Experimental Measurement and Prediction Modeling of Concrete Thermal Conductivity

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ACI Concrete Convention Boston

November 1st 2023

Thermal Conductivity

- Thermal conductivity (*k*): ability of a material to conduct heat and is defined as the constant of proportionality between heat flux and temperature gradient

$$\frac{Q}{A} = -k\frac{dT}{dx}$$

- Relevant to numerous applications of concrete:
  - Low *k* for thermal insulation like radiation shield in nuclear power stations
  - High *k* for floors and driveways with embedded heaters and for heated pavements
  - The knowledge of *k* is essential in predicting the temperature profile and heat flow through mass concrete

Experimental Measurement

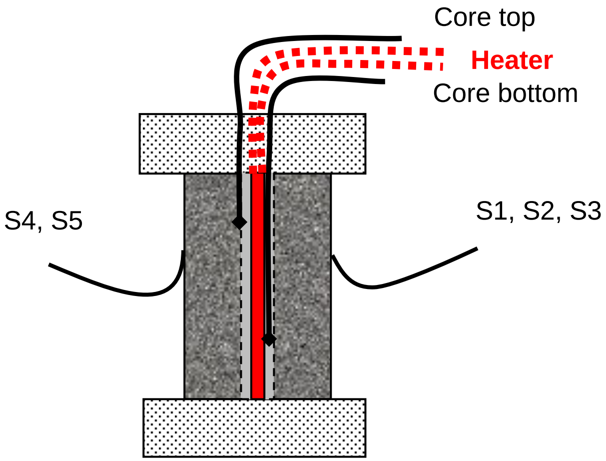
Part I: Experimental Measurement

Experiment details

- **Objective:** To analyze the effect of various modern concrete materials on thermal conductivity
- **Parameters:** w/b, age, aggregate type (NA, LWA, RCA), SCMs (FA, Slag), fibers (Steel, PP)
- **Test Method:**

Sample preparation

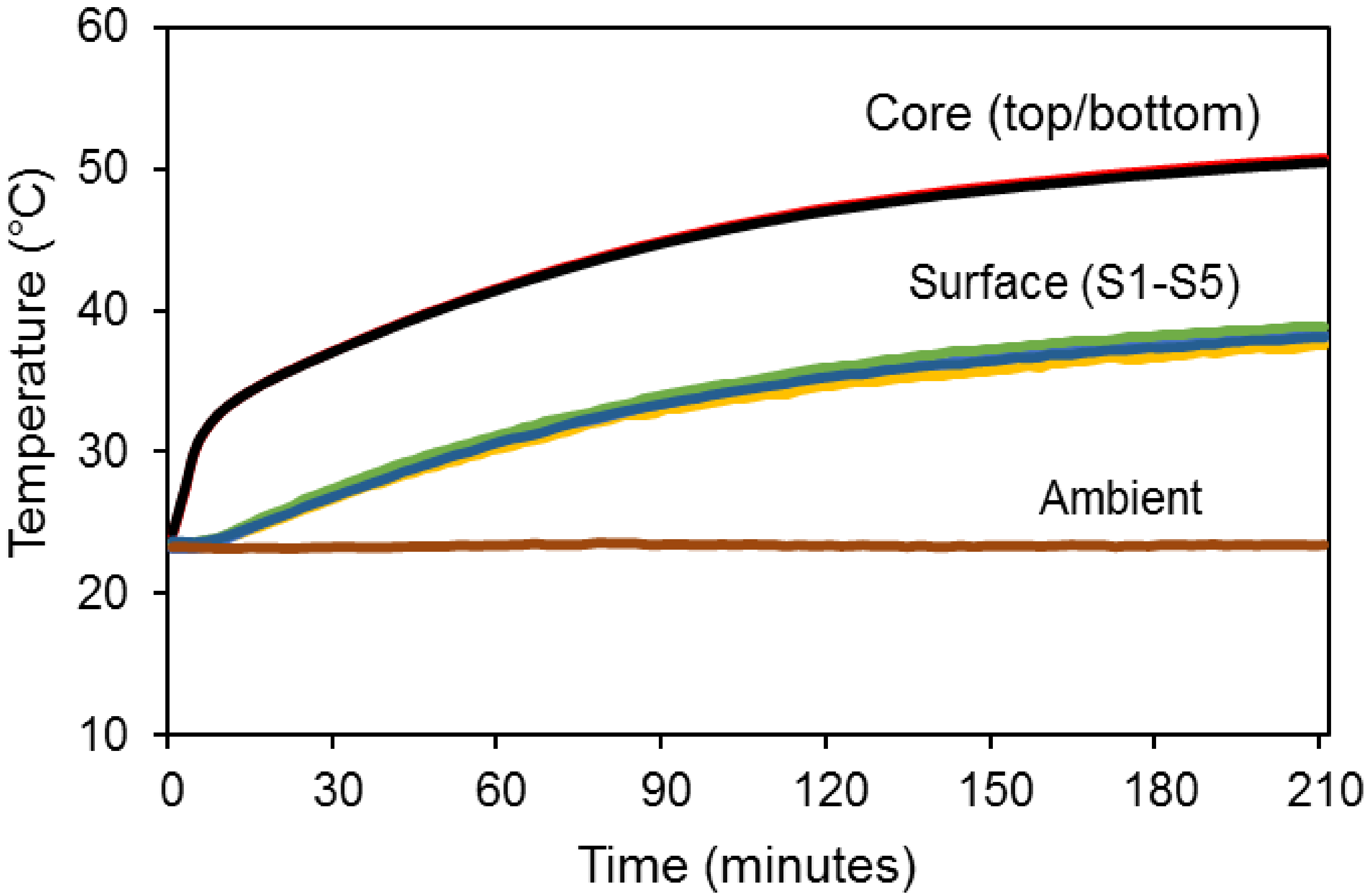
Assembling setup



Test setup

Test developed at ASU (Carlson et al 2010)

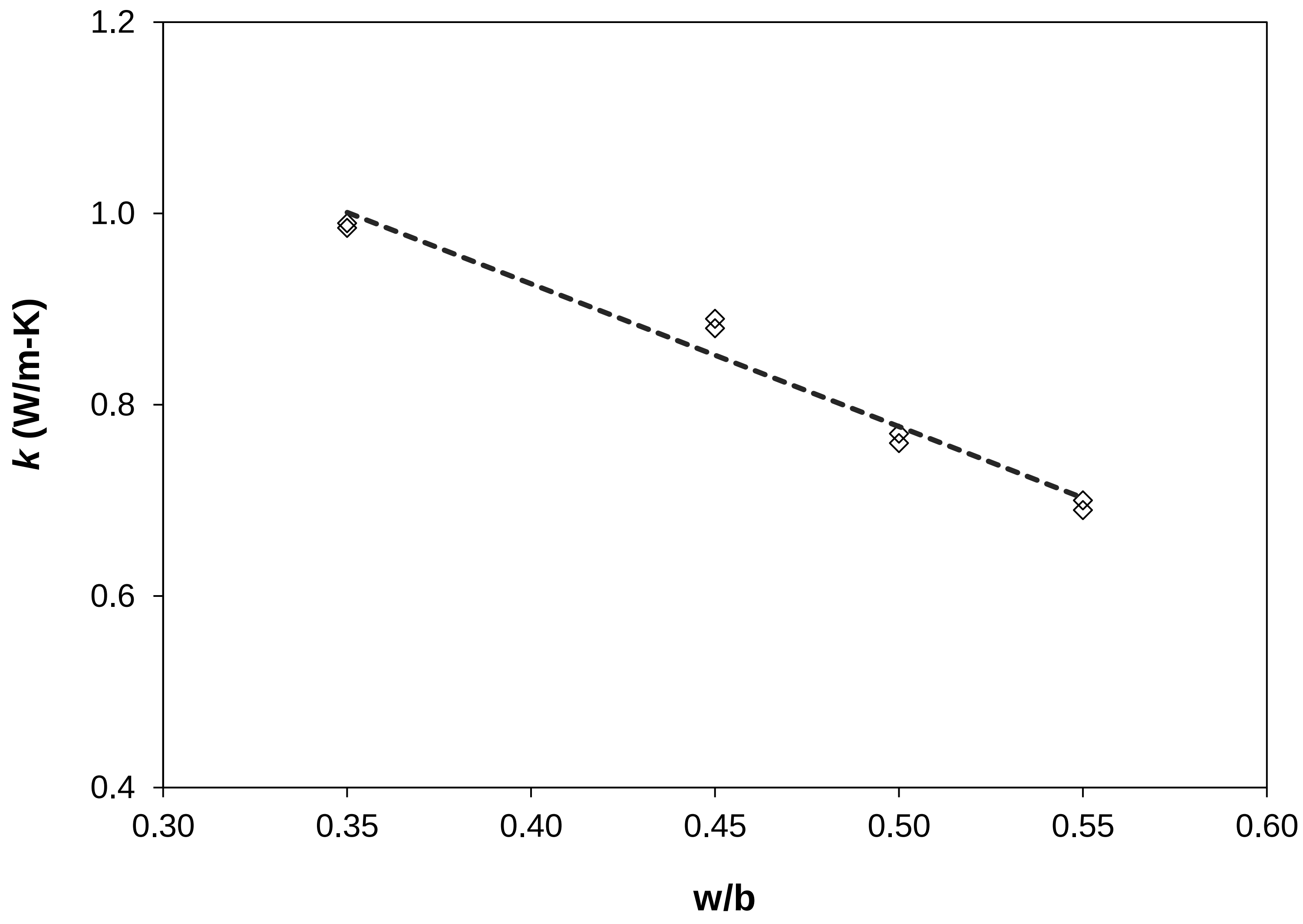
Conductivity (*k*) calculation



$$k = \frac{(VI)\ln(r_2/r_1)}{2\pi L(T_1 - T_2)}$$

Where:
k = thermal conductivity, W/m-K
VI = power input to the heater, W
$\mathbf{r_2}$ = inner radius, m
$\mathbf{r_1}$ = outer radius, m
L = length of the specimen, m
$\mathbf{T_1}$ = average temperature in the core of the specimen, K
$\mathbf{T_2}$ = average temperature on the surface of the specimen, K

Results: Effect of w/b

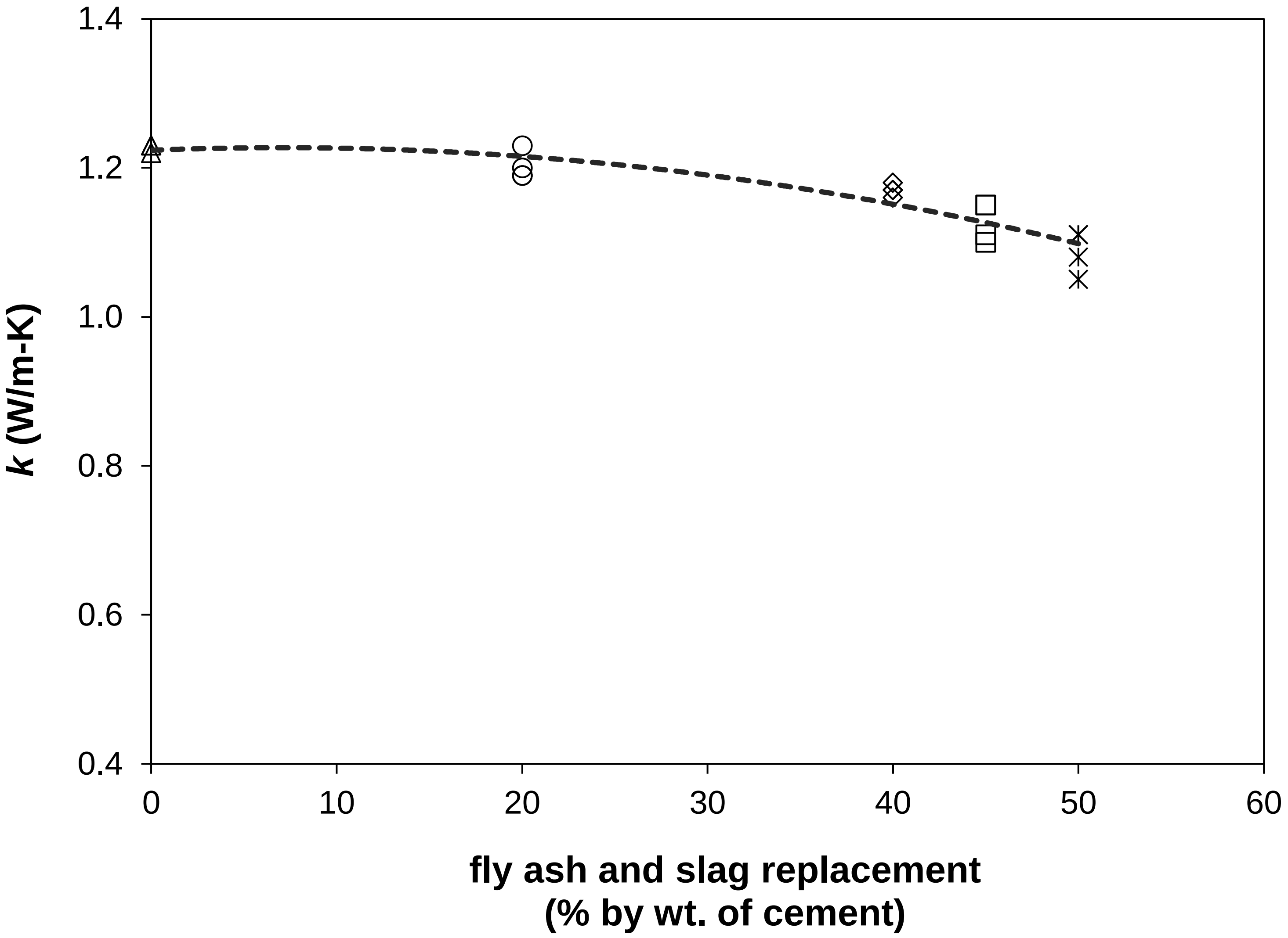


w/b	Dry density (Kg/m^3)	95% CI for mean '*k*' (W/m-K)
0.35	2112.19	(0.98, 0.99)
0.45	2087.21	(0.88, 0.89)
0.50	2075.35	(0.76, 0.77)
0.55	2069.91	(0.69, 0.70)

Observation:

An increase in w/b results in a decrease in *k* of concrete; attributed to increase in porosity

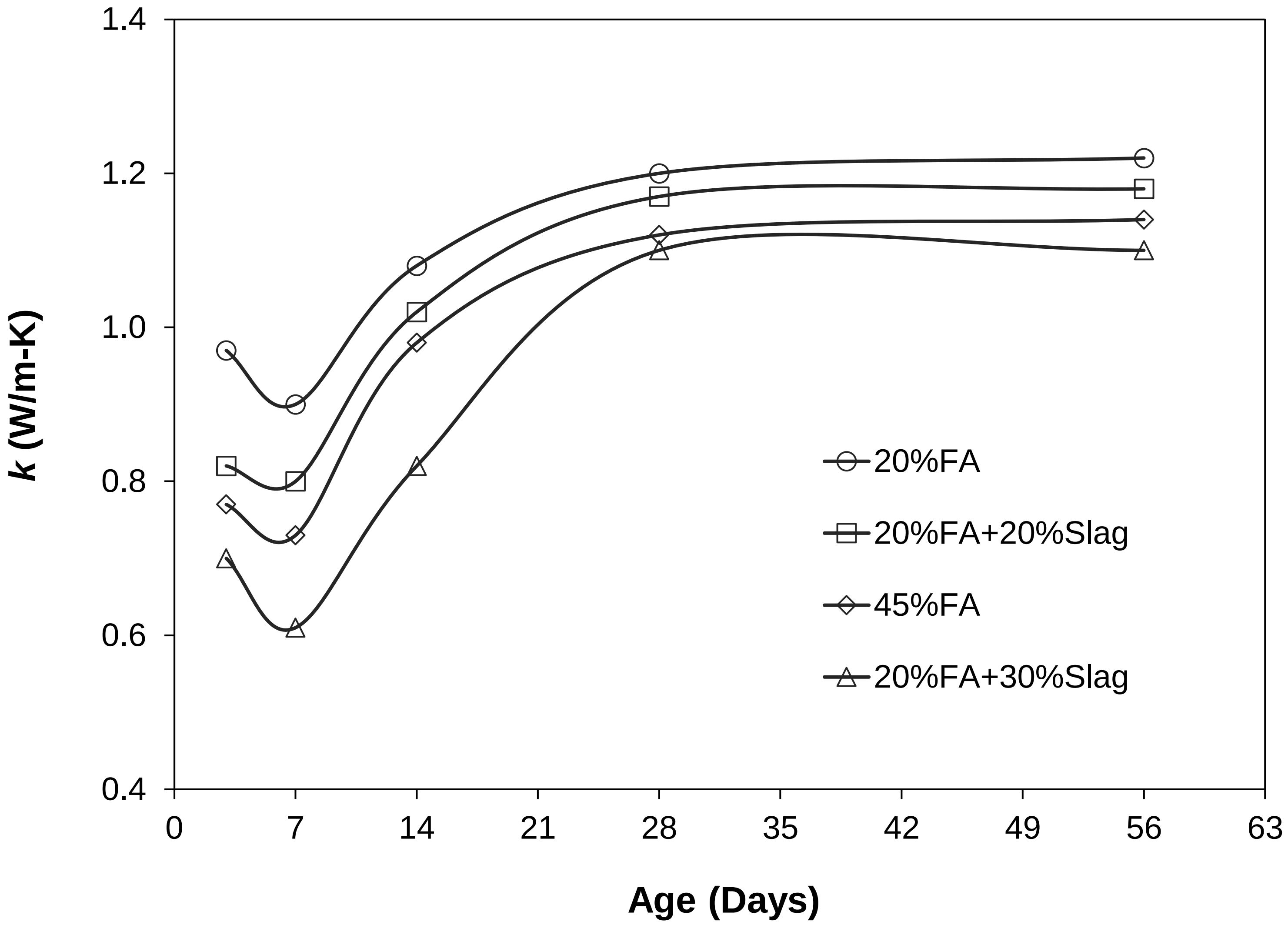
Results: Effect of SCMs



Legend	SCM replacement (%)	Dry density (Kg/m^3)	95% CI for mean 'k' (W/m-K)
△	0	2281.03	(1.22, 1.23)
○	20FA	2278.62	(1.18, 1.22)
◇	20FA+20Slag	2277.98	(1.16, 1.18)
□	45FA	2274.62	(1.10, 1.15)
⋇	20FA+30Slag	2270.55	(1.06, 1.12)

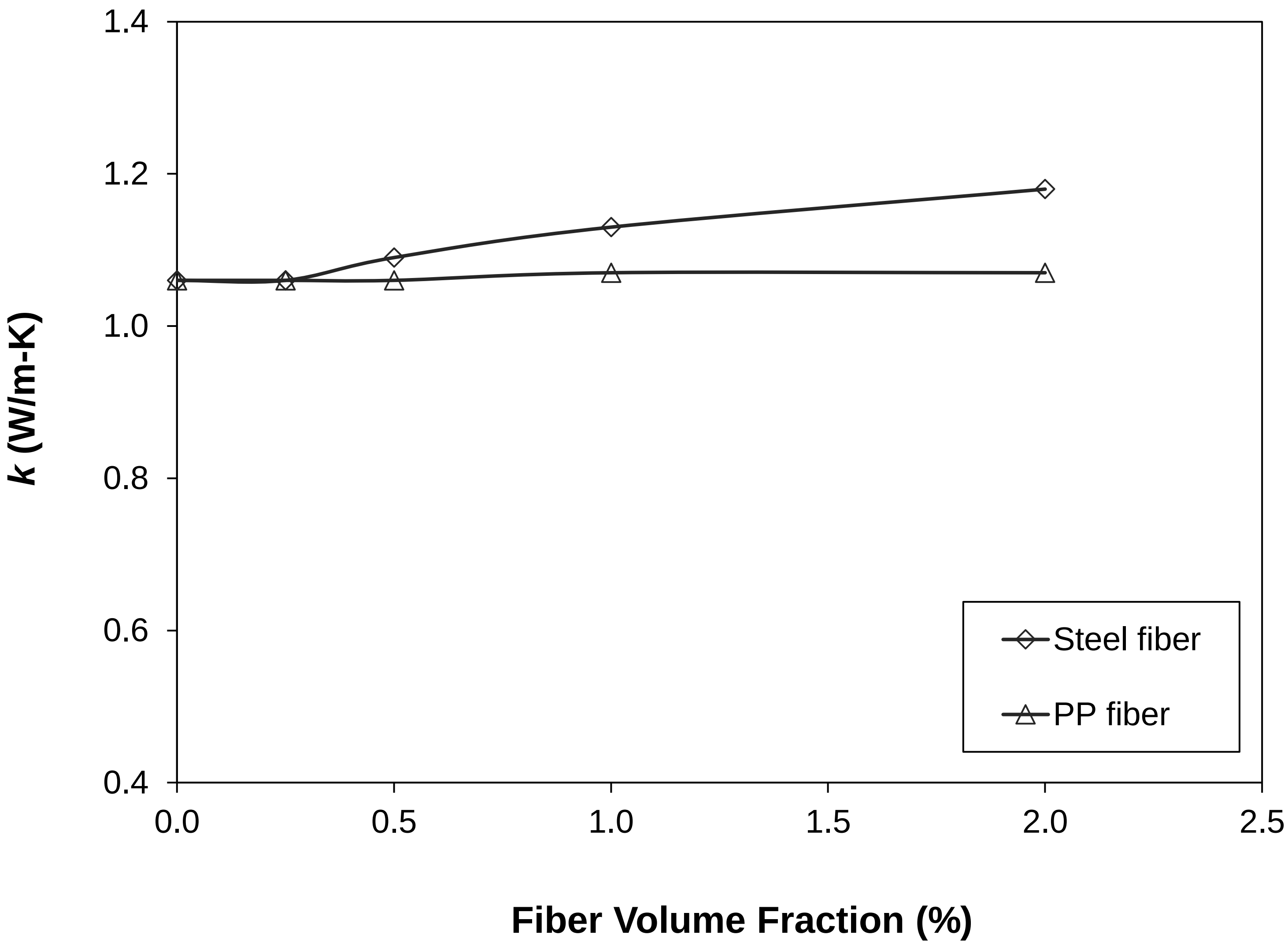
Observation:
With an increase in replacement %, *k* of concrete decreases; attributed to decrease in *k* of slag ad fly ash

Results: Effect of Age



Observation:
K of concrete decreased from 3 to 7 days, then increased from 7 to 28 days and became almost constant after that

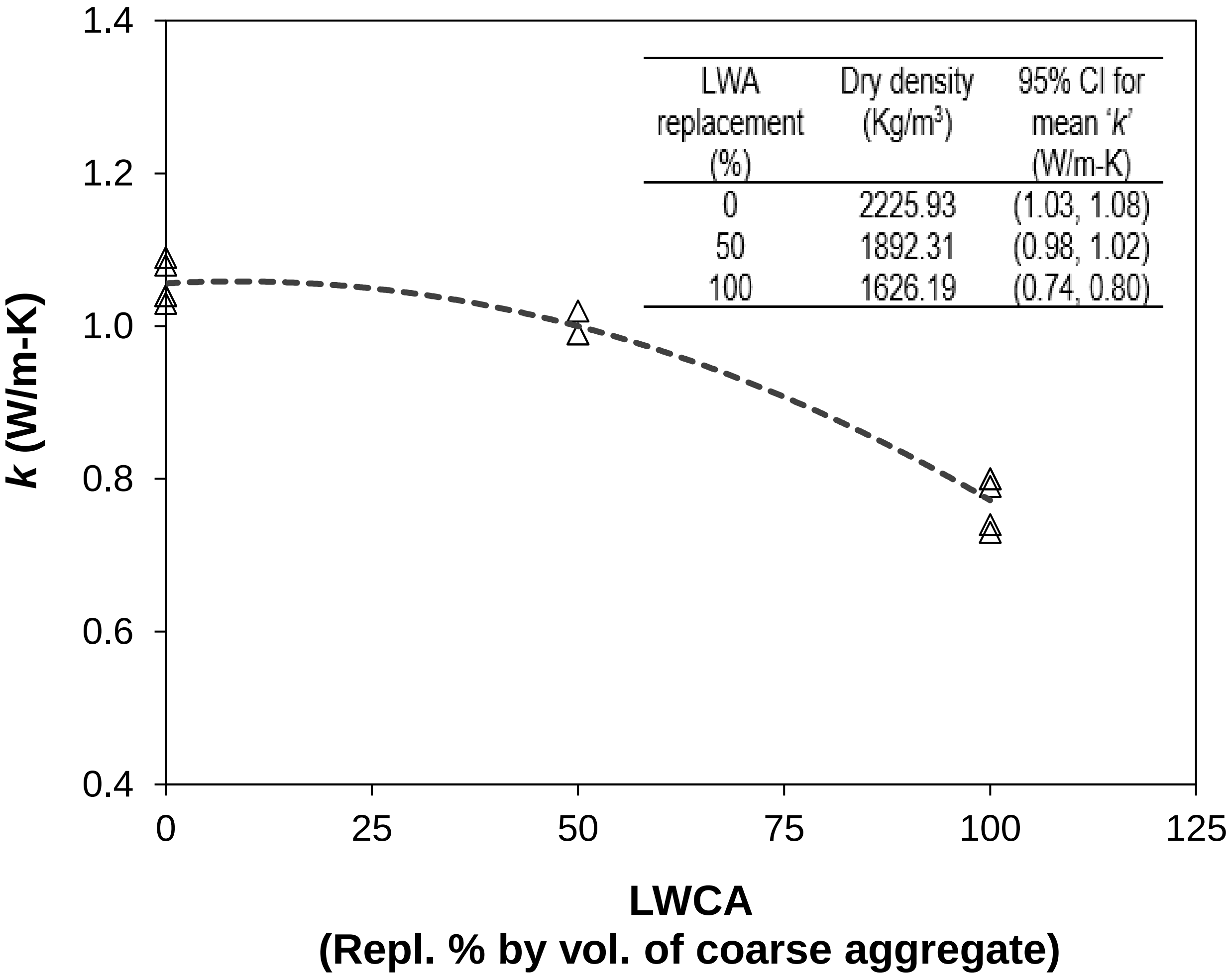
Results: Effect of fibers



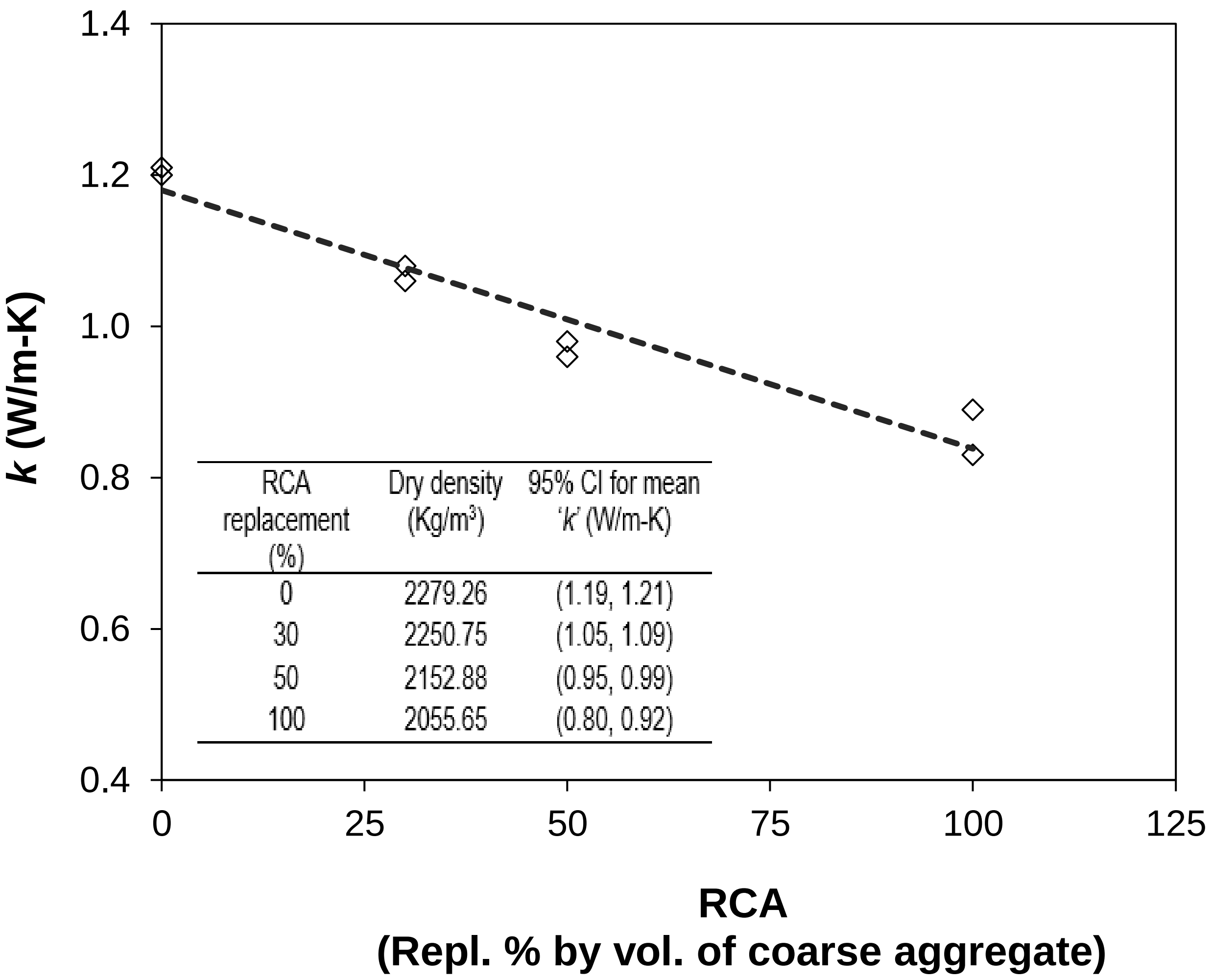
Fiber VF (%)	95% CI for mean 'k' (W/m-K)	
	Steel fiber	PP fiber
0	(1.03, 1.08)	(1.03, 1.08)
0.25	(1.04, 1.08)	(1.04, 1.07)
0.50	(1.08, 1.10)	(1.05, 1.07)
1	(1.10, 1.15)	(1.06, 1.08)
2	(1.16, 1.19)	(1.06, 1.08)

Observation:
Steel fiber (0.25 to 2% volume fraction) increased *k* whereas Polypropylene (PP) fiber had little effect

Results: Effect of aggregates

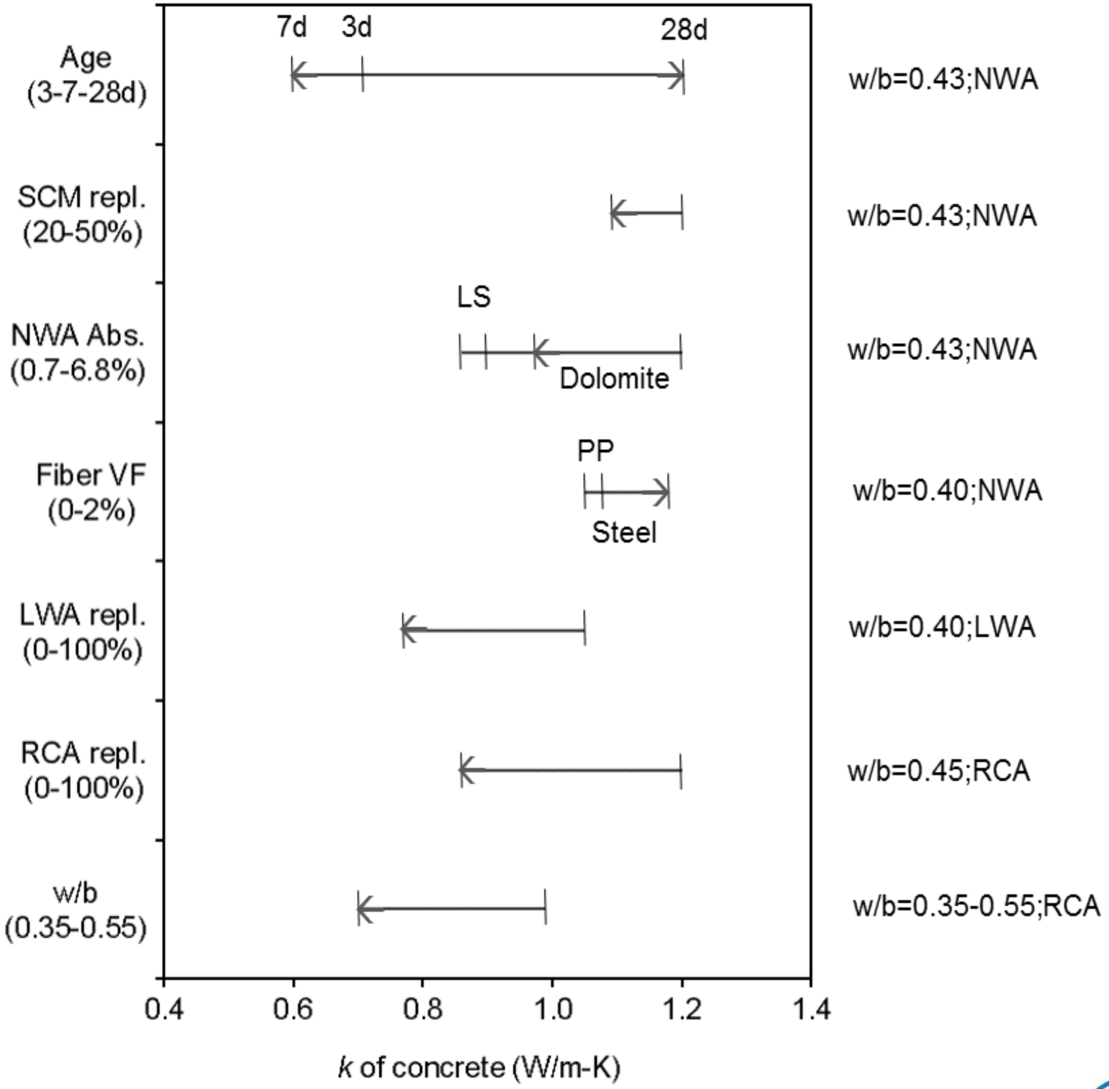


LWA replacement (%)	Dry density (Kg/m^3)	95% CI for mean 'k' (W/m-K)
0	2225.93	(1.03, 1.08)
50	1892.31	(0.98, 1.02)
100	1626.19	(0.74, 0.80)



RCA replacement (%)	Dry density (Kg/m^3)	95% CI for mean 'k' (W/m-K)
0	2279.26	(1.19, 1.21)
30	2250.75	(1.05, 1.09)
50	2152.88	(0.95, 0.99)
100	2055.65	(0.80, 0.92)

Summary


Age
(3-7-28d)
SCM repl.
(20-50%)
NWA Abs.
(0.7-6.8%)
Fiber VF
(0-2%)
LWA repl.
(0-100%)
RCA repl.
(0-100%)
w/b
(0.35-0.55)
7d
3d
28d
LS
Dolomite
PP
Steel
0.4
0.6
0.8
1.0
1.2
1.4
k of concrete (W/m-K)
w/b=0.43;NWA
w/b=0.43;NWA
w/b=0.43;NWA
w/b=0.40;NWA
w/b=0.40;LWA
w/b=0.45;RCA
w/b=0.35-0.55;RCA

Prediction Modeling

Part II: Prediction Modeling

- Background: Empirical models developed using smaller datasets and not including modern materials

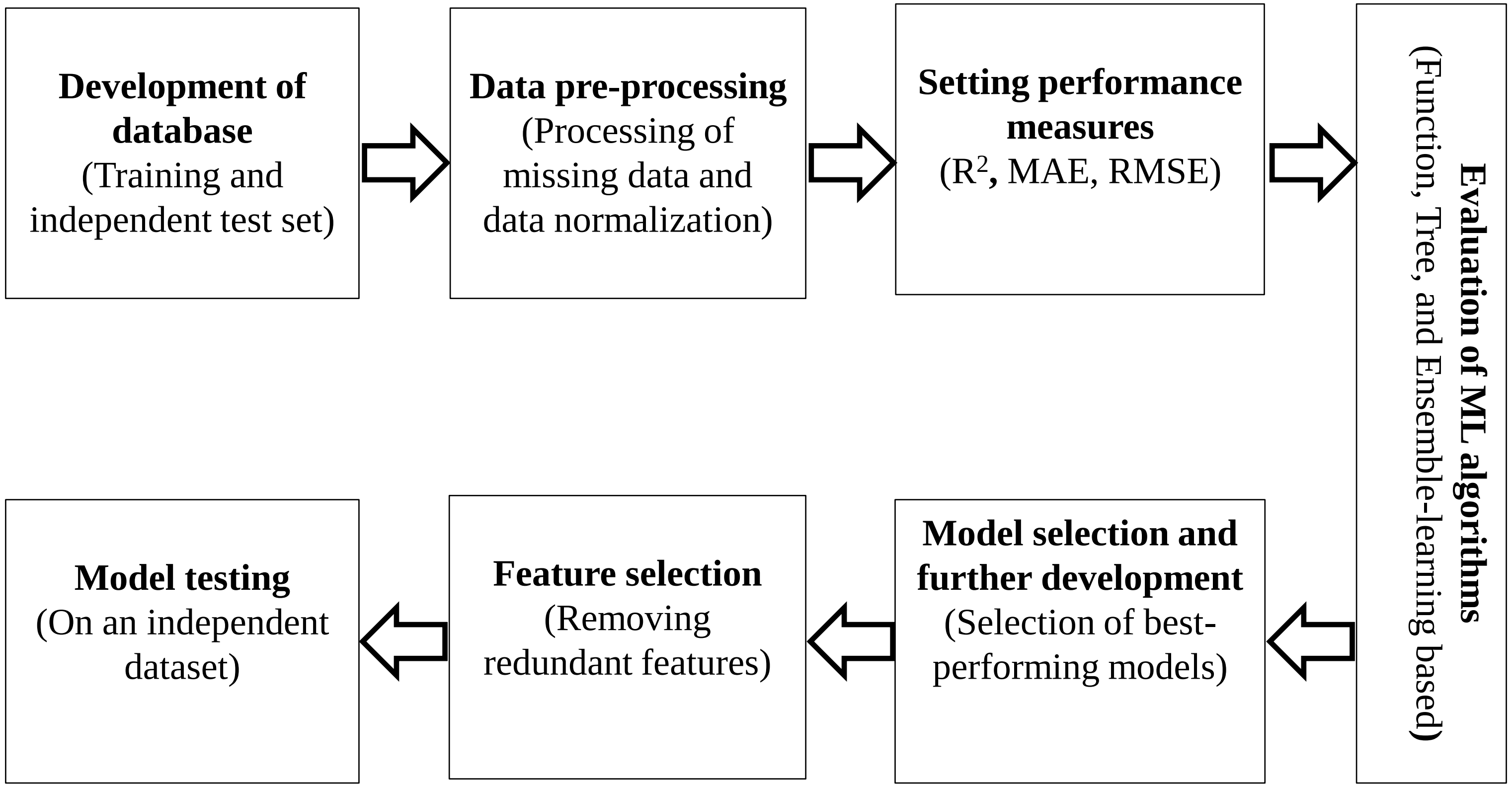
$k = 0.5e^{0.02d}$

$k = 0.0003d - 0.0140$

$k = 0.0236e^{0.0023d}$

$k = 0.0625e^{0.0015d}$

$$k_c = k_{ref}[0.293 + 1.01AG] \times [0.8(1.62 - 1.54(W/C)) + 0.2R_h] \times [1.05 - 0.0025T][0.86 + 0.0036(S/A)]$$



- Objective: Use ML algorithms to develop prediction model for *k* of concrete

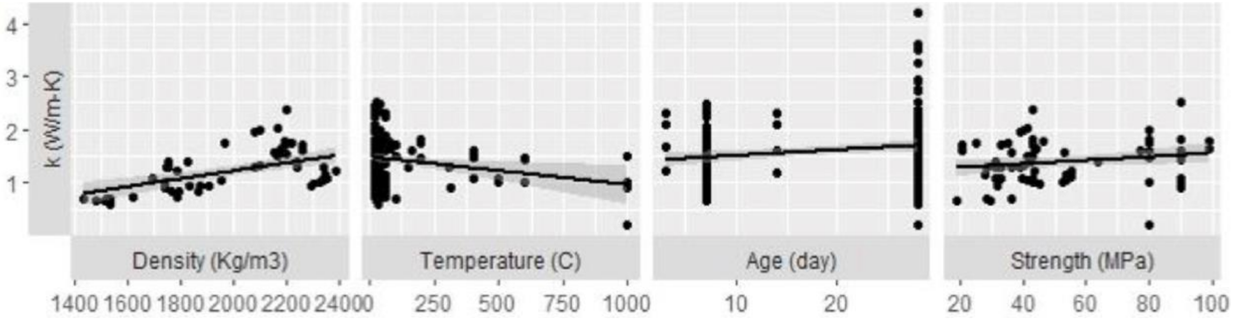
Database

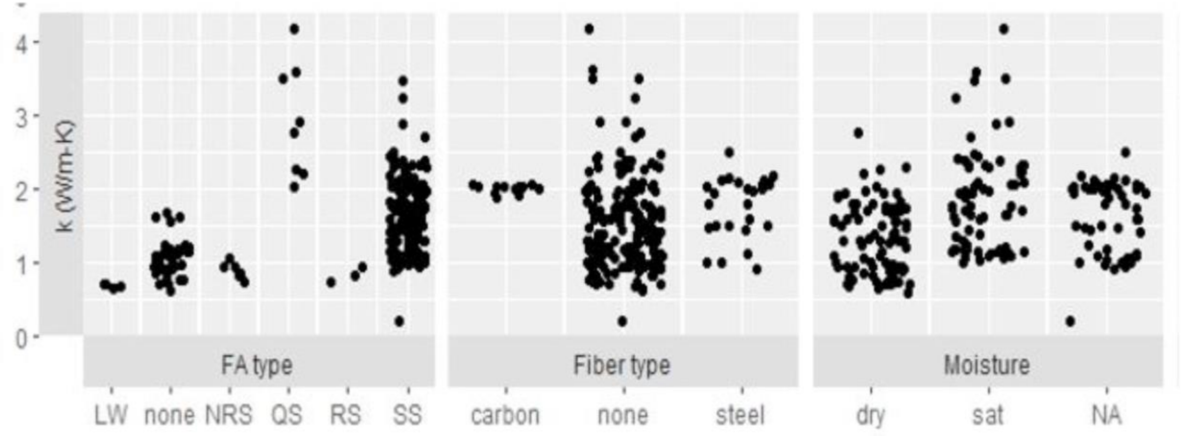
Training set

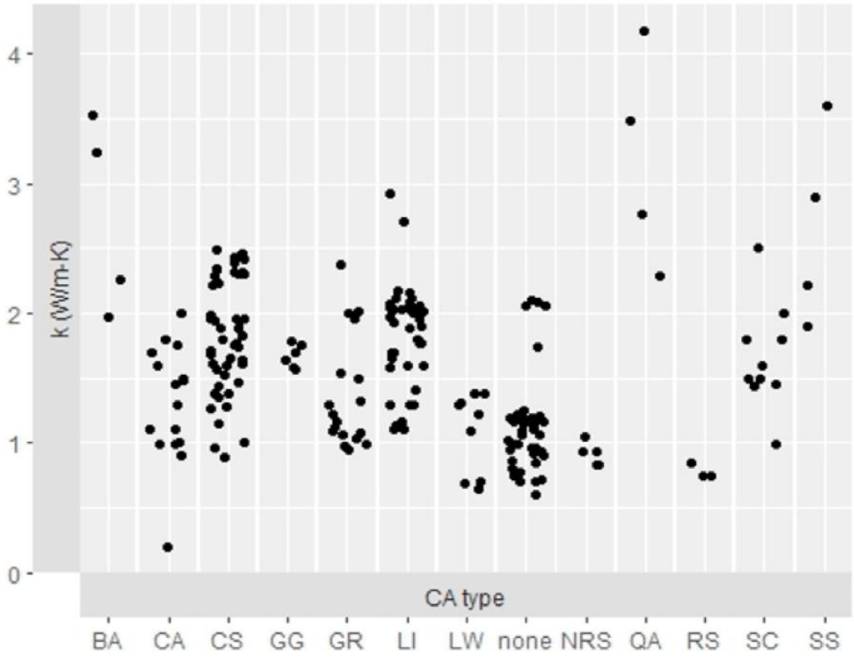
- Developed from published articles, 213 data points, 13 variables
- Mix variables: w/b, %SCM, %wt. of FA, CA, fiber
- Test variables: density, age, strength, temp.
- Categorical variables: moisture condition, type of FA, CA, fiber

Independent test set

- From previous lab study



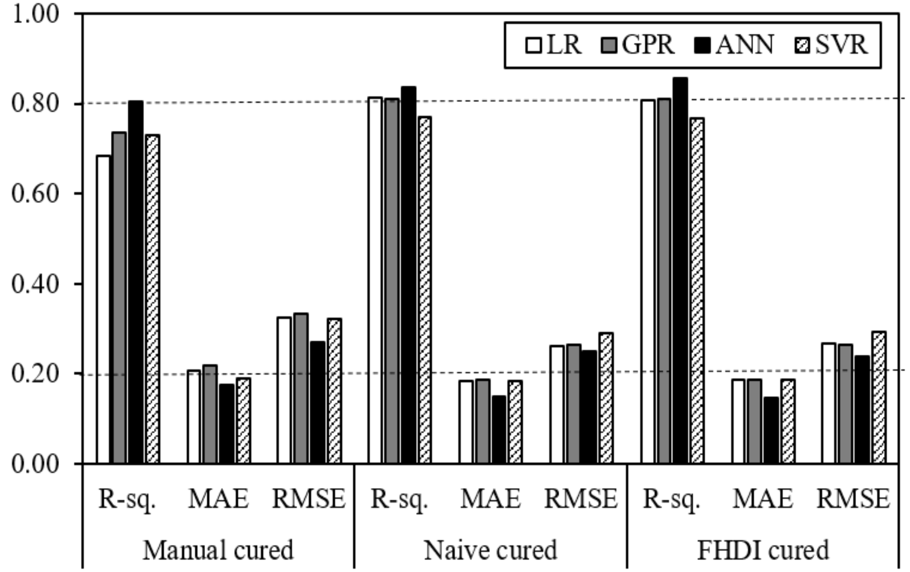




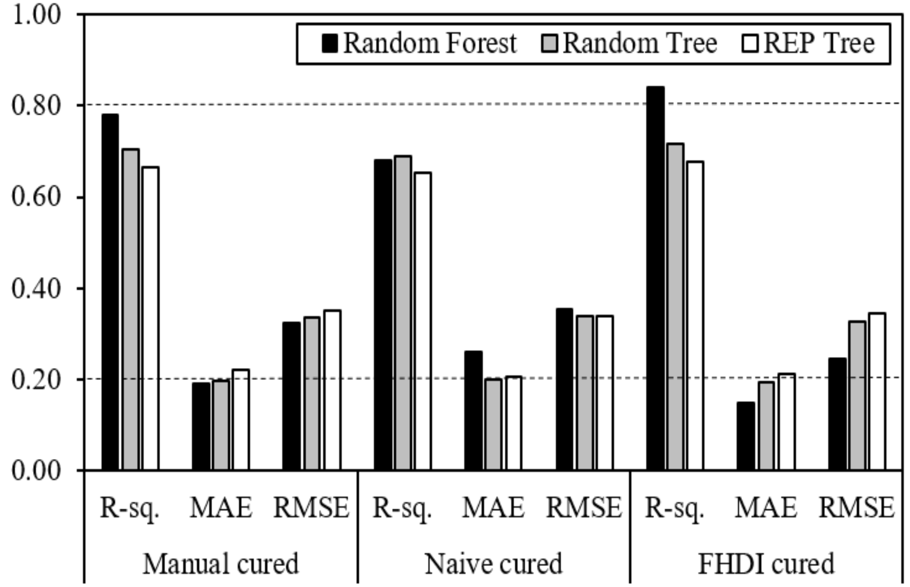
Abbreviations	
FA type	
LW	lightweight
NRS	natural+recycled
QS	quartz sand
RS	recycled
SS	silica sand
CA type	
BA	basalt
CA	carbonate
CS	crushed stone
GG	granitic gneiss
GR	gravel
LI	limestone
LW	lightweight
NRS	natural+recycled
QA	quartzite
RS	recycled
SC	siliceous
SS	siltstone

Performance of Algorithms

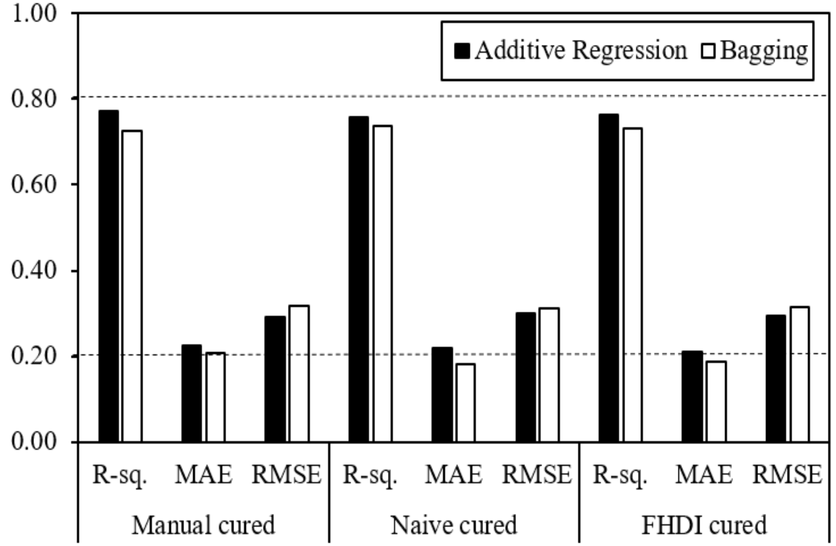
Function-based



Tree-based

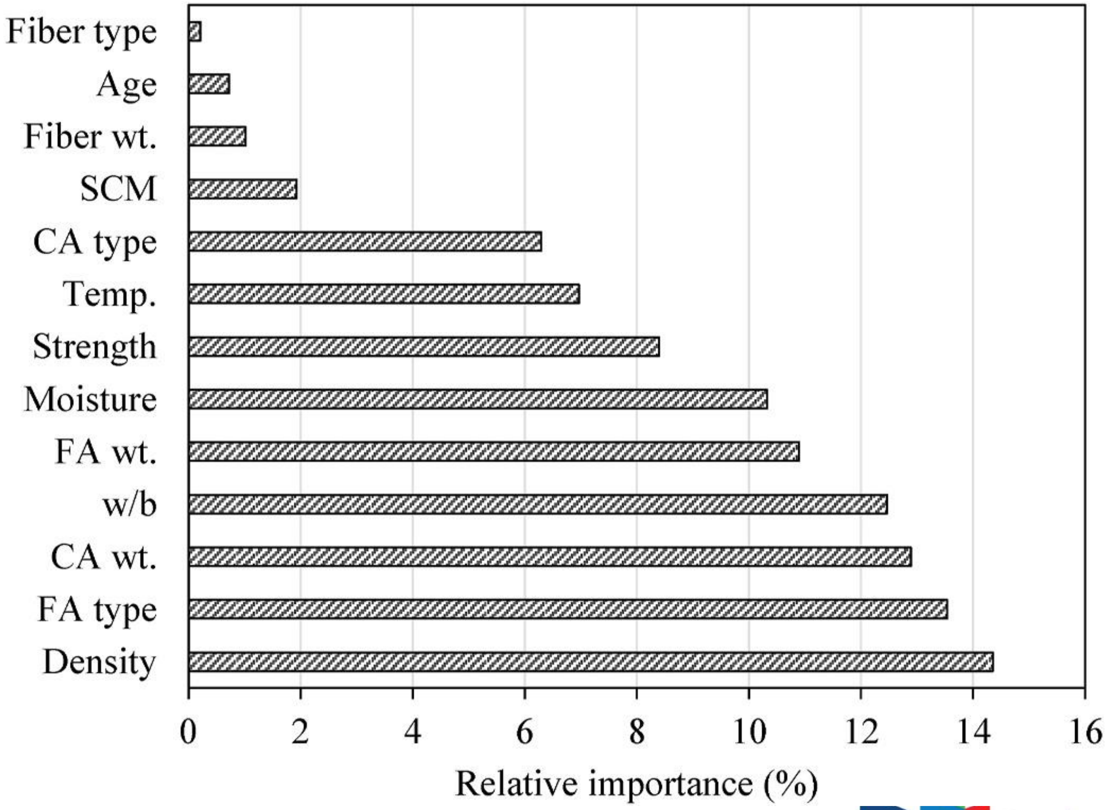


Ensemble-based

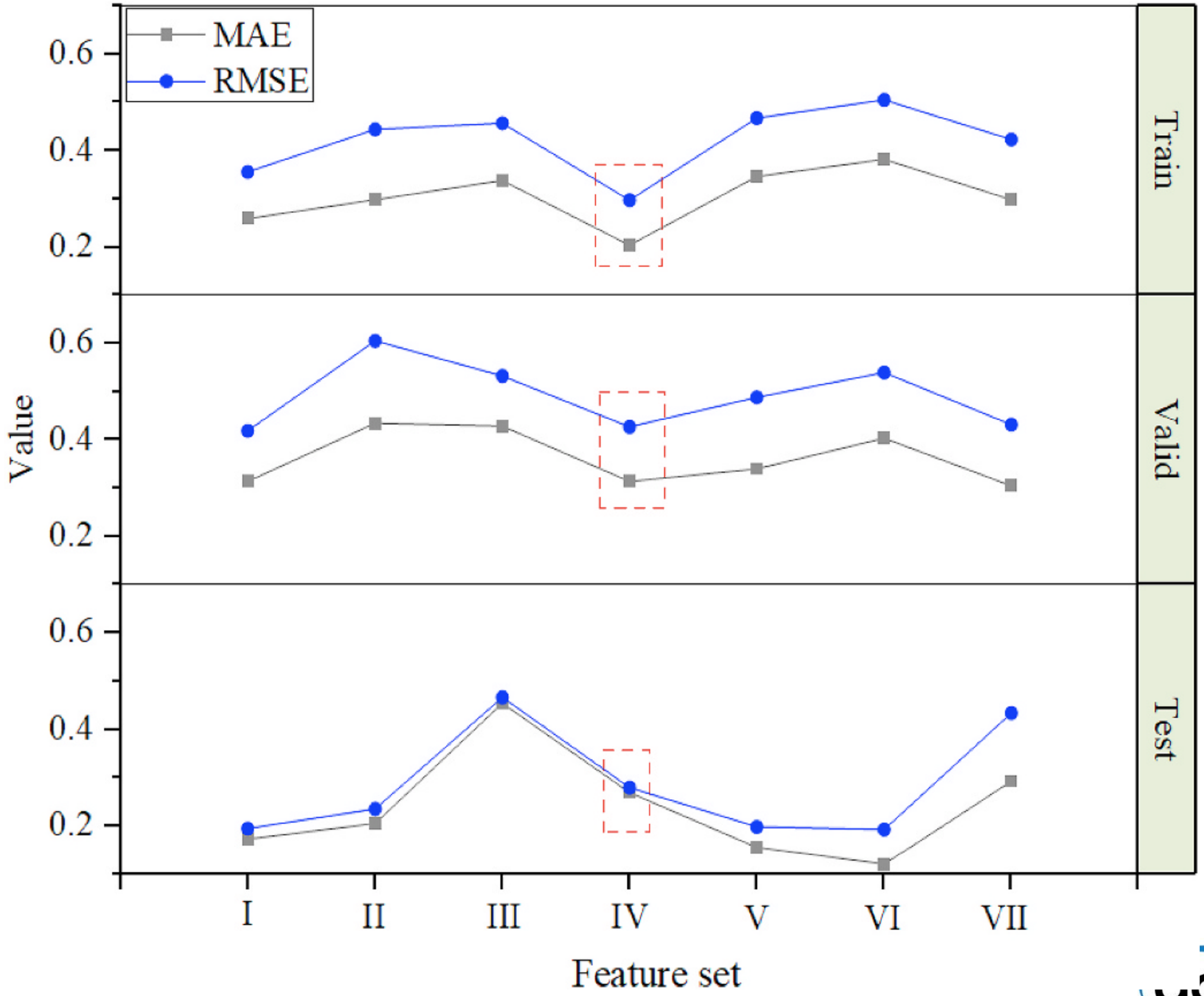


Variable Selection

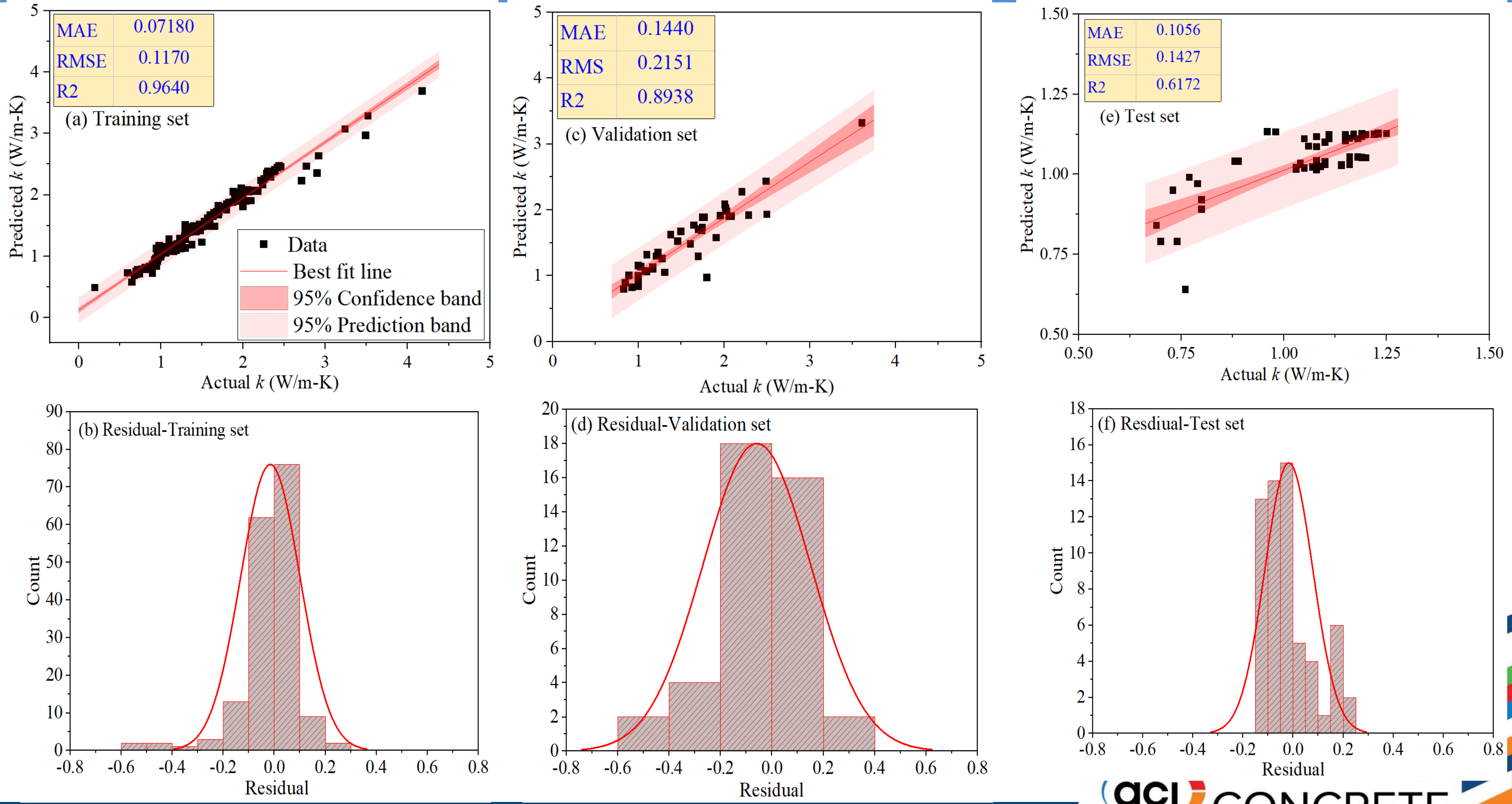
Variable set	Variable category (No.)	Variables
I-all	All (13)	w/b, SCM, w_{FA}, w_{CA}, w_{fiber}, density, temperature, age, strength, moisture, fiber type, FA type, CA type
II-mix	Only mix proportion (8)	w/b, SCM, w_{FA}, w_{CA}, w_{fiber}, fiber type, FA type, CA type
III-non-mix	Non-mix proportion (5)	density, temperature, age, strength, moisture
IV-MDI	Selected from MDI (9)	w/b, w_{FA}, w_{CA}, density, temperature, strength, moisture, FA type, CA type
V-CFS	Selected from CFS (6)	w/b, SCM, w_{CA}, density, temperature, age
VI- PCA +ve	Positive direction from PCA (3)	w/b, moisture, CA type
VII-PCA -ve	Negative direction from PCA (10)	SCM, w_{FA}, w_{CA}, w_{fiber}, density, temperature, age, strength, fiber type, FA type



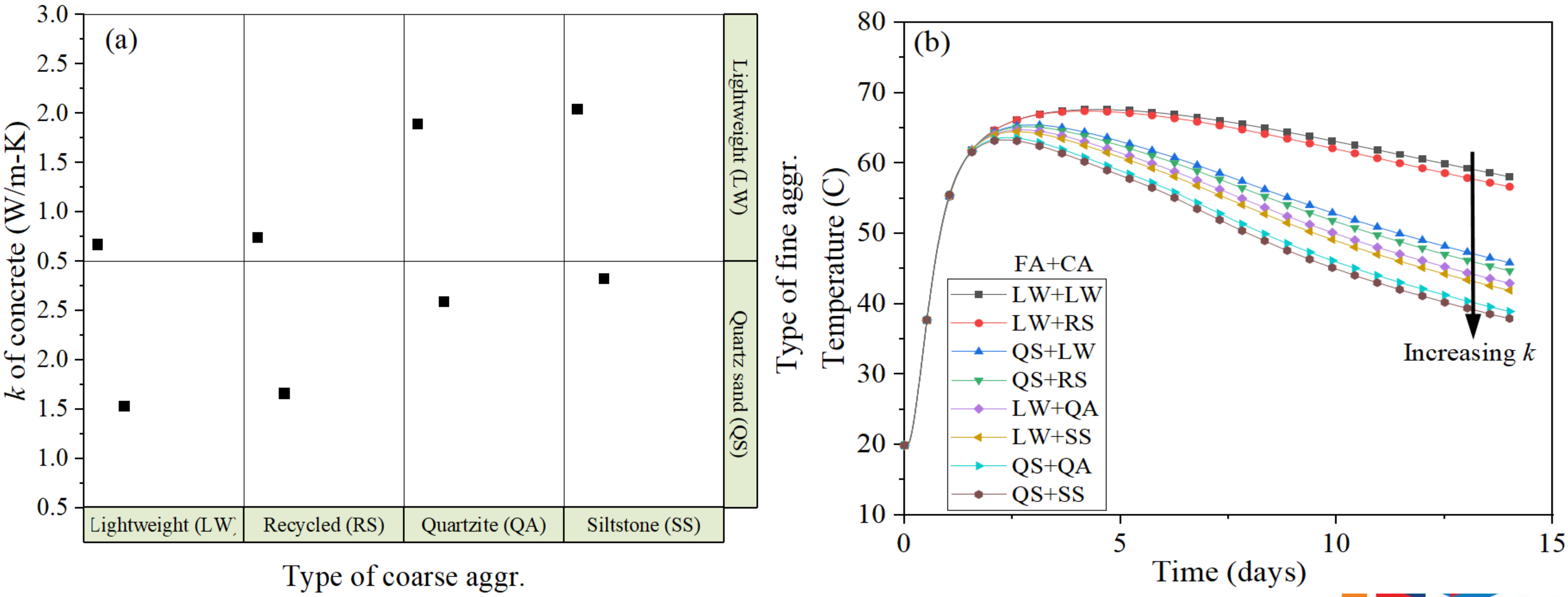
Variable Selection



Developed Model Performance



Case study: Mass Concrete



Conclusions and Future Work

Experimental Measurement

- Simple method of measuring thermal conductivity
- Increase in w/b, and replacement levels of SCM, LWA, RCA reduces *k* of concrete
- Increase in steel fiber volume (beyond a threshold) increases *k* of concrete

Prediction Model

- ML based prediction model for *k* developed
- Missing data imputation method also presented
- Low MAE of 0.07, 0.14, and 0.10 for training, validation, and test set
- Case study in mass concrete proves the applicability of model

Thank you for your attention!!

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