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An experimental study on thermal conductivity of concrete

Kook-Han Kim[a], Sang-Eun Jeon[b], Jin-Keun Kim[b], Sungchul Yang[c,*]

[a]Korea Highway Corporation, Seoul 461-703, South Korea
[b]Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, South Korea
[c]Department of Architectural Engineering, Hongik University, Chungnam 339-701, South Korea

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Abstract

Influencing factors on thermal conductivity of concrete are quantitatively investigated by QTM-D3—that is, a conductivity tester developed in Japan—and a prediction equation of thermal conductivity of concrete is suggested from the regression analysis of test results. To consider the interacted factors influencing thermal conductivity of concrete, mortar, and cement paste, seven testing variables such as age, water–cement (W/C) ratio, types of admixtures, aggregate volume fraction, fine aggregate faction, temperature, and humidity condition of specimen were adopted in this test.

According to experimental results, aggregate volume fraction and moisture condition of specimen are revealed as mainly affecting factors on the conductivity of concrete. Meanwhile, the conductivities of mortar and cement paste are strongly affected by the W/C ratio and types of admixtures. However, age hardly changes the conductivity except for very early age. Finally, the conductivity of concrete is represented in terms of the aggregate volume fraction, fine aggregate fraction, W/C ratio, temperature, and humidity condition of specimen.

Keywords: Thermal analysis; Aggregate; Mixture proportioning; Temperature; Humidity

1. Introduction

The heat of hydration of concrete or occurrence of temperature gradient may lead to cracks in a concrete structure. To predict cracking response and thus prepare for its ways to cope with it, a systematic way to do analysis on the heat conduction is needed. Through the analysis of the heat conduction, temperature profiles developed along with any given structures can be precisely estimated along with locations at a certain time. By using these determined values as input data, a stress–strain analysis may be performed with the help of any commercial program packages. It is apparent that the precise analysis for heat conduction needs to be preceded to accurately estimate any outbreak of cracking accruing to temperature variation from the heat of hydration. There are many commercial program packages such as ABAQUS, ADINA-T, etc., and FEM programs of heat conduction privately made by researchers [1]. Except for the specific conditions such as the pipe-cooling or multiple placing methods, a close agreement has been obtained between the commercial packages and the privately developed FEM program [2]. It means that the heat conduction programs so far based on FEM can be solely adopted for analyzing the boundary value problems associated with temperature variation.

However, temperature variation in a concrete structure due to the heat of hydration is remarkably varied with respect to the variation of concrete thermal properties. As important input variables in the heat conduction model, the thermal conductivity, specific heat, density of concrete, and the convective heat transfer coefficient need to be determined. And it is widely accepted that the conductivity and the heat transfer coefficient have an influence on temperature gradient along the concrete structure. Meanwhile, the exothermic phenomenon during the hardening process is mainly affected by the specific heat and density of concrete. Based on literature review [3], thermal conductivity values of concrete range from 2.15 to 2.51 kcal/m h °C in accordance with different aggregates that are widely used in Japan. Even this range of the concrete is further widened to 1.7–2.53 kcal/m h °C at 38 °C in accordance with different aggregates [4]. Accordingly, thermal conductivity values have been chosen with the abovementioned range

* Corresponding author. Tel./fax: +82-41-867-0754.
E-mail address: scyang@hongik.ac.kr (S. Yang).

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without much consideration. However, thermal conductivity of concrete is greatly affected by mix proportioning, aggregate types and sources, as well as moisture status and unit weight in the dry state [5–7]. In addition to the abovementioned influencing factors, thermal conductivities of the cementitious materials appear to be changed by the measuring equipment [6].

An experimental test program was conducted mainly to investigate various key factors and thus accurately predict the heat conduction responses during the hardening process. In the experiment, aggregates commonly used in our nation and type V cement were used. According to the test results, the conductivity of concrete is represented in terms of the amount of aggregate, fine aggregate fraction, temperature, and humidity condition of specimen.

2. Experimental preparation

2.1. Measurement device

There are various testing devices and their interpreting methods for measurement of thermal conductivity. Such ways of measuring thermal conductivity of concrete are broken into three distinct methods. First, the two-linear-parallel-probe (TLPP) method [5], originally proposed by Carslaw [8], has been widely accepted to determine thermal conductivity. Two probes are inserted into two parallel holes drilled in the sample, where one probe is used as a heating source and the other as a temperature sensor.

Also used are the plane–heat–source (PHS) method [6] and the hot-guarded plate (HGP) method to evaluate thermal conductivity. They are similar to the TLPP method in their basic principle but require additional efforts to cut the sample thin, and then firmly place the thermal probe on with epoxy.

In this study, the QTM-D3 device manufactured from KEM in Japan was used to measure thermal conductivity of concrete (Fig. 1). The basic principle of this device is the same as that of the TLPP method; however the thermal conductivity is measured by the probe method, which has been modified from the transient-hot-wire method. The QTM-D3 device makes it possible to measure the thermal conductivity of the sample within 60 s by using probes containing temperature sensors. Because of prompt measurement and relatively small temperature rise, it may be used even for materials whose thermal conductivities greatly depend on temperatures. The measurement range of this device is 0.02 to 10.0 kcal/m h °C with an error of about ± 3%. Because the thermal conductivity of normal concrete has at best 3.0 kcal/m h °C, it can be assumed that the maximum error of measured data is about ± 0.1 kcal/m h °C.

Fig. 1. Apparatus of conductivity tester.

Table 1
Physical properties of cement

Classification	Specific gravity	Specific surface (m^2/kg)	Compressive strength (MPa)
Type I	3.15	331.5	40
Type V	3.15	321.0	36

2.2. Specimen preparation

The measurement error performed by the QTM-D3 device can be reduced as its sample size becomes larger. However, the specimen size cannot be extremely large just to reduce its measurement error. To prevent error, a minimum specimen size of 80 × 60 × 25 mm is recommended for use below the range of thermal conductivity of 3.0 kcal/m h °C. In this study, thermal tests were performed from the rectangular specimens of 100 × 100 × 150 mm and thermal conductivity was measured from three faces of each sample and calculated as their average value. In this specimen size, it can be assumed that the development of hydration heat of specimens is small enough to be ignored.

Three identical specimens were prepared for each test variable and were tested at 7 days after mixing, except for the specimens which were made to consider the effect of thermal conductivity on the age of hardening concrete. Then, the mould was removed from test specimens at the age of 1 day.

In this paper, the test specimens denoted as "saturated" and "dried" were subjected to moist curing and air-dry curing under the specified temperature, respectively. For more specific estimation of the effect of test parameters on the thermal conductivity, mixture types such as concrete and paste were selected with each test parameter.

Table 2
Physical properties of aggregate

Type of aggregate		G_{max} (mm)	Specific gravity	Fineness modulus
Fine	River sand	–	2.55	2.95
Coarse	Crushed stone	19	2.58	7.23

Table 3
Thermal conductivity of general grounds

Type of ground	Thermal conductivity (kcal/m h °C)
Quartz	4.45
Granite	2.50–2.65
Limestone	2.29–2.78
Marble	2.11
Basalt	2.47

Table 5
Thermal conductivity of water at saturation pressure

Temperature (°C)	Thermal conductivity (kcal/m h °C)
0	0.494
10	0.507
20	0.521
30	0.533
40	0.545

2.3. Materials

2.3.1. Cement

Portland cement manufactured from H Company in South Korea was used throughout this study. Its physical properties are tabulated in Table 1. Generally, the thermal conductivity of Portland cements is about 0.26 kcal/m h °C [7].

2.3.2. Aggregate

River sand produced at the Keumkang Mountain was used as fine aggregate, and crushed stone at Youngkwang Mountain as coarse aggregate. Their physical properties are shown in Table 2. The thermal conductivity of aggregates is largely affected by types of grounds. Table 3 shows the thermal conductivity of general grounds [9].

2.3.3. Admixtures

Fly ash and blast furnace slag (BFS) were used as the replacement of cement to investigate their effects on concrete thermal conductivity. Table 4 summarizes their physical characteristics.

For reference, the thermal conductivity of mixing water is known to vary with its temperature. Table 5 shows the thermal conductivity of water at saturation pressure [10].

2.4. Test variables and mix proportions

Thermal conductivity measurements were performed with particular reference to their dependence on some other interacted factors such as age, water–cement (W/C) ratio, types of admixtures, amount of coarse aggregate, fine aggregate fraction to total volume of aggregate, temperature, and humidity condition of specimen. To analyze the sensitivity of each test parameter, a series of different values was selected, as shown in Table 6, for the concrete and paste specimens. Table 7 lists mix proportions for the reference specimens. Table 8 summarizes mix proportions for all the batches considered in this study where C denotes concrete, P is paste, M is mortar, and RE is reference mix proportion.

Table 4
Physical properties of admixtures

Classification	Specific gravity	Specific surface (m^2/kg)	Place of production
FA	2.10	430	Boryung
BFS	2.90	450	Kwangyang

3. Experimental results

3.1. Dependence of thermal conductivity on age

To understand the influencing mechanism of thermal conductivity on the age of concrete, a series of specimens was fully saturated at 20 °C and tested at 3, 7, 14, and 28 days after mixing. As indicated in Table 9 and Fig. 2(a), thermal conductivities of cement, mortar, and concrete mixtures were revealed independent of curing age, although these values were remarkably changed with respect to different mixtures. Fig. 2(a) also represents that the thermal conductivity of cement paste is lowest and almost drops to half that of concrete.

3.2. Dependence of thermal conductivity on volume of aggregates

By keeping the rest of the variables as shown in Table 10, volume fractions of aggregates in the concrete mixtures were increased from 0 to 0.71 (0, 0.21, 0.35, 0.57, 0.64, 0.71) with variations of specimen temperatures at 20, 40, and 60 °C and moisture status as fully wet or fully dry. Their experimental results are shown in Table 10 and Fig. 2(b). It is apparent in Fig. 2(b) that as the volume fractions of aggregates are increased, regardless of the temperature or moisture condition in the sample, a somewhat linear

Table 6
Test parameters

Parameters	Variables for test	Mixture type
Age (days)	3, 7, 14, 28	Concrete, Paste
Aggregate content (%)	0, 21, 35, 49, 57, 64, 71	Concrete, Paste
W/C ratio (%)	25, 30, 35, 40	Paste
Type of cementitious materials	Type I, Type V, Fly ash, Slag	Paste
S/A (%)	39, 45, 50, 55	Concrete
Temperature (°C)	20, 40, 60	Concrete, Paste
Humidity condition	Saturated, Dried	Concrete, Paste

Table 7
Mix proportions for reference specimen

Classification	W/C (%)	S/A (%)	Type of cementitious materials	Unit content (kg/m^3)				
				Water	Cement	Fine aggregate	Coarse aggregate	Admixture
Concrete	40	39	Type V	181	452	630	989	2.26
Paste	40	–	Type V	558	1394	–	–	–

increment of the thermal conductivity is to be acquired. Thus, it is logical to expect that concrete contained with the larger amount of aggregates will have the higher thermal conductivity value since the thermal conductivity of aggregate is highest in the constituents of the concrete mix.

3.3. Dependence of thermal conductivity on W/C ratio

To determine a change in the thermal conductivity affected by the W/C ratio, tests were conducted from cement pastes with a change of moisture and temperature conditions. The neat cement paste specimens, rather than concrete specimens, were adopted to show the dependence of thermal conductivity on the W/C ratio because the amount of aggregates in concrete should be changed according to a change in the amount of cement. Test results in Table 11 and Fig. 2(c) show that the coefficient of thermal conductivity of the cement paste is reduced at all different moisture and temperature conditions. With the addition of the amount of cement, i.e., a lower W/C ratio, the thermal conductivity of paste specimens increases, since cement has a higher thermal conductivity value than water.

3.4. Dependence of thermal conductivity on admixtures

Test results were compared to investigate the effect of the cement types and replacement of cement with different cementitious materials such as fly ash or slag (Table 12) on the thermal conductivity of concrete. Tests were conducted with pastes saturated fully around 20 °C. As shown in Fig. 2(d), the thermal conductivity of paste made with type I cement was similar to that made with type V cement. However, replacement of cement by fly ash or slag made the coefficient drop.

3.5. Dependence of thermal conductivity on fine aggregate fractions

By differentiating fine aggregate fractions from the total amount of aggregates, measurement of thermal conductivity was measured for four sets of specimens and was tabulated

Table 8
Mix proportions

Parameters	Name of specimens	W/C (%)	S/A (%)	Type of cementitious materials	Unit content (kg/m^3)				
					Water	Cement	Fine aggregate	Coarse aggregate	Admixture
Age	C-RE	40	39	Type V	181	452	630	989	2.26
	P-RE	40	–	Type V	558	1394	–	–	–
	M-S	40	–	Type V	285	713	994	–	–
	M-G	26.7	–	Type V	239	894	–	1304	–
Aggregate content, temperature, humidity condition	C-GC1	40	39	Type V	140	350	702	1103	1.75
	C-GC2	40	39	Type V	181	452	630	989	2.26
	C-GC3	40	39	Type V	220	550	559	880	1.10
	C-GC4	40	39	Type V	260	650	490	768	–
	C-GC5	40	39	Type V	340	850	345	546	–
	C-GC6	40	39	Type V	420	1050	206	321	–
W/C ratio	P-WC1	25	–	Type V	440	1762	–	–	8.81
	P-WC2	30	–	Type V	486	1619	–	–	8.10
	P-WC3	35	–	Type V	524	1498	–	–	–
	P-WC4	40	–	Type V	558	1394	–	–	–
Type of cementitious materials	P-FL1	57	–	Fly ash	558	973	–	–	8.81
	P-FL2	47	–	Fly ash /TypeV	558	487/696	–	–	8.10
	P-BFS1	44	–	Slag	558	1282	–	–	–
	P-BFS2	42	–	Slag/TypeV	558	641/696	–	–	–
	P-1T	40	–	Type I	558	1394	–	–	–
S/A	C-SA1	40	45	Type V	181	452	726	891	2.26
	C-SA2	40	50	Type V	181	452	810	806	2.49
	C-SA3	40	55	Type V	181	452	887	729	2.83

Table 9
Aging effect for thermal conductivity

Items	W/C (%)	S/A (%)	Type of cementitious materials	Thermal conductivity (kcal/m h °C)			
				3 days	7 days	14 days	28 days
C-RE	40	39	Type V	1.98	2.02	2.00	1.97
P-RE	40	–	Type V	1.04	1.02	1.03	0.99
M-S	40	–	Type V	1.80	1.78	1.81	1.78
M-G	26.7	–	Type V	1.43	1.39	1.40	1.35

in Table 13. These specimens were tested at 20 °C with fully saturated conditions. As indicated in Table 13, there seems to be a little, yet increasing, change of the values with respect to the fine aggregate fractions. This uprising trend may be due to the fact that thermal conductivity of fine aggregate is greater than that of coarse aggregate or the fact that aggregates are uniformly distributed in the mix with the addition of fine aggregate.

3.6. Dependence of thermal conductivity on temperature

The effect of temperature on thermal conductivity was studied and its results are plotted in Fig. 2(b) and (c) for the concrete and neat cement paste specimens, respectively. Fig. 2(b) shows that thermal conductivities decrease as the specimen temperature increases while a similar trend was obtained from the cement paste specimens as shown in Fig. 2(c). It has also been reported by Morabito [5] that thermal conductivity decreases linearly with temperature.

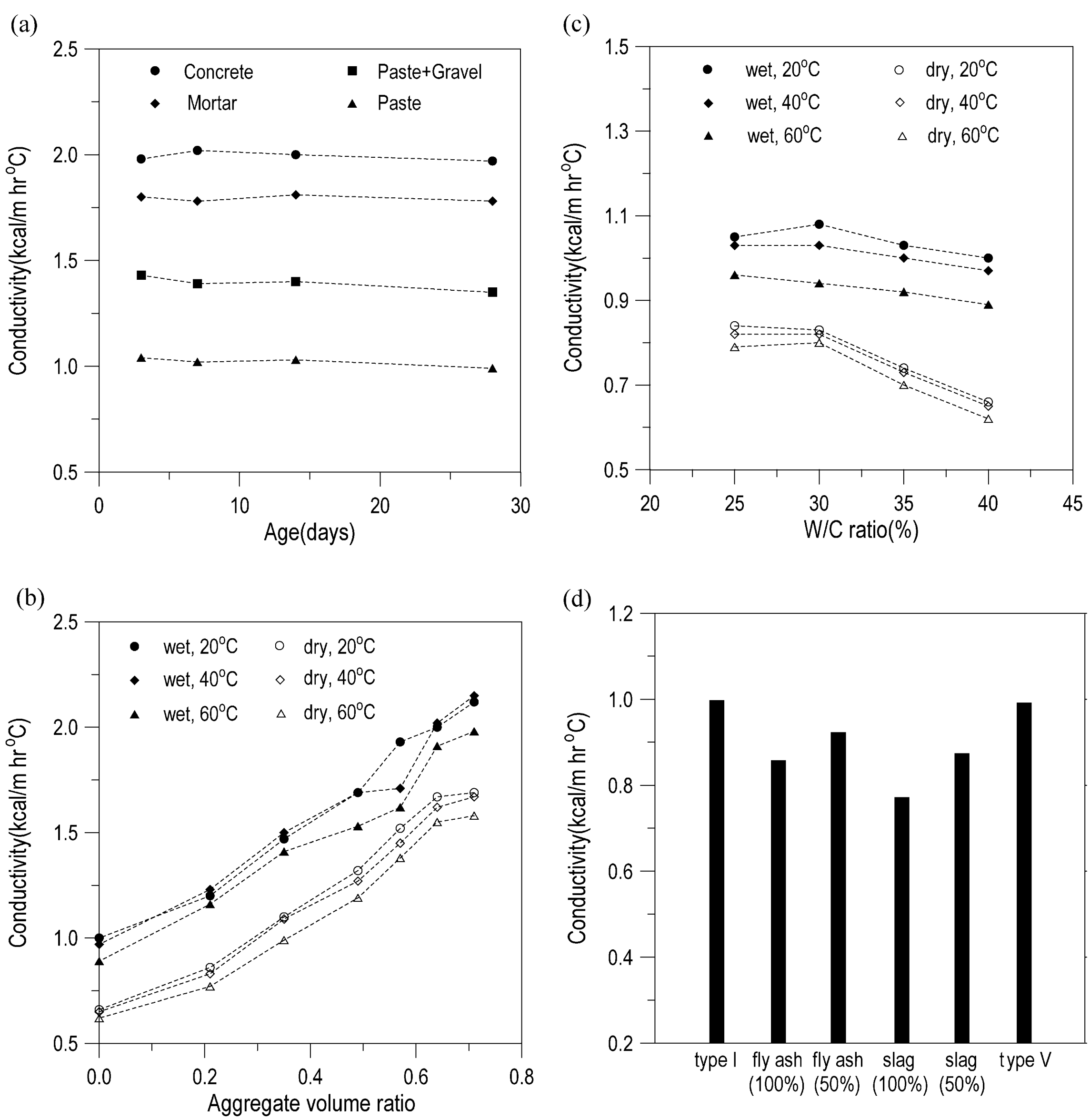

Fig. 2. Experimental results for thermal conductivity. (a) Age; (b) Aggregate content; (c) W/C ratio of paste; (d) Type of cementitious materials.

Table 10
Effects of aggregate content, temperature, and humidity condition

Items	W/C (%)	S/A (%)	Type of cementitious materials	Aggregate volume ratio	Thermal conductivity (kcal/m h °C)					
					Wet condition			Dry condition		
					20 °C	40 °C	60 °C	20 °C	40 °C	60 °C
C-GC1	40	39	Type V	0.70	2.12	2.15	1.98	1.69	1.67	1.58
C-GC2	40	39	Type V	0.63	2.00	2.02	1.91	1.67	1.62	1.55
C-GC3	40	39	Type V	0.56	1.93	1.71	1.62	1.52	1.45	1.38
C-GC4	40	39	Type V	0.49	1.69	1.69	1.53	1.32	1.27	1.19
C-GC5	40	39	Type V	0.35	1.47	1.50	1.41	1.10	1.09	0.99
C-GC6	40	39	Type V	0.21	1.20	1.23	1.16	0.86	0.83	0.77
P-WC4	40	–	Type V	0.0	1.00	0.97	0.89	0.66	0.65	0.62

3.7. Dependence of thermal conductivity on moisture condition

Moisture condition is known to be a key influencing factor among all the material parameters involved. As shown in both Fig. 2(b) and (c), thermal conductivity is dramatically increasing as the status changes from fully saturated to fully dried. This is attributed to changes in air voids filled with water, whose thermal conductivity is superior to that of air, therefore accounting for the effect of the degree of saturation on thermal conductivity.

4. Prediction equation

4.1. Relationship as a function of aggregate volume fraction

In this paper, the dependence of each test parameter on thermal conductivity assumes linear relationship to simplify the prediction equations. Selecting the thermal conductivity measured from the C-GC1 specimen as a base, relative values from all the specimens were replotted in Fig. 3(a) as a function of the aggregate volume fractions, either in concrete or in cement paste. Among these data, only those in Table 8, which meet a minimum aggregate volume fraction above 0.49, to be the common range of values, were used to draw a prediction equation. Though the relative values of thermal conductivities seem to be slightly changed, the following relationship can be used regardless of moisture or temperature condition in concrete:

$$\lambda_{AG} = 0.293 + 1.01\mathrm{AG} \tag{1}$$

where λ_{AG} is a modification index and AG is an aggregate volume fraction in concrete.

The above equation may be applied only to the same sources of aggregate as used in this study. However, with known thermal conductivities of different sources of aggregate, more precise and generalized relationships can be drawn along with the above-proposed equation.

4.2. Relationship as a function of temperature

As discussed previously, thermal conductivity decreases with temperature. This is mainly attributed to the variation of thermal conductivity affected by pastes. Fig. 3(b) represents normalized thermal conductivities taken from test results only with W/C ratios of 0.4 or above at a fully saturated condition, where thermal conductivity measured at 20 °C was selected as a base. By a linear regression using these data, the following equation was obtained to estimate the effect of temperature change on the thermal conductivity:

$$\lambda_T = 1.05 - 0.0025T \tag{2}$$

where λ_T is a modification index to account for the influence of temperature (T).

Table 11
Effects of W/C ratio

Items	Type of cementitious materials	W/C (%)	Thermal conductivity (kcal/m h °C)					
			Wet condition			Dry condition		
			20 °C	40 °C	60 °C	20 °C	40 °C	60 °C
P-WC1	Type V	25	1.05	1.03	0.96	0.84	0.82	0.79
P-WC2	Type V	30	1.08	1.03	0.94	0.83	0.82	0.80
P-WC3	Type V	35	1.03	1.00	0.92	0.74	0.73	0.70
P-WC4	Type V	40	1.00	0.97	0.89	0.66	0.65	0.62

Table 12
Effects of cementitious materials

Items	W/C (%)	Volume ratio of cementitious materials	Type of cementitious materials	Thermal conductivity (kcal/m h °C)	Replacement ratio (%)
P-WC4	40	0.44	Type V	1.00	–
P-FL1	57	0.44	Fly ash	0.86	100
P-FL2	47	0.44	Fly ash/ Type V	0.92	50
P-BFS1	44	0.44	Slag	0.77	100
P-BFS2	42	0.44	Slag/Type V	0.87	50
P-1T	40	0.44	Type V	0.99	–

Table 13
Effects of S/A ratios

Items	W/C (%)	Type of cementitious materials	Aggregate volume ratio	S/A (%)	Thermal conductivity (kcal/m h °C)
C-GC1	40	Type V	0.63	39	2.00
C-SA1	40	Type V	0.63	45	2.06
C-SA2	40	Type V	0.63	50	2.09
C-SA3	40	Type V	0.63	55	2.10

4.3. Relationship as a function of moisture condition

It has been confirmed that the increase of water content would lead to higher thermal conductivity value. Test results from data in Table 11 were rearranged in Table 14 as relative values of thermal conductivities measured from dried specimens to those from saturated specimens. Their normalized values, which are based on thermal conductivity measured from a sample of W/C = 0.4, were plotted in Fig. 3(c). Moreover, supposing the value of thermal conductivity has a linear change between a fully saturated condition

Table 14
Conductivity ratio with different water contents

W/C (%)	Conductivity ratio (dried/saturated)		
	20 °C	40 °C	60 °C
25	0.800	0.796	0.823
30	0.769	0.796	0.851
35	0.718	0.730	0.761
40	0.660	0.670	0.697

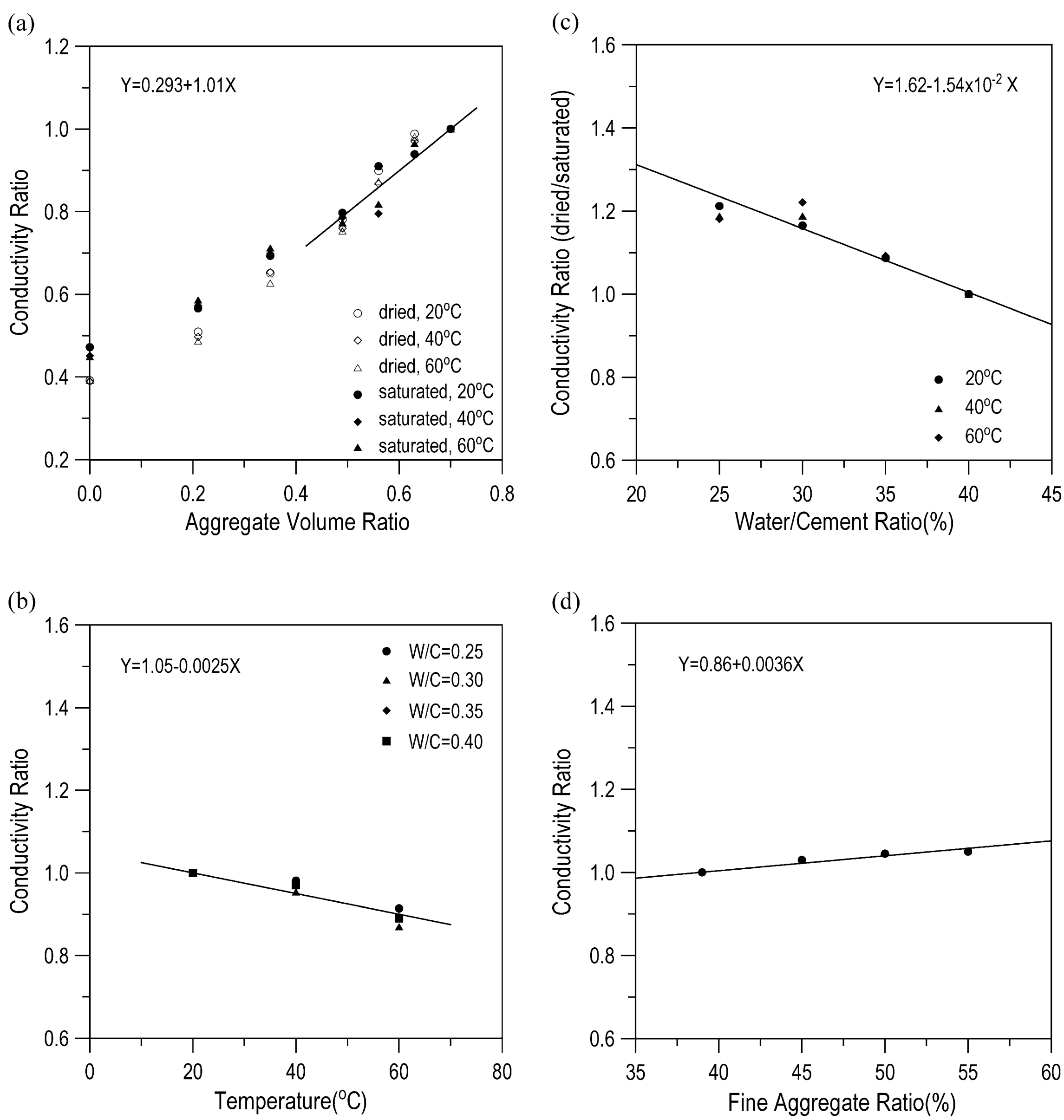

Fig. 3. Normalization curve. (a) Aggregate content; (b) Temperature; (c) W/C ratio; (d) Fine aggregate fraction.

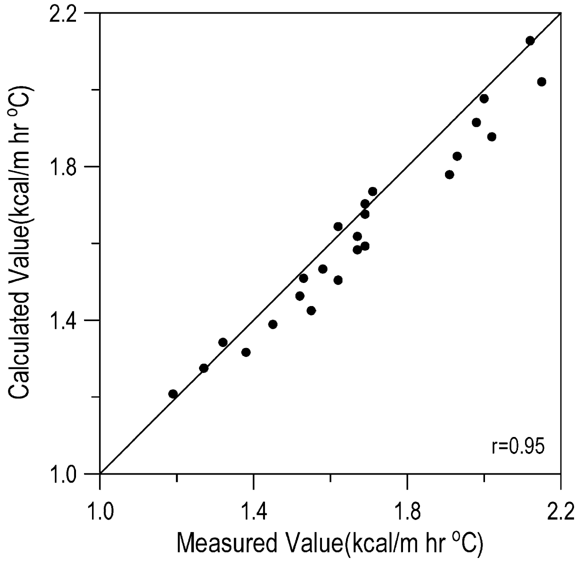

Fig. 4. Comparison of the measured and calculated values.

and a fully dried condition, the following equation can be obtained:

$$\lambda_R = 0.8 \times [1.62 - 1.54 \times (\mathrm{W/C})] + 0.2R_\mathrm{h} \tag{3}$$

where λ_R is a modification index associated with R_h as an average relative humidity and W/C ratio.

4.4. Relationship as a function of fine aggregate fraction

To determine the thermal conductivity affected by fine aggregate fraction, the following normalized equation is generated linearly with the fine aggregate fraction of 0.4 as a base.

$$\lambda_{\mathrm{S/A}} = 0.86 + 0.36(\mathrm{S/A}) \tag{4}$$

where $\lambda_{\mathrm{S/A}}$ is a modification index associated with S/A as fine aggregate volume fraction. The results are plotted in Fig. 3(d).

4.5. Model equation of thermal conductivity

Among the factors, which influence on the thermal conductivity, observation of test results reveals age does not provide a significant effect. Therefore, thermal conductivity of concrete can be predicted by the relationship as functions of aggregate volume fraction, fine aggregate fraction, W/C ratio, temperature, and moisture condition in concrete as follows:

$$\begin{aligned} k_\mathrm{c} = k_\mathrm{ref}&[0.293 + 1.01\mathrm{AG}] \\ &\times[0.8(1.62 - 1.54(\mathrm{W/C})) + 0.2R_\mathrm{h}] \\ &\times[1.05 - 0.0025T][0.86 + 0.0036(\mathrm{S/A})] \end{aligned} \tag{5}$$

where k_c denotes thermal conductivity of concrete and k_ref is a referenced thermal conductivity measured from specimens at a condition of AG = 0.70, W/C = 0.4, S/A = 0.4, T = 20 °C, and R_h = 1.0.

Fig. 4 reveals a close relationship between thermal conductivity of concrete predicted from Eq. (5) and its measured values. The sample correlation coefficient R of .95 indicates that Eq. (5) is quite reasonable. If one applies Eq. (5) to the analysis of heat conduction in any concrete structures, one can make accurate evaluation of the spatial and temporal temperature distribution through any numerical techniques.

5. Conclusions

An experimental study was conducted to determine the influencing factors on the thermal conductivity through the use of the QTM-D3 device of which the principle of TLPP is adopted. Based on test results, an empirical equation to evaluate thermal conductivity was derived. The following are research findings from this study.

1) In the experiment, seven parameters which mostly affect thermal conductivities of concrete, mortar, and neat cement paste were considered: age, aggregate volume fraction, amount of cement, types of admixtures, fine aggregate fraction, temperature, and moisture status of specimen. According to test results, aggregate volume fraction and moisture condition of specimen are revealed as mainly affecting factors on the conductivity of concrete.

2) It was also found that the conductivities of the mortar and cement paste are affected by the types of admixtures as well as by the amount of cement.

3) It was however noted that age hardly affects the thermal conductivity of concrete except for very early age, i.e., about 2 days.

4) Based on test results from the aggregate volume fraction, fine aggregate fraction, temperature and moisture contents in concrete, a model equation was derived to accurately estimate the thermal conductivity of concrete. The proposed relationship correlates test results well by indicating the sample correlation coefficient of .95, but needs to be further examined with additional and precise experimental test results.

5) One expects to elucidate the analysis of heat conduction by incorporating the proposed relationship. Thus, enhancement of the analysis will be obtained by the evaluation of the spatial and temporal temperature distribution through any numerical techniques.

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