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Predicting the moment capacity of RC slabs with insulation materials exposed to fire by ANN

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Abstract. Slabs prevent harmful effects of fire that may occur in any floor. However, it is necessary to protect the slabs from fire. Insulation materials may be appropriate to protect reinforced concrete (RC) slab from elevated temperature. In the present study, a model has been developed in artificial neural network (ANN) to predict the moment capacity (M_r) of RC slabs exposed to fire with insulation material. 672 data were obtained for ANN model through author's prepared program. Input layer in model consisted of seven input parameters; such as effective depth (d), ratio of d'/d, thermal conductivity coefficient ($k_{insulation}$), insulation materials thickness ($L_{insulation}$), reinforcement area (A_{st}), fire exposure time (t_{exp}), and concrete compressive strength (f_c). The predicted M_r by ANN was consistent with the obtained M_r by author. It is proposed to ease computational complexity in determining M_r using ANN. The effects of using insulation material on the moment capacity in RC slabs were also investigated. Insulating material with low thermal conductivity has been found to be more effective for durability to high temperature.

Keywords: insulation material; fire; slab; reinforced concrete; moment capacity; artificial neural network

1. Introduction

In structures exposed to fire, the temperature rise occurs as a function of time. The RC slabs are also affected from elevated temperature as columns and beams exposed to fire. Increased temperature reduces of both material strengths and M_r. To reduce the harmful effects on the materials due to high temperature, insulation materials or thicker coating materials may be used. But, the insulation material is more convenient to use because of low thermal conductivity of insulation material. To determine the M_r of RC slab with insulation material exposed to fire, the parameters such as the fire exposure time, insulation thickness, thermal conductivity coefficient, temperature inside slab, section properties and material strengths, compression and tension forces in slices, compressive stress depth, and equilibrium of the tension and compressive forces should be obtained. In order to obtain some of these parameters, a large number of calculations are required a large number of calculations. The ANN approach can be an effective tool to predict M_r avoiding complex computations. According to author's knowledge, there were no similar studies in the literature concerning the modeling of M_r of RC slabs with insulation materials exposed to fire using ANN method.

ANN architecture imitates learning ability of human brain. ANN is an interconnected network of processing elements that has the capable to be trained to map a given input into the desired output. ANN can also be used for complex problems involving large amounts of data. It defines the relationships in a data set and applies to problems when it is difficult to solve the problems with conventional mathematical methods.

In recent years, there has been some works on the RC structure elements exposed to fire. Some of them are as follows. Moss *et al.* (2008) described numerical modelling of fire behaviour of RC slabs. Erdem (2008) examined effect of high temperature on the M_r of RC slabs with one layer. It has been shown that the effect of high temperature on the M_r of RC slab was reduced by the concrete cover. ANN method was used to account the M_r of RC sections by many researchers. Some of them were about estimation of the performance FRP beams and slabs (Flood *et al.* 2001, Pannirselvam *et al.* 2008, Bisby and Kodur 2007), the shear and moment capacity (Rao and Babu 2007), and the M_r and reinforcement area (Keleşoğlu 2006) of RC beams, and the optimum depth (Rafiq *et al.* 2001) of RC slabs, the M_r of RC slabs in fire (Erdem 2010) and etc.

Halwatura and Jayasinghe (2008) studied thermal performance of RC roof slabs with insulation located in warm, humid climatic conditions. It was shown that insulated roof slabs could improve indoor conditions. Williams *et al.* (2006) investigated performance in fire of insulated FRP slabs. Erdem (2010) investigated effect of insulation materials on the M_r of RC slabs exposed to fire.

Balaji *et al.* (2016) presented a finite element analysis for evaluating the fire response of reinforced concrete slabs. Nigro et al. 2005 provided a conceptual approach to fire safety checks for bending moment resistance of FRP-RC members. Firmo *et al.* (2015) presented a state-of-the-art review on the fire performance of FRP-strengthened RC structural elements. Uygunoğlu *et al.* (2016) conducted tests to determine combustion characteristics of insulation boards with different plaster thicknesses of 2, 4, 6 and 8 mm. Silva and Landesmann (2013) presented a numerical investigation on a unidirectional coupling procedure between fluid and

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thermo-mechanical modeling for assessing composite steel-concrete structures under fire conditions.

There is no similar study in predicting the M_r of RC slabs with insulation material exposed to fire by using ANN. In the present study, a model for the M_r of RC slabs using insulation materials exposed to fire was developed using ANN. Each slab was divided into small slices. Then, temperature and material strengths in each slice were determined. Heat transfer through the slab was modelled as one dimensional and steady. Heat transmission from layers consisting of covering material, concrete plane slab, insulation materials and coating, etc., was obtained by using a simulation of electrical flow. The M_r of RC slabs was determined from force equilibrium. The obtained M_r by author for the RC slabs using insulation materials exposed to fire were crosschecked with the M_r predicted by the ANN model to verify reliable application of the ANN model. This study explores the feasibility of using ANN to create an intelligent model for prediction of the M_r of RC slabs with insulation materials exposed to fire. In addition to, the effects on the M_r of insulation materials used in the description of the ANN model are been examined using ANN model.

2. Moment capacity of the RC slab with insulation materials in fire

After the temperature distribution and fire exposure time in the slab were known, the effects of high temperature may be calculated on material strengths and M_r. The negative effects of high temperature can be decreased by reducing the surface temperature of the slab. If the surface temperature of RC slab could be lowered, the materials used in slabs may be less affected. The insulation material to protect the RC slab from the fire was used in this study.

To obtain the M_r of RC slabs with insulation materials exposed to fire, fire exposure time, rising temperature, temperature-fire exposure time relation, reduced material strengths and temperature distribution should be obtained. Then, the compression and tension forces in slab should be calculated. The moment calculated when there is the equilibrium of forces is the M_r of the RC slab in fire. The mentioned calculations are discussed in the next sections.

2.1 Temperature time relation

ISO834, BS476, ASTM119, NFPA251, and the Eurocode1 present time-temperature relations. ISO834 is used in this study. Temperature function is as follows

$$T = 345 log_{10}\left(8t_{exp} + 1\right) + T_a \qquad (°C) \qquad (1)$$

where T_a is ambient temperature (°C) and t_{exp} is fire exposure time (minute).

2.2 Rebar and concrete strengths at high temperature

The reduced material strength at high temperature should be taken into account in the calculations. The tensile

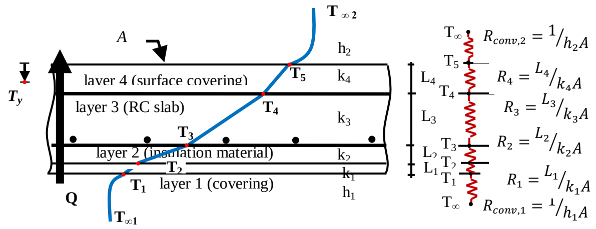

Fig. 1 Thermal resistance network

strength of reinforcement and compressive strength of concrete can be calculated by the relationship given in Eurocode2 .

$$k_{steel} = \frac{f_{suT}}{f_{su\,20°C}} \qquad (2)$$

$$k_{conc} = \frac{f_{c\,T}}{f_{c\,20°c}} \qquad (3)$$

where $f_{su\,T}$ and $f_{su\,20°C}$ are the steel tensile strength at the elevated temperature and at 20°C, respectively, k_{steel} is reduction factor for steel tensile strength, f_{cT} and $f_{c20°C}$ are the concrete compressive strength at elevated temperature and at 20°C, respectively, k_{conc} is reduction factor

2.3 Heat conduction in multilayer RC slabs

Temperature change in the direction of thickness of slab is large. If the air temperature in both the surface of the slab is constant, then heat transfer from inside slab could be modeled as one-dimensional and steady. For steady-state operation, there is no change in the temperature of the slab with time at any point. The rates of heat transfer into the slab should be equal to the rates of the heat of transfer out of it. The rate of heat transfer through layers should be constant: $Q_{cond,slab}$= $Q_{conv,slab}$=constant.

In practice, slab consists of layers having different material properties. The thermal resistance concept may be used to obtain the rate of steady heat transfer from inside composite slabs. This is done by noting that the conduction resistance of each layer (L/kA) is connected in a series and by using electrical analogy, which means dividing the temperature difference between known temperatures on both surfaces of the slab by the total thermal resistance between them, as given in Eq. (4) (Çengel 1998).

Consider a slab consisting of four layers (a ceramic coating, RC slab, insulation material, covering). The rate of steady-state heat transfer from inside this four-layer composite slab can be explicited as shown in Fig. 1 (Erdem 2010)

$$Q = \frac{T_{\infty 1} - T_{\infty 2}}{R_{total}} \qquad (4)$$

$$\begin{aligned} R_{total} &= R_{conv,1} + R_{slab,1} + R_{slab,2} + R_{slab,3} + R_{slab,4} + R_{conv,2} \\ &= \frac{1}{h_1A} + \frac{L_1}{k_1A} + \frac{L_2}{k_2A} + \frac{L_3}{k_3A} + \frac{L_4}{k_4A} + \frac{1}{h_2A} \end{aligned} \qquad (5)$$

where R_{total} is total thermal resistance, k_i is thermal conductivity coefficient, h_i is convection heat transfer coefficient, L_i is thickness of material in slab and A is the surface area. The subscripts 1, 2, 3 and 4 in R_i relations above indicate the first, second, third and the fourth layers, respectively.

If Q is known, a surface temperature T_j can be calculated from

$$Q = \frac{T_i - T_j}{R_{total}} \tag{6}$$

where T_i is a known temperature at location i. The thermal resistance concept is limited to systems from inside which rate of heat transfer Q remains constant, that is, to systems involving steady heat transfer with no heat generation within the medium.

2.4 The use of insulation materials in RC slabs

Insulation materials should be used to protect RC slabs exposed to fire. An insulation material should have durability under fire and low thermal conductivities. There are some properties as water vapour, thermal conductivity, diffusion resistance, corrosion risk and fire durability of insulation materials. Additionally, the applicability of the material, low price and availability of materials are other important factors (Erdem 2010). In the literature, glass fiber (k=0.040 W/mK, usable up to 250℃), mineral wool (k=0.040 W/mK, usable up to 700℃), ceramic fiber (k=0.20 W/mK, usable up to 1500℃), calcium silicate (k=0.055 W/mK, usable up to 1000℃) and perlite (k=0.050 W/mK, usable up to 1000℃) are suggested to be used as fire insulation materials. Lower thermal conductivity, thicker insulation material, maximum temperature reached and strength of insulation material positively affect the Mr of RC slabs with insulation materials exposed to fire.

2.5 Moment capacity of the RC slab with insulation materials in fire

To obtain the M_r, the RC slab is divided into N slices and temperature, reduction factor and material strengths are determined for materials in each slice. Tension force equation is written as

$$F_s = \sum_{i=1}^{M} k_{si} f_y \tag{7}$$

Compressive force is obtained by summing the compressive forces.

$$F_c = 0.85 \sum_{i=1}^{a/\Delta y} k_{ci} f_c \Delta y \tag{8}$$

If the tension and compressive forces in RC slab are in equilibrium, Eqs. (7) and (8) are equal. If not, the compressive depth is increased progressively until equilibrium and the calculation is repeated. When the forces are in equilibrium, the M_r can be determined as

$$M_r = 0.85 \sum_{i=1}^{\frac{a}{\Delta y}} k_{ci} f_c \Delta y \left(d - \frac{\Delta y}{2} - i\Delta y\right) \tag{9}$$

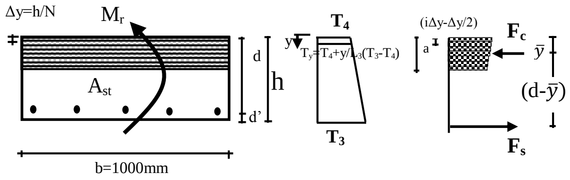

Fig. 2 Mesh grid of topographic model

where f_c is concrete compressive strength at 20℃, f_y is steel yielding strength at 20℃, and F_s and F_c are tensile and compressive forces in slab, respectively. M_r is the moment capacity of RC slab with insulation materials. k_{ci} and k_{si} are the reduction coefficients of material strengths for each slice inside slab (Fig. 2).

3. Artificial neural network

ANN is an estimation tool. ANN process is similar the human brain's information processing format. ANN involves a large amount of interconnected processing elements that can be trained to map a given input into the desired output. ANN has got input, hidden and output layers. The back-propagation (BP) learning algorithm learns by checking the output with the target. The mean square error (*MSE*) and the correlation coefficient (*R)* are used to check the accuracy of the trained network. A multi-layered perception (MLP) transforms i inputs into k outputs through non-linear mapping functions (Erdem 2010, Kahraman *et al.* 2006).

The used sigmoid activation function is written as follows

$$x_o = \frac{1}{1 + \exp(-\sum x_h w_{ho})} \tag{10}$$

An error using the differences between the determined output x_o and the target value t_o is as follows

$$E = \frac{1}{2} \sum_{S}^{D} \sum_{O}^{P} \left(t_o^{(s)} - x_o^{(s)}\right)^2 \tag{11}$$

where D and P are the number of data and output neurons, respectively.

The aim of the training process is to decrease the error to ensure the interconnection between layers. The weights are arranged using a BP algorithm. The MLP starts with a random set of initial weights. After that the training process continues through a set of w_{ih} and w_{ho} are optimized.

4. ANN model for the RC slabs with insulation materials in fire

In this study, it is proposed to develop a model for predicting the M_r of RC slabs with insulation material by ANN. The data needed for process was calculated for different thermal conductivity coefficient, insulation thickness, material strengths, geometric properties and fire time. Temperature, steel and concrete properties in each

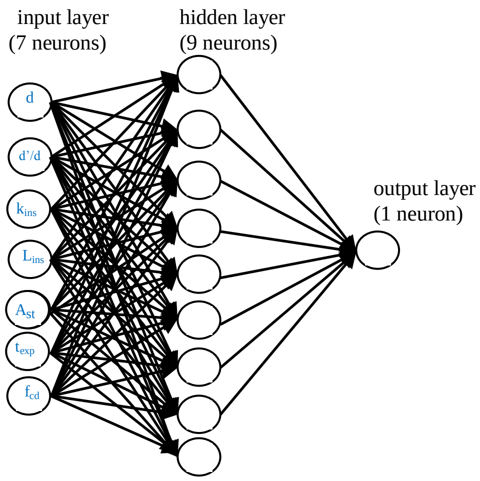

Fig. 3 The archtitecture of ANNs

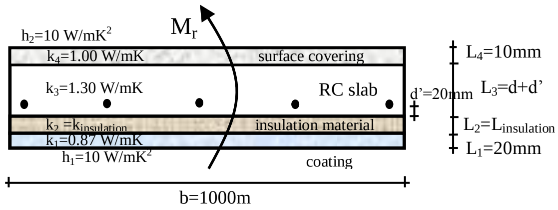

Fig. 4 RC plane slab with four layers

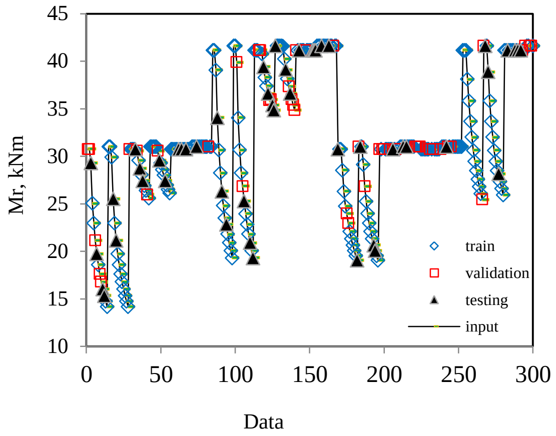

Fig. 5 Randomly selected data for ANN

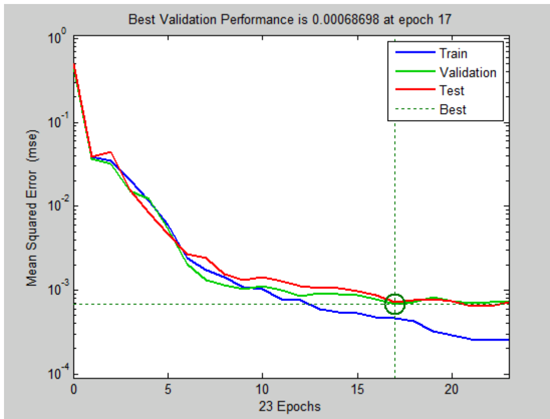

Fig. 6 Performance of ANN

slice were determined with slicing. Forces in all slices were calculated using the deterioated properties of concrete and steel. Heat transfer through slab was modeled as one-dimensional and steady. Heat transmission inside the RC slab with insulation material, covering and surface covering was computed using a simulation of electrical flow. The M_r of RC slab was also determined from tensile and compression forces equilibrium. An ANN model with 7 neurons in the input layer, 9 neurons in the hidden layer and 1 neuron in the output layer has been selected. The input parameters were slab depth (d), ratio d'/d, thermal conductivity coefficient ($k_{insulation}$), insulation materials thickness ($L_{insulation}$), steel area (A_{st}), fire exposure time (t_{exp}), and concrete compressive strengt (f_c). The tensile strength of rebar (f_y) and the convection heat transfer coefficient (h_1=h_2) were taken as constant. The output parameter was selected as the M_r of RC slabs with insulation material in fire. In the present study, the Levenberg-Marquardt network (LM) was selected as the learning algorithm. The architecture of the ANN is shown in Fig. 3.

The data obtained using the process given in section 2 from 672 RC slabs exposed to fire were used for the prediction the M_r with ANN model. The slab in Fig. 4 was analysed for different materials, section properties, thermal conductivity coefficients and insulation material thickness. In order to calculate the rising temperatures and the deteriorated material properties caused by fire, the slab was divided into slices. The values in the input layer were taken as d (130, 150 mm), d'/d (0.133 and 0.154), A_{st} (678.58 and 923.63 mm^2), $k_{insulation}$ (0.001, 0.05, 0.20 W/mK), t (0, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120 minute) and f_c (25, 30 N/mm^2). The tensile strength of rebar (f_y) was taken as 365MPa. The convection heat transfer coefficient (h_1=h_2) was taken constant as 10W/m^{2}K. Other values used are given in Fig. 4. The ANN model was developed using the Matlab software for the present problem. The 672 data were used in the analyses. They were divided into data for training (70% of data), testing (15% of data) and validation (15% of data).

The values selected randomly for three stages are shown in Fig. 5. They were normalised by maximum parameter values. The training patterns were randomly input into the network to train it. In this way the ANN was applied to identify the M_r of a given data.

The change of MSE for LM network training, testing and validation stages are illustrated in Fig. 6. The MSE value reduces quickly with the increasing of epoch. The result is acceptable for MSE, according as test and validation set error have similar features. The correlation between the calculated M_r using the program developed by the author and the estimated M_r by the ANN is shown in Fig. 7. R^2 was 0.9873 in training stage and 0.9788 in testing stage. It is clear that the ANN model is extremely feasible

Table 1 The ANN model statistical values

	Number of data	MSE	R^2
Training	470	0,0004647	0.9873
Testing	101	0,0007262	0.9788
Validation	101	0,0006870	0.9741

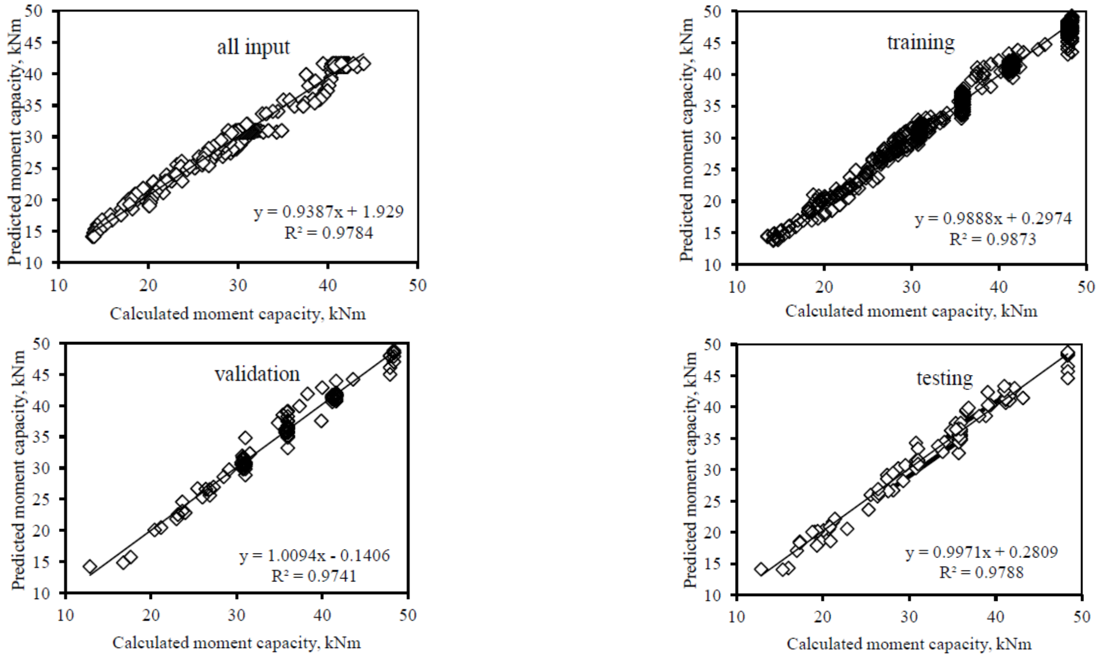

Fig. 7 The correlations for input, training, testing and validation

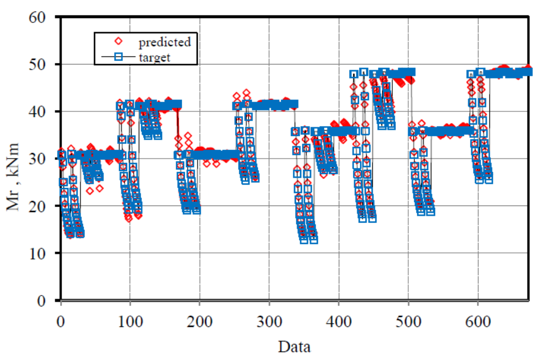

Fig. 8 The target and predicted moment capacities

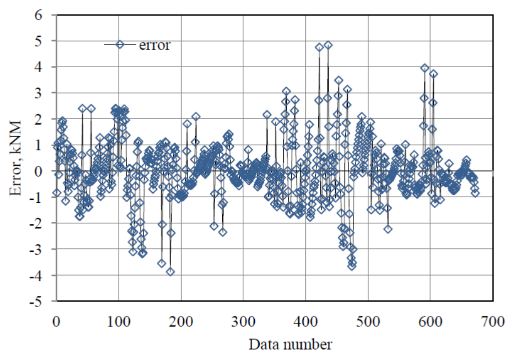

Fig. 9 The difference between target and predicted moment capacities

for obtaining the M_r from the performance and generalization capacity of ANN. Table 1 shows R^2 and *MSE* for the obtained results.

The target and predicted M_r are shown in Fig. 8. The errors between the target and output M_r are as shown in Fig. 9. As can be seen in Fig. 9, the ANN model may estimate the M_r. Therefore the results from ANN may be used for the estimation of the M_r of RC slabs exposed to fire with insulation material.

The first 56 data out of the total 672 data are given in Table 2. The results represent that ANN was succesful in both learning and testing.

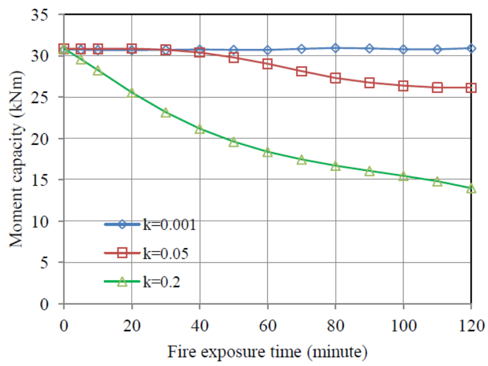

Fig. 10 Moment capacities for different thermal conductivity coefficients and constant insulation material thickness (10 mm)

5. Analysis results

The effects on the M_r of RC slabs with insulation materials exposed to fire were investigated using trained ANN. In the first case, different thermal conductivity coefficients and constant insulation thickness were considered. In this case, thermal conductivity coefficient was taken as 0.001, 0.05 and 0.20W/mK, respectively and the insulation material thickness was taken as 10mm, and the M_r of RC slab with insulation material was predicted by the ANN model. The predicted moment capacities are shown in Fig. 10. If the value of thermal conductivity coefficient was 0.20 W/mK, the slab was quickly affected

Table 2 The target and predicted M_r

Data Number	d mm	d'/d	f_c MPa	$k_{insulation}$ W/mK	$L_{insulation}$ mm	A_{st} mm^2	$t_{exposure}$ minute	$M_{r\ target}$ kNm	$M_{r\ predicted}$ kNm
1	130	0.153846	25	0.2	10	678.58	0	30.76	31.58
2	130	0.153846	25	0.2	10	678.58	5	30.76	29.84
3	130	0.153846	25	0.2	10	678.58	10	29.29	28.22
4	130	0.153846	25	0.2	10	678.58	20	25.02	25.18
5	130	0.153846	25	0.2	10	678.58	30	22.96	22.59
6	130	0.153846	25	0.2	10	678.58	40	21.14	20.48
7	130	0.153846	25	0.2	10	678.58	50	19.73	18.56
8	130	0.153846	25	0.2	10	678.58	60	18.57	16.99
9	130	0.153846	25	0.2	10	678.58	70	17.6	15.76
10	130	0.153846	25	0.2	10	678.58	80	16.75	14.85
11	130	0.153846	25	0.2	10	678.58	90	16.01	14.31
12	130	0.153846	25	0.2	10	678.58	100	15.34	14.06
13	130	0.153846	25	0.2	10	678.58	110	14.73	13.92
14	130	0.153846	25	0.2	10	678.58	120	14.18	13.79
15	130	0.153846	30	0.2	10	678.58	0	31	32.14
16	130	0.153846	30	0.2	10	678.58	5	31	30.42
17	130	0.153846	30	0.2	10	678.58	10	29.88	28.84
18	130	0.153846	30	0.2	10	678.58	20	25.52	25.99
19	130	0.153846	30	0.2	10	678.58	30	22.96	23.75
20	130	0.153846	30	0.2	10	678.58	40	21.14	21.66
21	130	0.153846	30	0.2	10	678.58	50	19.73	19.78
22	130	0.153846	30	0.2	10	678.58	60	18.57	18.22
23	130	0.153846	30	0.2	10	678.58	70	17.6	16.96
24	130	0.153846	30	0.2	10	678.58	80	16.75	15.96
25	130	0.153846	30	0.2	10	678.58	90	16.01	15.21
26	130	0.153846	30	0.2	10	678.58	100	15.34	14.65
27	130	0.153846	30	0.2	10	678.58	110	14.73	14.24
28	130	0.153846	30	0.2	10	678.58	120	14.18	13.96
29	130	0.153846	25	0.05	10	678.58	0	30.76	31.31
30	130	0.153846	25	0.05	10	678.58	5	30.76	31.08
31	130	0.153846	25	0.05	10	678.58	10	30.76	30.93
32	130	0.153846	25	0.05	10	678.58	20	30.76	30.77
33	130	0.153846	25	0.05	10	678.58	30	30.76	30.71
34	130	0.153846	25	0.05	10	678.58	40	30.55	30.59
35	130	0.153846	25	0.05	10	678.58	50	29.54	30.54
36	130	0.153846	25	0.05	10	678.58	60	28.72	30.22
37	130	0.153846	25	0.05	10	678.58	70	28.02	29.78
38	130	0.153846	25	0.05	10	678.58	80	27.42	29.15
39	130	0.153846	25	0.05	10	678.58	90	26.89	28.28
40	130	0.153846	25	0.05	10	678.58	100	26.41	27.05
41	130	0.153846	25	0.05	10	678.58	110	25.98	25.35
42	130	0.153846	25	0.05	10	678.58	120	25.59	23.18
43	130	0.153846	30	0.05	10	678.58	0	31	32.47
44	130	0.153846	30	0.05	10	678.58	5	31	32.18
45	130	0.153846	30	0.05	10	678.58	10	31	31.92
46	130	0.153846	30	0.05	10	678.58	20	31	31.48
47	130	0.153846	30	0.05	10	678.58	30	31	31.13
48	130	0.153846	30	0.05	10	678.58	40	30.55	30.91
49	130	0.153846	30	0.05	10	678.58	50	29.54	30.72
50	130	0.153846	30	0.05	10	678.58	60	29.3	30.38
51	130	0.153846	30	0.05	10	678.58	70	28.59	29.96
52	130	0.153846	30	0.05	10	678.58	80	27.97	29.37
53	130	0.153846	30	0.05	10	678.58	90	27.43	28.55
54	130	0.153846	30	0.05	10	678.58	100	26.95	27.40
55	130	0.153846	30	0.05	10	678.58	110	26.51	25.79
56	130	0.153846	30	0.05	10	678.58	120	26.11	23.71

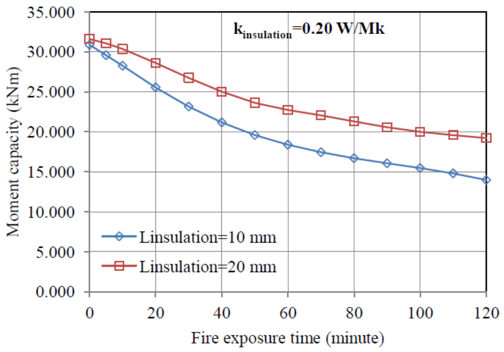

Fig. 11 Moment capacities for constant thermal conductivity (k=0.20 W/mK) and different insulation thickness

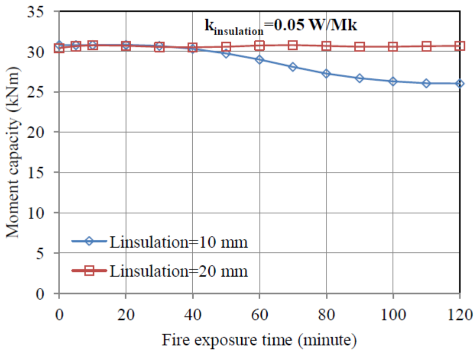

Fig. 12 Moment capacities for constant thermal conductivity (k=0.05 W/mK) and different insulation thickness

by fire. However, the slab was less affected by fire for k=0.05 W/mK. It can be seen from Fig. 10 that the M_r value gets affected by after 40 minutes. In case of very low conductivity (k=0.001 W/mK), the fire effect was lost.

In the second case, the M_r for constant thermal conductivity coefficient and different insulation thicknesses were considered (Figs. 11 and 12). In this case, firstly, thermal conductivity coefficient was taken as 0.20 W/mK, and insulation material thickness was taken as 10mm and 20 mm, and the M_r of RC slab with insulation material was predicted by the ANN model. The predicted moment capacities are shown in Fig. 11. Because of large thermal conductivity coefficient, the M_r of RC slab was quickly affected by fire and decreases the value. Secondly, thermal conductivity coefficient was taken as 0.05 W/mK, and the insulation material thickness was taken as 10 mm and 20 mm, and M_r was predicted by the ANN model. The predicted moment capacities are illustrated in Fig. 12. If the insulation material thickness was selected 20 mm, RC slab was not affected by fire. However, if the insulation material thickness was selected as 10 mm, the RC slab was less affected by fire.

6. Conclusions

The RC slabs get quickly affected by fire and their Mr value get reduced. To preserve their Mr value, the slabs must be protected from temperature due to fire. In this study insulation materials were used to protect the RC slabs from fire.

The M_r of RC slabs with insulation materials exposed to fire for different thermal conductivity coefficients, insulation material thickness, effective depths, reinforcement area, fire exposure time, and the compressive strengths of concrete were calculated for training the ANN model by the author. The data obtained from 672 slabs exposed to fire were used to build, train and test the ANN model. The R was obtained as 99.363% for training stage and 98.934% for testing stage. These values indicate that the proposed ANN model is highly successful. The test results also indicate that the generalization ability of ANN is appreciable. Without making several computations in the calculation stage, the trained ANN model can be used to predict the M_r of RC slab with insulation material with high accuracy.

The effects of insulation material thickness and thermal conductivity coefficient on the Mr of RC slabs were examined using trained ANN model. If thermal conductivity coefficient was high, the RC slab was largely affected by elevated temperature and the M_r of RC slabs reduced rapidly. Insulation material with low thermal conductivity coefficient protects the slab from the harmful effects of fire. Also increasing the insulation material thickness may protect the RC slab from the negative effects of elevated temperature.

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