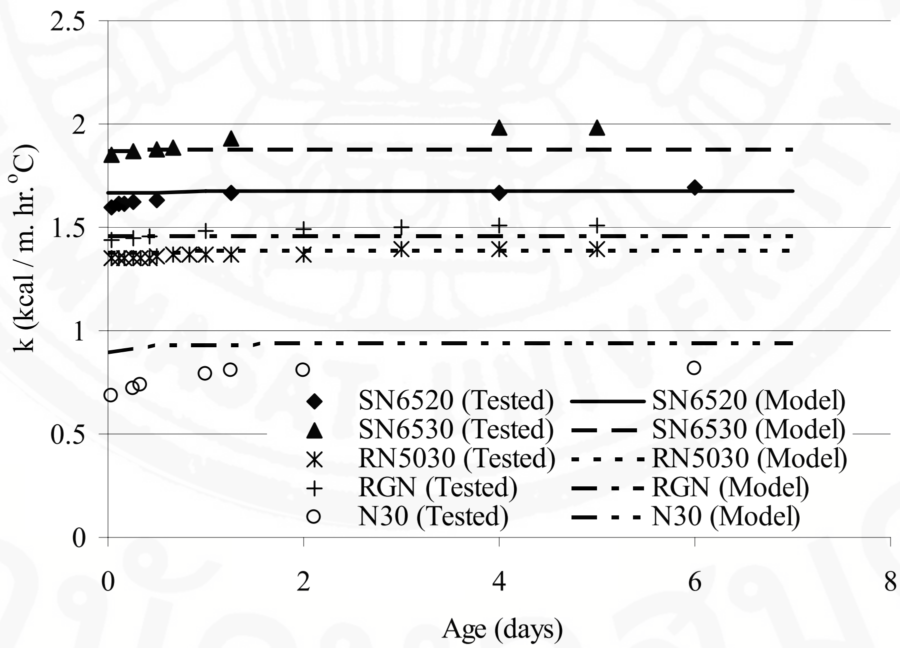


Fig. 6.11 Comparison between Toyokazu et al.'s test results and *k* model of paste, mortars and concrete

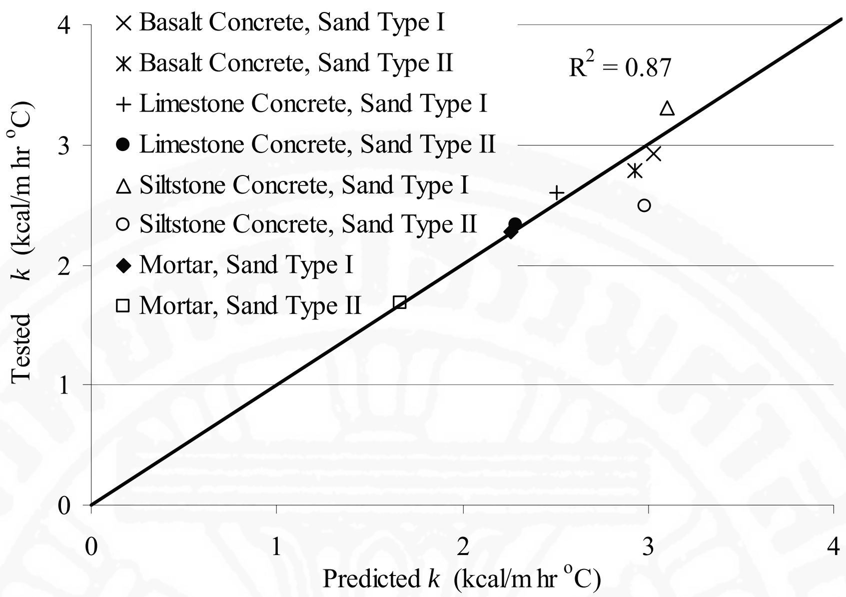


Fig. 6.12 Comparison between Khan's test results and *k* model of mortars and concrete

For Kim et al.'s research (2003), cement – fly ash pastes, mortars, no-fine concrete and concrete were cast with different *w/b*. The details of the test which were mix proportion, test age and type of cement are shown in Appendix C (Table C8). Two types of cement (Type I and Type V) were used. Chemical composition and physical properties of cement used in the verification are shown in Appendix C (Table C1). It was found in his research that type of cement had no effect on *k* so in this verification, both types of cement were assumed to have the same *k*. *k* of the coarse aggregate used in the verification was obtained by using the same regression method as mentioned above. *k* of the fine aggregate used in the verification is shown in Table 6.2 and *k* of the coarse aggregate is equal to 2.56 kcal/ m hr °C. Fig 6.13 shows the comparison between the test results and the predicted *k* values of pastes, mortar, no-fine concrete and concretes and the predictions were also satisfactory with R^2 equal to 0.95.

Fig. 6.14 shows the overall accuracy of the model. It was found that the predictions were satisfactory to predict the test results conducted in this study and other researchers' test results with the value of R^2 equal to 0.97.

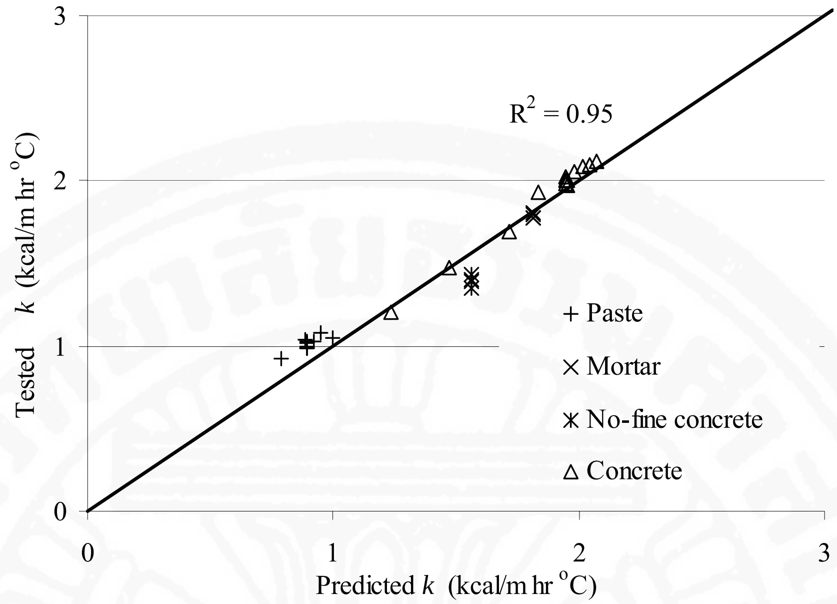


Fig. 6.13 Comparison between Kim et al.'s test results and *k* model of paste, mortars, no-fine concrete and concrete

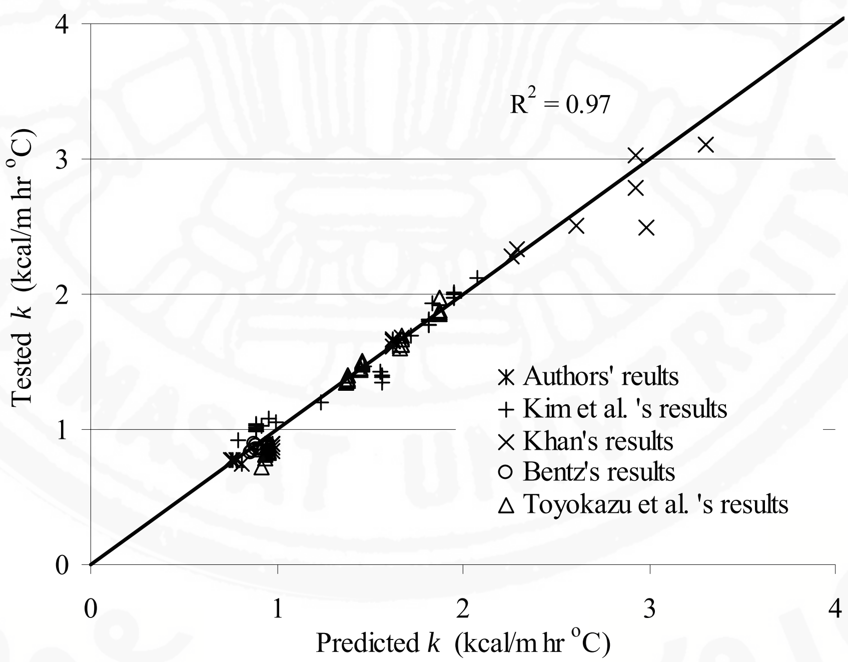


Fig. 6.14 Comparison between the predicted and the tested values of *k* measured by the authors' and all other referred data