



# 마이크로웨이브 발열거푸집으로 양생된 콘크리트의 압축강도발현 모델

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## Compressive Strength Development Model for Concrete Cured by Microwave Heating Form

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**ABSTRACT** Time dependent model for prediction of compressive strength development of concrete cured by microwave heating form was presented in this study. The presented model is similar to the equation which is given in ACI 209R-92 but the constants which is dependent on cement type and curing method in the presented model are modified by the regression analysis of the experimental data. Laboratory scale concrete specimens were cast and cured by the microwave heating form and drilled cores extracted from the specimens were fractured in compression. The measured core strengths are converted to standard core and in-situ strengths. These in-situ strengths are used for the regression.

**Keywords** : accelerated curing, microwave, form, compressive strength development model, drilled core strength

### 1. 서 론

본 연구는 마이크로웨이브 발열거푸집을 사용하여 양생된 콘크리트의 압축강도발현 모델을 제시하고, 이를 실험 결과와 비교하여 검증하였다. 본 연구는 ACI 209R-92에 제시된 압축강도발현 모델과 유사하지만, 시멘트 종류와 양생 방법에 따라 달라지는 상수들을 실험 데이터를 통한 회귀 분석을 통해 수정하였다. 실험을 위해 실험실 규모의 콘크리트 시편을 마이크로웨이브 발열거푸집을 사용하여 양생하고, 시편에서 추출된 코어를 압축 시험을 통해 파괴하였다. 측정된 코어 강도를 표준 코어 강도와 현장 강도로 변환하였다. 이 현장 강도를 회귀 분석에 사용하였다.

**Keywords** : accelerated curing, microwave, form, compressive strength development model, drilled core strength

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## 2. 실험

Table 2

### 2.1 실험개요

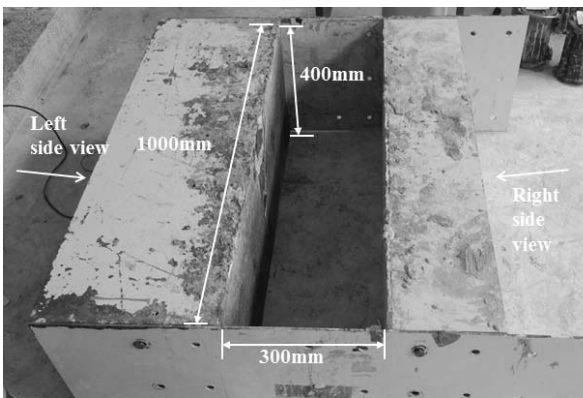
24 MPa 1  
(Table 1)  
25 mm  
5 (100×200)  
28

**Table 1** Mix proportion of concrete

$f_{ck}$ (MPa)	W/C (%)	S/a	Mix amount (kg/m <sup>3</sup> )			
			W	C	S	G
24	50.0	40.05	191.69	383.38	669.53	1062.3

**Table 2** Compressive strength results

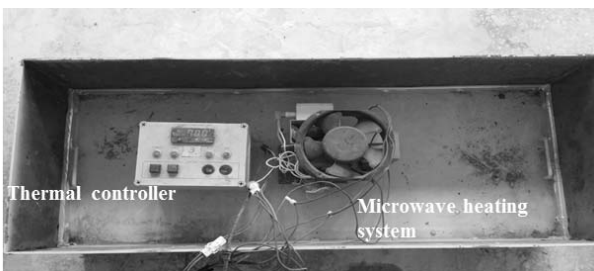
$f_{ck}$	Mean (MPa)	Std. (MPa)	CoV (%)
		27.05	0.49



(a) Microwave heating form



(b) Right side view



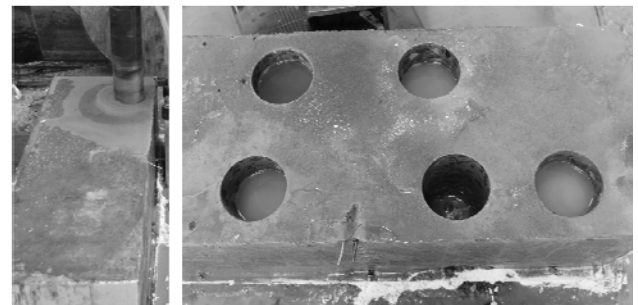
(c) Left side view

**Fig. 1** Steel form used for the experimental program

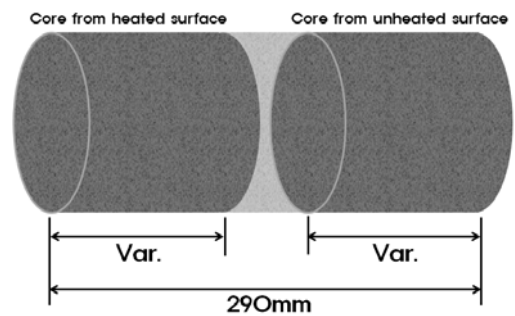
**Fig. 1**

300 mm, 400 mm  
1,000 mm  
300 mm  
가  
(Microwave heating system)  
(Thermal controller)

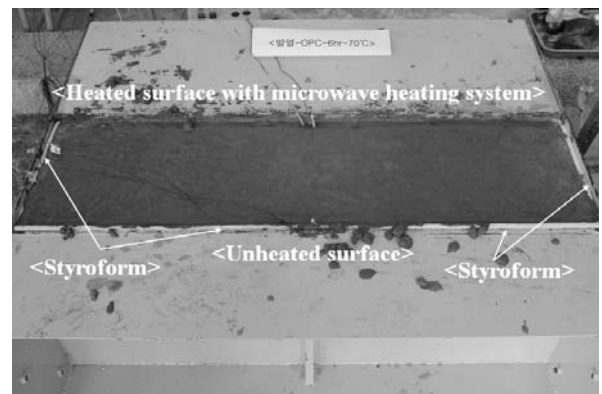
가



**Fig. 2** Core drilling



**Fig. 3** Surface identification of the drilled core



**Fig. 4** Specimen curing

**Table 3** Measured core and converted strengths

	Core from heated surface																			
	0.25day				3day				7day				15day				28day			
	<i>l</i>	$f_c$	SCS	IS	<i>l</i>	$f_c$	SCS	IS	<i>l</i>	$f_c$	SCS	IS	<i>l</i>	$f_c$	SCS	IS	<i>l</i>	$f_c$	SCS	IS
1	152	7.6	7.4	8.6	145	17.1	16.5	19.1	140	21.6	20.8	24.0	140	22.0	21.1	24.4	140	24.9	23.9	27.7
2	150	8.4	8.2	9.4	145	17.6	17.0	19.7	140	21.5	20.7	23.9	140	20.8	20.0	23.1	140	24.0	23.1	26.7
3	150	10.6	10.3	11.9	145	17.5	16.9	19.5	140	20.6	19.8	22.9	140	23.0	22.1	25.5	140	21.9	21.1	24.3
4	150	12.1	11.8	13.6	145	17.3	16.7	19.3	140	20.4	19.6	22.7	140	22.0	21.1	24.4	140	23.9	23.0	26.6
5	150	12.2	11.9	13.7	145	17.3	16.7	19.3	140	20.5	19.7	22.8	140	22.6	21.7	25.1	140	22.8	21.9	25.3
Avg.	150	10.2	9.9	11.4	145	17.4	16.8	19.4	140	20.9	20.1	23.3	140	22.1	21.2	24.5	140	23.5	22.6	26.1
Std.	0.9	2.1	2.1	2.4	0.0	0.2	0.2	0.2	0.0	0.6	0.6	0.6	0.0	0.8	0.8	0.9	0.0	1.2	1.1	1.3
CoV	0.6	20.7	20.7	20.6	0.0	1.1	1.2	1.2	0.0	2.8	2.9	2.7	0.0	3.8	3.7	3.7	0.0	5.0	4.9	5.1

	Core from unheated surface																			
	0.25day				3day				7day				15day				28day			
	<i>l</i>	$f_c$	SCS	IS	<i>l</i>	$f_c$	SCS	IS	<i>l</i>	$f_c$	SCS	IS	<i>l</i>	$f_c$	SCS	IS	<i>l</i>	$f_c$	SCS	IS
1	-	-	-	-	145	16.8	16.2	18.8	130	16.1	15.2	17.6	140	23.5	22.6	26.1	130	24.7	23.4	27.1
2	-	-	-	-	145	15.6	15.1	17.4	130	20.2	19.1	22.1	140	23.4	22.5	26.0	130	24.0	22.8	26.3
3	-	-	-	-	145	15.6	15.1	17.4	130	16.8	15.9	18.4	140	23.8	22.9	26.4	131	26.9	25.6	29.5
4	-	-	-	-	145	15.7	15.2	17.5	130	21.8	20.7	23.9	140	25.1	24.1	27.9	130	22.8	21.6	25.0
5	-	-	-	-	145	15.8	15.3	17.7	130	17.0	16.1	18.6	140	24.3	23.4	27.0	130	24.6	23.3	26.9
Avg.	-	-	-	-	145	15.9	15.4	17.8	130	18.4	17.4	20.1	140	24.0	23.1	26.7	130	24.6	23.3	27.0
Std.	-	-	-	-	0.0	0.5	0.5	0.6	0.0	2.5	2.4	2.7	0.0	0.7	0.7	0.8	0.4	1.5	1.5	1.6
CoV	-	-	-	-	0.0	3.2	3.0	3.3	0.0	13.5	13.6	13.6	0.0	2.9	2.9	2.9	0.3	6.1	6.2	6.1

*l*: Core length (mm),  $f_c$ : Measured core strength (MPa), SCS: Standard core strength (MPa), IS: In-situ strength (MPa)

Fig. 2 100 mm  
5  
“(Core from heated surface)”,  
“(Core from unheated surface)”

(Fig. 3 )

Table 3

5 0.25, 3, 7, 15, 28

가 KS F 2422

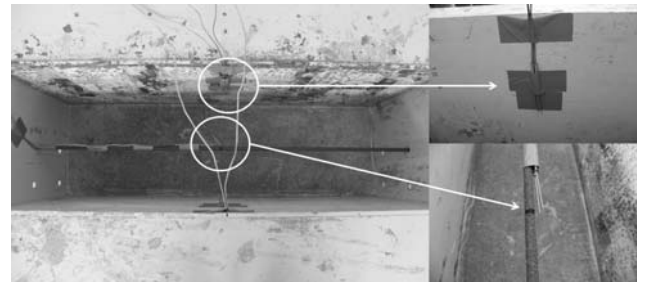
. Fig. 4

10 mm ( )

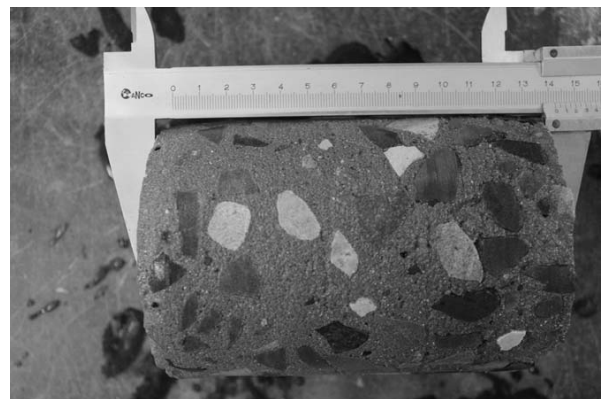
Fig. 3 290 mm

70°C

가 0.25 (6 )



**Fig. 5** Location of thermal couples attached



**Fig. 6** Measurement of core height

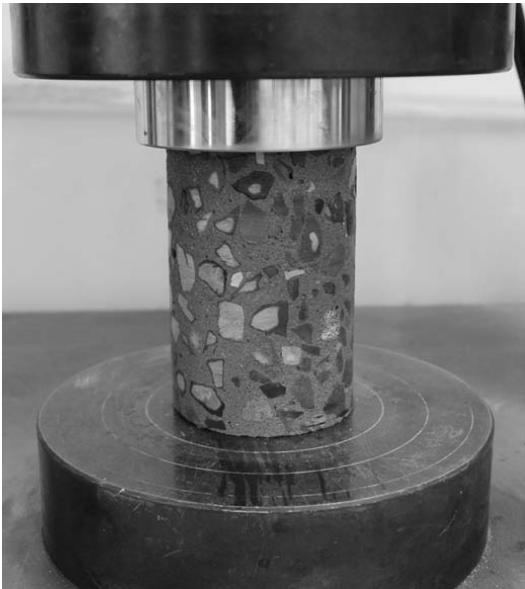


Fig. 7 Compressive strength test of drilled core

7, 15, 28  
 ( )  
 Fig. 5  
 10  
 0.01 mm (Fig. 6)  
 KS F 2405  
 (Fig. 7)

## 2.2 온도변화

“Heated surface”,  
 “Center”, “Unheated surface”  
 Fig. 8 Fig. 8(a)  
 6  
 가 가  
 6  
 Center, Unheated surface  
 가 Heated  
 surface (A)  
 (B)가  
 75°C(A+B)  
 가

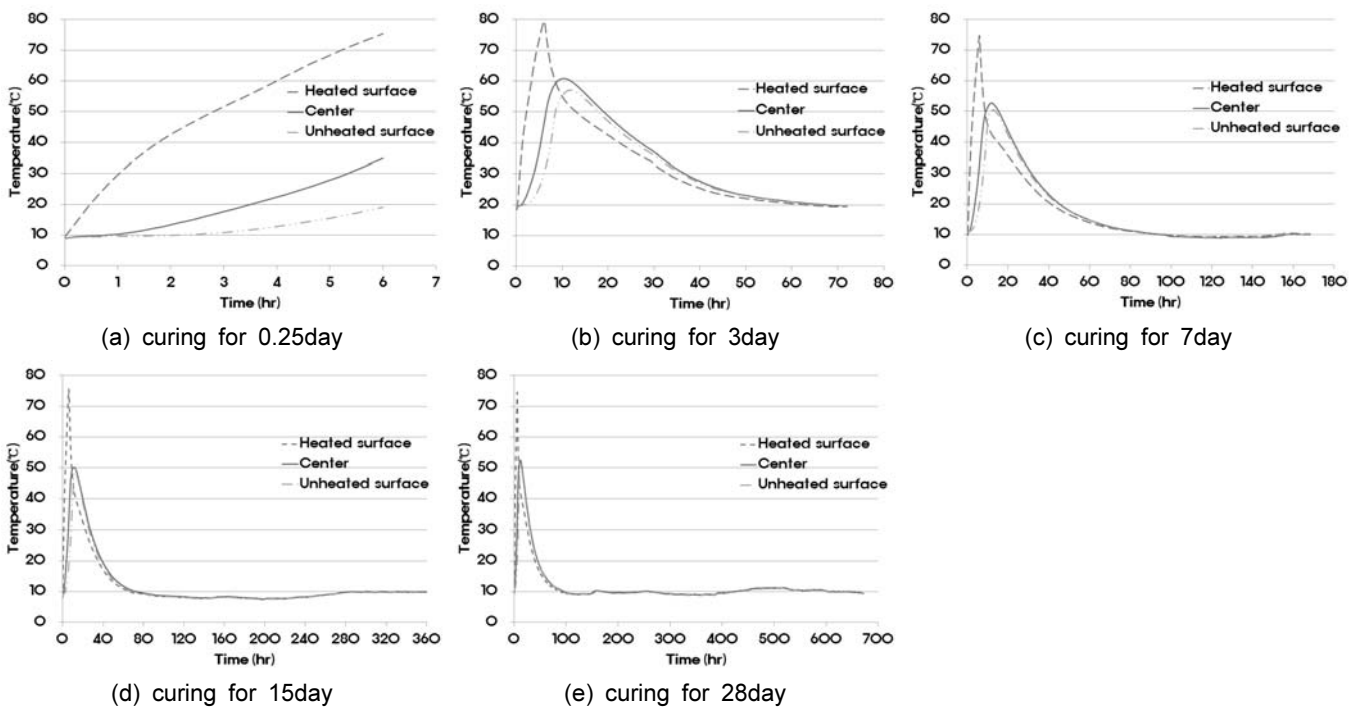


Fig. 8 Measured temperature histories

70°C  
 Ettringite Formation)  
 DEF (Delayed  
 가  
 Fig. 8(b)~(c)  
 Heated surface  
 Fig. 4  
 Heated surface  
 Fig. 8(b)  
 가 20°C  
 10°C  
 가  
 10°C  
 가  
 10°C

$$F_{c, is} = F_{mc} F_d F_{c, s} \quad (4)$$

$F_{c, is}$  IS (MPa)  
 $F_{mc}$  가 1.09,  
 0.96  $F_d$   
 1.06  $F_{mc}$  1.09,  
 $F_d$  1.06  
 IS Table 3 5  
 가 10%  
 0.25 Heated  
 surface 가 20%  
 가  
 Heated surface Unheated  
 surface

### 2.3 표준코어강도와 현장 콘크리트강도 보정

(Standard core strength, SCS),  $F_{c, s}$   
 (In-situ strength, IS),  $F_{c, is}$

Bartlett and MacGregor<sup>8)</sup>

(1)

SCS

$$F_{c, s} = F_{l/d} F_{dia} F_r F_{c, NS} \quad (1)$$

$F_{c, s}$  가 2  
 SCS(MPa),  $F_{l/d}$ ,  $F_{dia}$ ,  $F_r$   
 100 mm  
 $F_{dia}$   $F_r$  1  
 $F_{l/d}$  (2) (3)

(3)

$l$  (mm)  
 $d$  (mm),  $f_c$  (MPa)

$$F_{l/d} = 1 - (0.144 - 4.3(10^{-4})f_c) \left(2 - \frac{l}{d}\right)^2 \text{ for air dried} \quad (2)$$

$$F_{l/d} = 1 - (0.117 - 4.3(10^{-4})f_c) \left(2 - \frac{l}{d}\right)^2 \text{ for soaked} \quad (3)$$

Bartlett and MacGregor<sup>8)</sup> (4) SCS IS

### 2.4 보정식에 대한 평가

Bartlett and MacGregor<sup>8)</sup>

가 2.1

5

100 mm

Table 4 Cylinder strength results

Curing period (day)	1	2	3	4	5	Avg. (MPa)	Std. (MPa)	CoV (%)
0.25	-	-	-	-	-	-	-	-
3	18.03	17.44	17.13	18.91	16.92	17.69	0.72	4.1
7	20.52	19.97	21.16	22.59	21.20	21.09	0.88	4.2
15	26.84	25.23	25.79	26.01	25.03	25.78	0.64	2.5
28	27.91	27.00	26.38	27.05	26.91	27.05	0.49	1.8

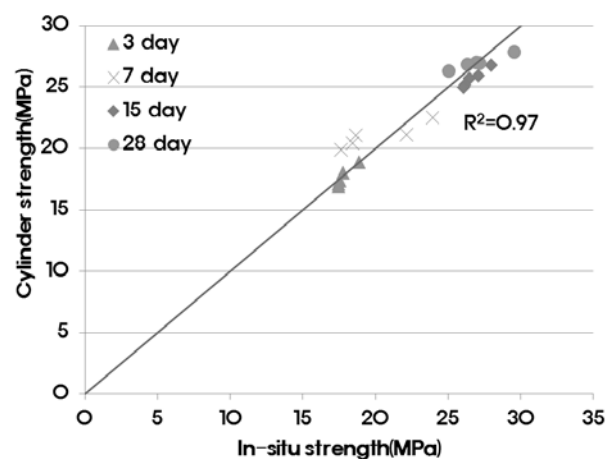


Fig. 9 Comparison of SCS with cylinder strength

Table 4

(Table 4 Cylinder strength) Unheated surface IS  
(Table 3)가 Bartlett and MacGregor<sup>8)</sup> 가

Fig. 9 (Cylinder strength) Unheated surface IS 가 0.97

### 3. 강도발현 평가

#### 3.1 SCS의 비교

Fig. 10 Heated surface Unheated surface SCS 0.25 Unheated surface 가 가 , 0.25 Heated surface SCS 10 MPa , 15 28 Heated surface 가 Unheated surface 가

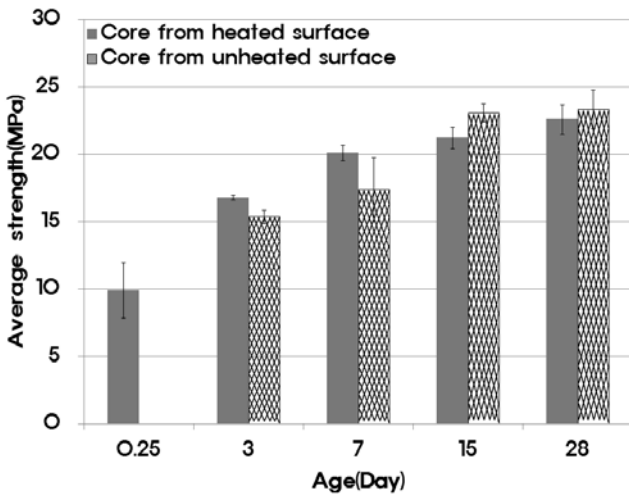


Fig. 10 Comparison of standard core strength (SCS)

Table 5 a, b, d<sub>i</sub> in KCI model

Cement type	a	b	d <sub>i</sub>
Ordinary portland cement	4.5	0.95	1.11
Moderate heat portland cement	6.2	0.93	1.15
High early strength portland cement	2.9	0.97	1.07
Low heat portland cement	16.2	0.82	1.40

가 6

#### 3.2 재령에 따른 압축강도발현 모델 고찰

, PSC

( KCI ) (5)

$$f_{cu}(t) = \left[ \frac{t}{a+bt} \right] d_i f_{ck} \quad (5)$$

, f<sub>cu</sub>(t) t (MPa) , f<sub>ck</sub> 28 (MPa) , a, b, d<sub>i</sub> , Table 5 . t ( )

, a , b , d<sub>i</sub> 91 KCI 1 a = 4.5, b = 0.95, d<sub>i</sub> = 1.11, f<sub>ck</sub> = 24MPa IS

(Fig. 11 ) .

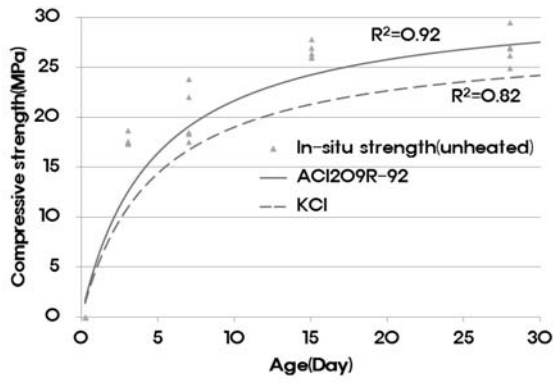
, ACI 209R-92 KCI (6) KCI

$$f_{cmt} = \left[ \frac{t}{a+bt} \right] f_{cm28} \quad (6)$$

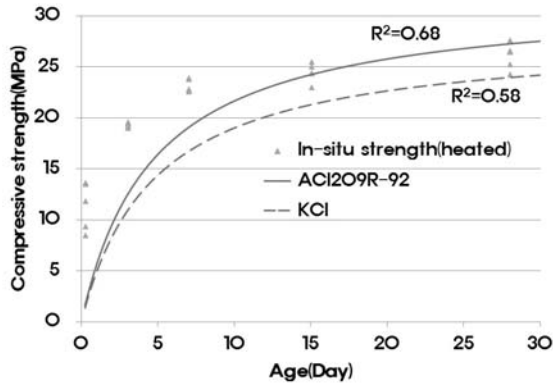
, t ( ) , a, b , Table 6 . f<sub>cm28</sub>

Table 6 a, b in ACI 209R-92 model

Type of curing	Type of cement	a	b
Moist cured	ordinary portland cement	4.0	0.85
	high early strength portland cement	2.3	0.92
Steam cured	ordinary portland cement	1.0	0.95
	high early strength portland cement	0.7	0.98



(a) Unheated



(b) Heated

Fig. 11 Comparisons of IS with strength development model curves

Table 7 Constants presented in case of using microwave heating form

Type of curing	Type of cement	a		b	
		lower bound	upper bound	lower bound	upper bound
Microwave heating form	ordinary portland cement	1.50	1.00	1.09	0.98

28  
 ACI 209R-92 (Steam cured)  $a = 1.0$ ,  
 $b = 0.95$ ,  $f_{cm28} = 27.05$  MPa (Table 2 )  
 IS

(Fig. 11 ).  
 Unheated surface ACI 209R-92  
 0.92, KCI 0.82  
 가 0.68 0.58  
 209R-92 KCI ACI

ACI 209R-92

a, b

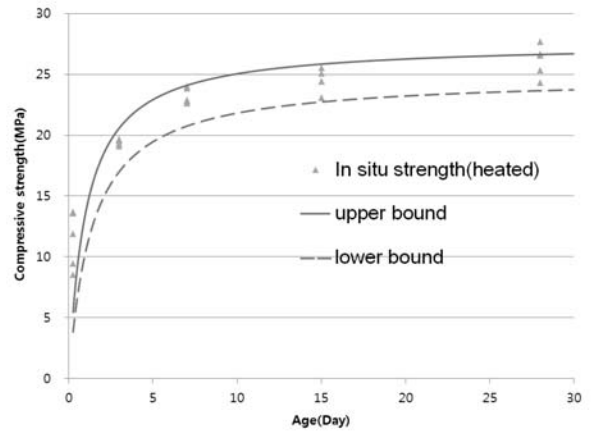


Fig. 12 Upper and lower strength Vs. age curves for using ordinary portland cement and microwave heating

#### 4. ACI 209R 강도발현 모델 계수 범위

Table 7

Heated surface IS  
 a, b

3

가 10°C

가

Table 6

1.5 , , 1.0 a 2.3 . a

b

Fig. 12 Table 7

IS가 6 ,

#### 5. 결 론

24 MPa 1

가  
가

### 감사의 글

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요 약

ACI 209R-92

**핵심용어** : 촉진양생, 마이크로웨이브, 거푸집, 압축강도발현모델, 규어강도