ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 9, NO. 4 (2008)
PAGES 391- 409

UTILIZING EXPERIMENTAL MODEL TESTS AND ARTIFICIAL NEURAL-NETS TO ESTIMATE THE STRENGTH LOSS OF HEATED REINFORCED CONCRETE COLUMNS

A.M. Rashad[a*], N.O. Farag[a], O. Hodhod[b] and M.M. Razik[a]
[a]*Housing and Building National Research Center, Cairo, Egypt*
[b]*Department of Structural Engineering, Cairo University,Cairo, Egypt*

Abstract

An artificial neural network-based model is developed to predict the loss in capacity of reinforced concrete columns subjected to elevated temperature. A series of RC column models have been tested. The process of increasing the temperature is performed while the model columns carrying the service loads, thus simulating the actual condition taking place during real fire event. Different column sections; and aggregate, plaster and admixture types are used. To study the effect of these factors on the residual strength. Results of experimental model tests are then analyzed, clustered and used to train a specially designed artificial neural network (ANN) to be capable of predicting reduced concrete strength. ANN estimations, when compared to model test results, showed very good agreement. Such observation indicates that ANN could be effectively used to accurately predict strength reduction due to exposed to elevated temperature.

Keywords: Elevated temperature; concrete cover; axial load; coating types; ann; fire severity

1. Introduction

As reported by Dotreppe et al. [1], many parameters affect the behavior of reinforced concrete columns subjected to fire conditions. Among these parameters are the dimensions of column section, the thickness of concrete cover, the amount of reinforcement and the applied stress level. Some other factors were investigated by Shields et al. [2] namely concrete type, and quality; type of reinforcement; size and shape of the concrete element and concrete cover. Fire resistance of columns can be increased by using either concrete with low density, i. e. with lower coefficient of thermal conductivity, or changing the cross sections to avoid, as far as possible, reaching high temperature due to fire, Roytman [3]. One of the critical issues in the fire resistance of concrete is the nature of the used aggregate, as certain aggregates are more resistant to spalling and having a lower thermal conductivity.

*E-mail address of the corresponding author: alaarashad@yahoo.com (A.M. Rashad)

The issue of thermal conductivity is particularly important as it is necessary to limit heat transfer to the inside of the element [4].

Malhotra [5] reported that concrete partially loses its strength at temperature of 200^{o}C to 250^{o}C, but cracks start to occur at about 300 ^{o}C where the concrete loses about 30% of its compressive strength and the loss of strength continues with the increase in temperature. Abrams [6] experimentally proved that all concrete types loses strength at elevated temperatures but the rate of reduction differs with the type of used aggregate. Moreover, mitigating the negative effects of elevated temperature on concrete elements is usually a main concern There are many different possible strategies to protect RC columns from fire/elevated temperature such as using bigger dimensions of the cross section, increasing thickness of the concrete cover, using lightweight aggregate and finally adding coating. Zhou and Zhang [7] reported that most concrete structures have coating or plaster, either non-combustible or combustible. For non-combustible coating, such as mortar, it acts as a retardant which slows the propagation of fire heat to the inner structural member. Thus, the fire safety of concrete structures is improved by this kind of coating. Repeated tests have demonstrated that perlite gypsum and perlite Portland cement coating are exceptionally effective in blocking flames and/or retarding the transmission of high temperature (Abrahams and Stollard, [4]). Perlite plaster offers up to 4-6 times more resistance to heat transmission than ordinary sand plaster [8]. The fire resistance of concrete elements may be also increased by protecting the reinforcement bars from high temperatures by increasing the thickness of the protective layer, by applying a facing or plastering with low heat-conducting materials as shown by Shields and Silcock [9]. Vermiculite plaster has 4 times more resistance to heat transmission than sand plaster. Thus permits savings in heating and air conditioning costs and conserves energy. As well as being fire retardant/non-combustible and non-toxic, it provides up to 5 hours fire protection with minimum weight and thickness. It provides protection for columns, partitions and undersides of floors and roof assemblies [10].

On the other hand, artificial neural networks, ANNs, have been widely used through the last decade. ANNs have been successfully applied in several areas of Civil and Structural Engineering. Chan et al. [11] developed a prototype ANN model to establish the correlation between the concrete properties and its fire resistance. Chan et al. [12] developed a model based on an artificial neural network for predicting the loss of strength of concrete under high temperature (75–1200^{o}C). Tung et al. [13] developed a neural network model capable of assessing the liquefaction potential. A back-propagation network with "4" input nodes, "6" hidden neurons and one output node was developed adopting the hyperbolic function as a transfer function. Moreover, Penumadu et al. [14] studied the effect of strain rate on the behavior of clay using ANNs. Behavior predicted using the ANNs agreed well with that measured experimentally.

In this work, a wide parametric study is conducted to investigate the effect of different factors controlling the residual strength of heated columns. Totally 113 model tests are performed. The conducted parametric study included changing the column geometry, concrete cover thickness, type of coating, coating thickness, type of aggregate and admixture. All samples are made of local materials. For each set of parameters, tow specimens are tested. The first specimen is heated while the second one, non-heated, is considered as control specimen. Results of different testes are analyzed and clustered then used by the ANN as training data to estimate the residual strength of heated columns in terms of controlling factors.

2. Problem Identification

As a main goal of this research, it is required to predict the residual strength of loaded columns subjected to elevated temperature. The residual strength is to be predicted depending on some controlling factors. Based on the previous work and on the analyzed model test results, these controlling factors can be classified into three main categories as follows:

- Factors related to column geometry such as aspect ratio of column section, a/b where a is the width and b is the breadth of the column section, concrete cover ratio C/b where C is the thickness of the concrete cover and the ratio of exposed to cross-sectional area, A_{ex}/A_{co}, where A_{co} = a x b and A_{ex} = (a + b) x 2H while H is the column height.
- Factors related to the used material such as type of coarse aggregate, type of coating and type of the used admixtures, if any.
- Factor related to fire such as fire severity, S_v, that is defined as the area under the characteristic time-temperature curve.

Mathematically, the process of predicting residual strength, RS, is equivalent to obtaining the value of this strength in terms of the controlling factors at different levels. In other words, our problem is to obtain the following function:

$$RS = RS\ (a/b,\ C/b,\ A_{ex}/A_{co},\ S_v,\ \ldots..).$$

Graphical solutions, based on design charts, of such function are too complicated to be achieved. So, the artificial neural nets, ANNs, shall be adopted to predict the values of the function RS for different values of the controlling factors. To be capable of that, the used ANN need some data to learn. These data shall be extracted from a wide experimental parametric study while considering different values of the controlling factors.

3. Experimental Details

To study the variation of the residual strength of axially-loaded heated concrete columns, an experimental program has been suggested and planned. The experimental program including the testing of 113 model RC column specimens. Gravel, dolomite and basalt coarse aggregate have been used to produce three different types of concretes. Different section dimensions, (10 x15, 15 x15 and 15 x20 cm^2), and different concrete cover thickness, (1.0, 1.5 and 2.0 cm), have been investigated. Effects of heat resistant mortar coating has been studied by considering the following coating types; LECA-cement, perlite-cement, perlite-gypsum, sand-gypsum, traditional-cement, vermiculite-cement and vermiculite-gypsum. The coating thicknesses of 1.5, 2.5 and 3.5 cm were considered. Moreover, in some tests, a 25% (by weight) of sand content is replaced by refractory additives of different types, namely Aswan-clay (AC), firedbrick-powder (FB), pottery (PP) and refractory-mortar (RM). Table 1 lists the characteristics of 113 model columns. The specimens reinforcement are given in Table 2, while the ratio of the longitudinal reinforcement ranges from 0.8% to 0.9%.

Local Egyptian concrete ingredients have been used. The characteristic strength (f_{cu})=250kg/cm^2. Coating mixes have been selected to give proportions that represent adequate workability in the field, bond strength and compressive strength to resist the service loads. For the constitutions of both concrete and mortar mixes, refer to Rashad [15].

Table 1. Scale model columns designations

Series	Coarse Aggregate Type	Dimension a×b×H (cm×cm×cm)	Test ID	Cover (cm)	Adm. Type	Coating		Exposure Time (min.) after 650°C
						Type	Thick. (cm)	
			1	1.0				Control
			2	1.0				30
			3	1.0				60
		10×15×70	4	1.0	----	----	0	120*
			5	1.5				Control
			6	1.5				30
			7	2.0				Control
			8	2.0				30
			9	1.0				Control
1	Gravel		10	1.0				30
		15×15×70	11	1.5	----	----	0	Control
			12	1.5				30
			13	2.0				Control
			14	2.0				30
			15	1.0				Control
			16	1.0				30
		15×20×70	17	1.5	----	----	0	Control
			18	1.5				30
			19	2.0				Control
			20	2.0				30
2			21	1.0				Control
			22	1.0				30
		10×15	23	1.5	----	----	0	Control
			24	1.5				30
			25	2.0				Control
			26	2.0				30
			27	1.0				Control
			28	1.0				30
	Dolomite	15×15	29	1.5	----	----	0	Control
			30	1.5				30
			31	2.0				Control
			32	2.0				30
			33	1.0				Control
			34	1.0				30
		15×20	35	1.5	----	----	0	Control
			36	1.5				30
			37	2.0				Control
			38	2.0				30

Duration 30 min. Equivalent to Temperature Severity Sv= 3.0653×10^4 min.°C — Duration 60min. Equivalent to Temperature Severity Sv = 5.01533×10^4 min. °C

Duration 120 min. Equivalent to Temperature Severity Sv = 8.9153×10^4 min. °C

Table 1. Continued

Series	Coarse Aggregate Type	Dimension a×b×H (cm×cm×cm)	Test ID	Cover (cm)	Adm. Type	Coating		Exposure Time (min.) after 650 ^oC
						Type	Thick. (cm)	
			39	1.0				Control
			40	1.0				30
		10×15	41	1.5	----	----	0	Control
			42	1.5				30
			43	2.0				Control
			44	2.0				30
			45	1.0				Control
			46	1.0				30
3	Bazalt	15×15	47	1.5	----	----	0	Control
			48	1.5				30
			49	2.0				Control
			50	2.0				30
			51	1.0				Control
			52	1.0				30
		15×20	53	1.5	----	----	0	Control
			54	1.5				30
			55	2.0				Control
			56	2.0				30
4			57		AC			Control
			58		AC			30
5			59		FB			Control
	Gravel	10×15	60	1.0	FB	----	0	30
6			61		PP			Control
			62		PP			30
7			63		RM			Control
			64		RM			30
1			65				1.5	30
			66				1.5	60
			67				1.5	120
			68	1.0	----	LECA-Cement (LC)	2.5	30
			69				2.5	60
			70				2.5	120
	Gravel	10×15	71				3.5	30
			72				1.5	30
			73				1.5	60
			74				1.5	120
			75	1.0	----	Perlite-Cement (PC)	2.5	30
			76				2.5	60
			77				2.5	120
			78				3.5	30

Table 1: Continued

Series	Coarse Aggregate Type	Dimension a×b×H (cm×cm×cm)	Test ID	Cover (cm)	Adm. Type	Coating Type	Coating Thick. (cm)	Exposure Time (min.) after 650 °C
1	Gravel	10×15	79	1.0	----	Perlite-Gypsum (PG)	1.5	30
			80				1.5	60
			81				1.5	120
			82				2.5	30
			83				2.5	60
			84				2.5	120
			85				3.5	30
			86	1.0	----	Sand-Gypsum (SG)	1.5	30
			87				1.5	60
			88				1.5	120
			89				2.5	30
			90				2.5	60
			91				2.5	120
			92				3.5	30
			93	1.0	----	Traditional-Cement (TC)	1.5	30
			94				1.5	60
			95				1.5	120
			96				2.5	30
			97				2.5	60
			98				2.5	120
			99				3.5	30
			100	1.0	----	Vermiculite-Cement (VC)	1.5	30
			101				1.5	60
			102				1.5	120
			103				2.5	30
			104				2.5	60
			105				2.5	120
			106				3.5	30
			107	1.0	----	Vermiculite-Gypsum (VG)	1.5	30
			108				1.5	60
			109				1.5	120
			110				2.5	30
			111				2.5	60
			112				2.5	120
			113				3.5	30

Table 2. Cross-Sections, reinforcements and concrete covers for column specimens

Dimension axb (cmxcm)	Long Rein. (mm)	Stirrups* (mm)	Cover (cm)
	4 ø 6	7 ø 3.5	1.0
10x15	4 ø 6	8 ø 3.5	1.5
	4 ø 6	8 ø 3.5	2.0
	4 ø 8	8 ø 3.5	1.0
15x15	4 ø 8	9 ø 3.5	1.5
	4 ø 8	8 ø 4	2.0
	4 ø 8 + 2 ø 6	9 ø 3.5	1.0
15x20	4 ø 8 + 2 ø 6	10 ø 3.5	1.5
	4 ø 8 + 2 ø 6	8 ø 4	2.0

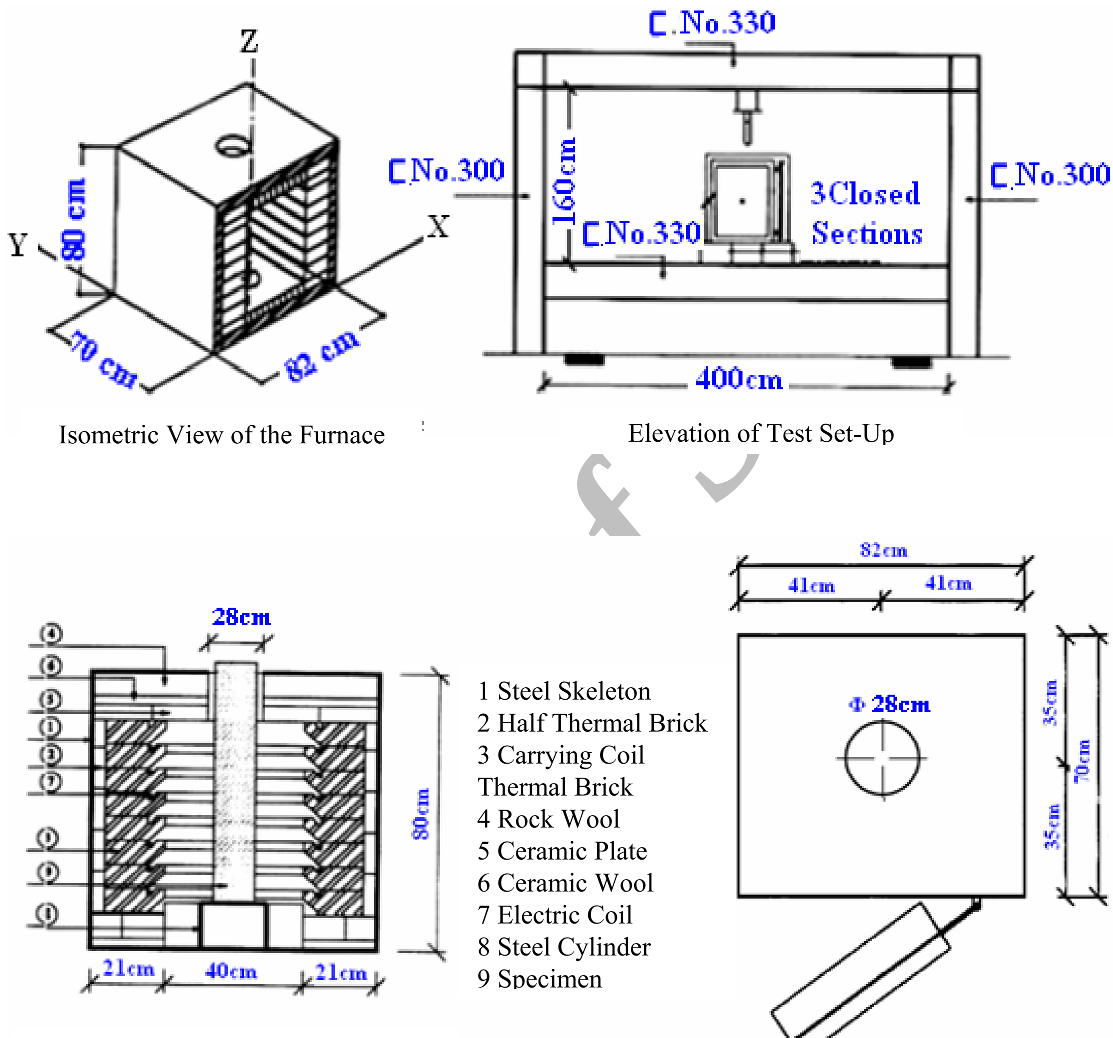
***: Total Number per Sample**

3.1 Test set up

An electrical symmetrical furnace was used in this study. This furnace is a part of the available facilities of the Materials Testing Laboratory of the Faculty of Engineering at Cairo University. Figure 1 shows isometric, top and sec-elevation views of the furnace. Loading frame was used for loading the specimens during heating. To allow for simulating the condition of actual fire, model columns are axially-loaded to service loads then temperature is gradually elevated, from ambient temperature, to 650^{o}C through 110 minutes then maintained constant at this value for either 30, 60 or 120 minutes. This is to allow for varying the fire severity, S_v. A hydraulic jack connected to a loading pump having maximum capacity of 22 ton is used to provide the required load.

3.2 Test procedure and test results

Thirty one samples are tested directly under axial load only without heating. These samples are referred to as control samples. The remaining specimens are put inside the furnace and stressed to the service load. The temperature inside the furnace is increased gradually up to 650^{o}C in 110 minutes then the furnace temperature is kept unchanged for 30, 60 or 120 minutes. Applied load and furnace temperature are recorded every 5 minutes. Temperature values at specified points inside column section are monitored utilizing thermocouples. After completing the exposure duration, the furnace is turned off and the specimen is left to cool to the ambient temperature. After cooling down to room temperature, each specimen is stressed to failure to determine its residual load capacity (RL), that shall be compared to the corresponding control strength. Table 3 summarizes the obtained test results for different model columns.



Isometric View of the Furnace

Elevation of Test Set-Up

Sectional Elevation of the Adopted Testing Furnace

Top View Plane in the Testing Furnace

Figure 1. Details of the elevated temperature test set-up

Table 3. Scale model residual load capacities and residual strengths

Test ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
RL	37.1	7.285	5.1	0**	35.2	7.805	32.65	8.045
% RL	100	19.64	13.75	0	100	22.17	100	24.64
% RS*	100	9.7293	3.1137	0	100	11.994	100	13.904
Test ID	9	10	11	12	13	14	15	16
RL	59.5	16.93	56.65	20.1	54.5	21.52	74.35	26.9
% RL	100	28.45	100	34.48	100	39.48	100	36.18
% RS	100	18.545	100	26.029	100	30.218	100	64.031
Test ID	17	18	19	20	21	22	23	24
RL	68.9	30.75	64.75	32.35	49.25	17.05	48.75	17.36
% RL	100	44.63	100	49.96	100	34.62	100	35.61
% RS	100	76.865	100	82.198	100	28.728	100	29.743
Test ID	25	26	27	28	29	30	31	32
RL	47.5	17.72	79.25	30.75	77.05	34.15	74.35	36.57
% RL	100	37.31	100	38.8	100	44.32	100	49.19
% RS	100	31.428	100	32.649	100	38.549	100	45.706
Test ID	33	34	35	36	37	38	39	40
RL	113	52.45	108	54.05	103	60.8	51.75	21.95
% RL	100	46.42	100	50	100	59.3	100	42.42
% RS	100	42.503	100	46.216	100	55.723	100	37.489
Test ID	41	42	43	44	45	46	47	48
RL	49.45	24.87	48.9	25.25	81	35.2	79.3	40.35
% RL	100	50.29	100	51.64	100	43.46	100	50.88
% RS	100	45.833	100	47.243	100	37.908	100	45.949
Test ID	49	50	51	52	53	54	55	56
RL	75.85	42.05	116	55.25	111	57.2	107	65.25
% RL	100	55.44	100	47.63	100	51.53	100	60.98
% RS	100	50.737	100	43.911	100	47.923	100	57.959
Test ID	57	58	59	60	61	62	63	64
RL	30.1	18.52	33.34	17.1	34.12	15.75	31.4	13.72
% RL	100	61.53	100	51.89	100	46.16	100	43.69
% RS	100	55.510	100	44.514	100	38.866	100	35.306
Test ID	65	66	67	68	69	70	71	72
RL	23.4	19.85	15.24	28.45	20.5	19.25	31.47	30.3
% RL	63.073	53.504	41.08	76.685	55.256	51.887	84.825	81.671
% RS	58.517	47.772	27.635	73.809	49.74	45.956	82.797	79.408
Test ID	73	74	75	76	77	78	79	80
RL	28.75	22.75	35.15	43.1	28.35	38.05	33.07	27.15
% RL	77.493	61.32	94.663	91.914	76.415	102.56	89.175	73.181
% RS	74.217	50.497	94.005	90.917	73.505	102.87	87.797	69.871
Test ID	81	82	83	84	85	86	87	88
RL	23.25	37.35	35.78	34.15	37.55	23.87	22	21.6
% RL	62.669	100.67	96.442	92.048	101.21	64.39	59.299	58.221
% RS	58.063	100.75	96.003	91.067	101.36	59.943	54.280	24.102

****Specimen Failed inside the Furnace after 75 min. before reaching the planned duration.**
***Residual Strength Values Are Calculated Based on the Equation Given by the Egyptian Code of Practice of RC Structures, ECC 203-2007, Chapter (4), Page 4-11, Clause (4-12a).**

Table 3. Continued

Test ID	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**
RL	30.32	29	23.8	32.4	18.72	16.7	11.15	20.7
% RL	81.725	78.167	64.151	87.332	50.458	34.367	30.054	55.795
% RS	79.472	75.476	27.127	85.767	44.348	38.235	21.431	50.343
Test ID	97	98	99	100	101	102	103	104
RL	18.45	15.7	22.7	23.85	20.35	19.8	30.6	28.95
% RL	49.731	42.318	61.186	64.286	54.852	53.369	82.479	78.032
% RS	43.531	35.206	56.401	59.88	49.285	47.618	80.317	75.321
Test ID	105	106	107	108	109	110	111	112
RL	22.1	37.12	21.65	19.22	14.5	22	21.3	18.85
% RL	59.569	100.05	58.356	51.806	39.084	59.299	57.412	50.809
% RS	54.585	100.06	53.222	45.865	31.573	54.28	52.159	44.744
Test ID	113							
RL	28.75							
% RL	77.463							
% RS	74.72							

4. Results and Analysis

Effect of heating process on the specimen strength is reflected herein as the percentage of residual strength, %RS, where it is calculated by obtaining the percentage ratio of the reduced concrete strength after heating and cooling to that of unheated column, control strength. The first set of results is given in Figures 2 and 3 with the first one presents the variation of %RS in addition to the average core temperature, T_{av}, with the concrete cover thickness for different aggregate types.

It is clear that, for all types of used aggregate, increasing the concrete cover thickness results in increasing the residual strength and decreasing the average core temperature reached during heating. In Figure 3, variation of %RS and T_{av} is introduced versus the ratio A_{ex}/A_{co} for different values of concrete cover thickness and different types of aggregate. It is found that for the same cross-sectional area, A_{co}, increasing the exposure area, A_{ex}, shall lead to increasing the average core temperature and consequently reducing the residual strength. This is, simply due to the fact that the amount of heat transferred to the sample core is increased.

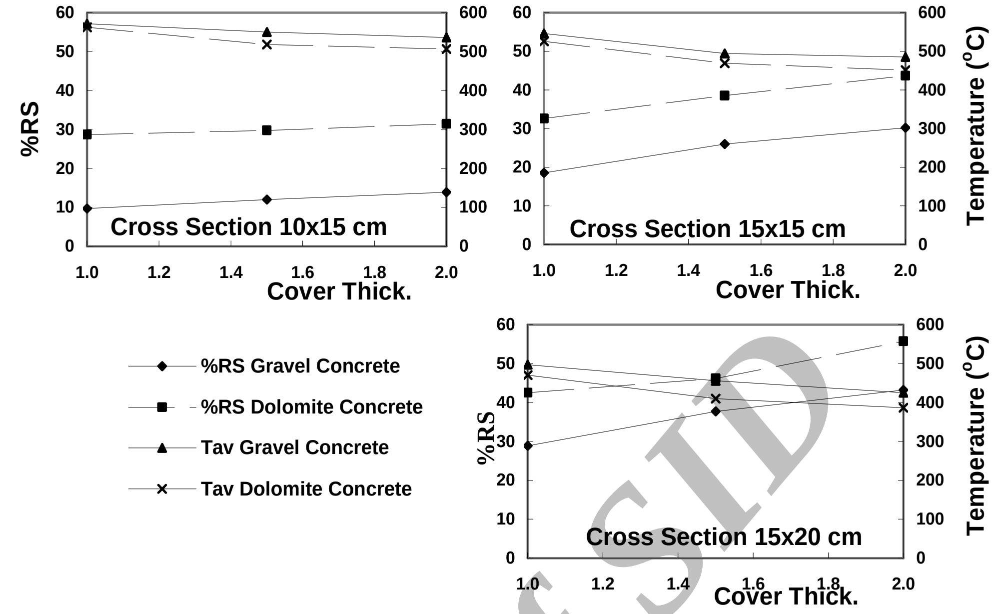


Figure 2. Average core temperature /residual strength versus concrete cover thickness for various column specimens sizes and aggregate type

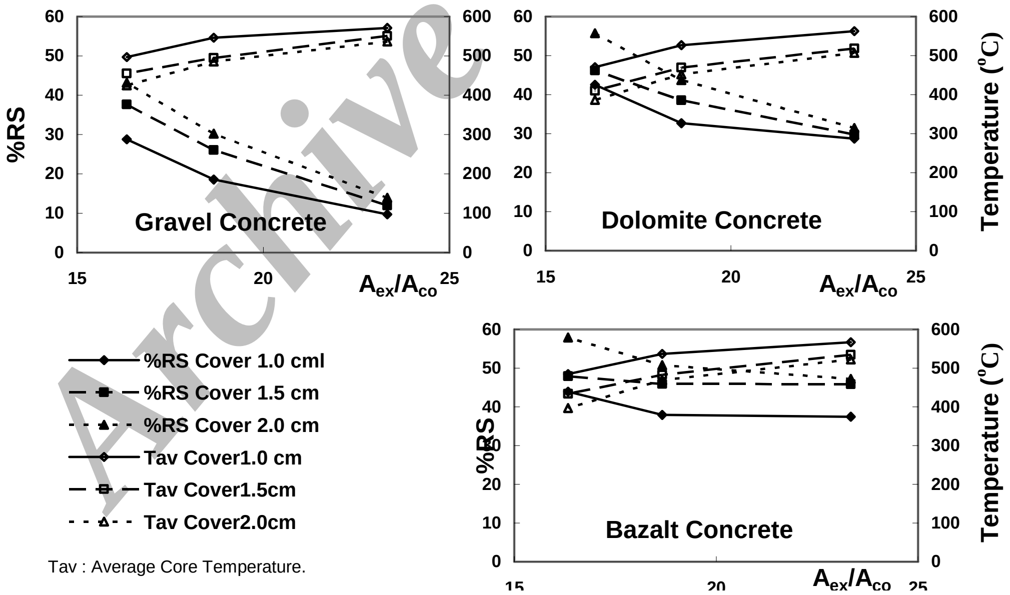


Figure 3. Average core temperature /residual strength versus the ratio of exposed area to cross sectional area for different concrete cover and aggregate type

To investigate the effect of coating type and thickness, a factor ζ, that is defined as the ratio of the residual strength of coated to non-coated columns for a given elevated temperature level or a given level of fire severity. Figure 4 presents the values of the factor ζ for different coating types and coating thicknesses. It is found that, for a given coating thickness, the most effective type is the perlite-gypsum, PG, and perlite-cement, PC, and the least one is the traditional-cement, TC. Moreover, increasing the coating thickness shall act as a mitigating factor that increases the strength of concrete elements to fire.

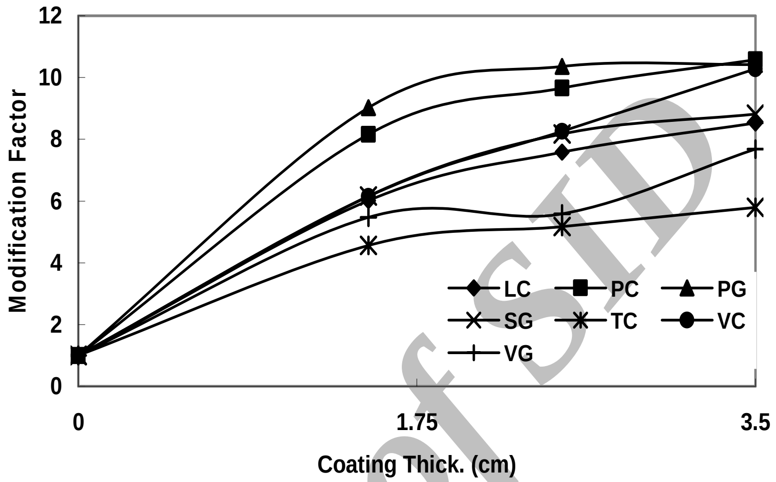


Figure 4. Modification factors considering the effect of coating conditions on the residual strength

The next set of results is concerned with the effect of fire severity. For different coating types and coating thicknesses, different severity levels are accounted for by changing the fire application duration. Thus, to quantify the impact of severity on residual strength, the control and the heated specimens strengths are obtained and the value of %RS is obtained for the case of a reference fire severity, where the maximum temperature of 650°C is reached in 110 minutes and maintained for additional 30 minutes, $Sv = 3.0653\times10^4$ min°C.

The same is repeated for severity values other than the reference one. This is achieved for different coating types with different thicknesses. A reduction factor, β, is defined as the percentage of the residual strength for a given severity level to that of the standard one. Thus, simply, if one obtained the value of the residual strength for the standard severity, the corresponding value for any severity level can be estimated by multiplying by the factor β. Values of factor β are given for different severity values, coating types and coating thicknesses in Figure 5. Moreover, the factor β can be expressed in terms of the fire severity, S_v, depending on coating type and thickness. This is given in Table 4 with the value of the correlation coefficient, R^2.

The last factor that its effect has been investigated is the use of admixtures. Figure 6 shows the effect of replacing a 25% of sand content with Aswan-clay, Firebrick-powder, Pottery or Refractory-mortar. Thus, to account for the effect of admixtures, if used, a factor α is calculated as the ratio of %RS for the case of admixture to that of the case where no admixture is utilized.

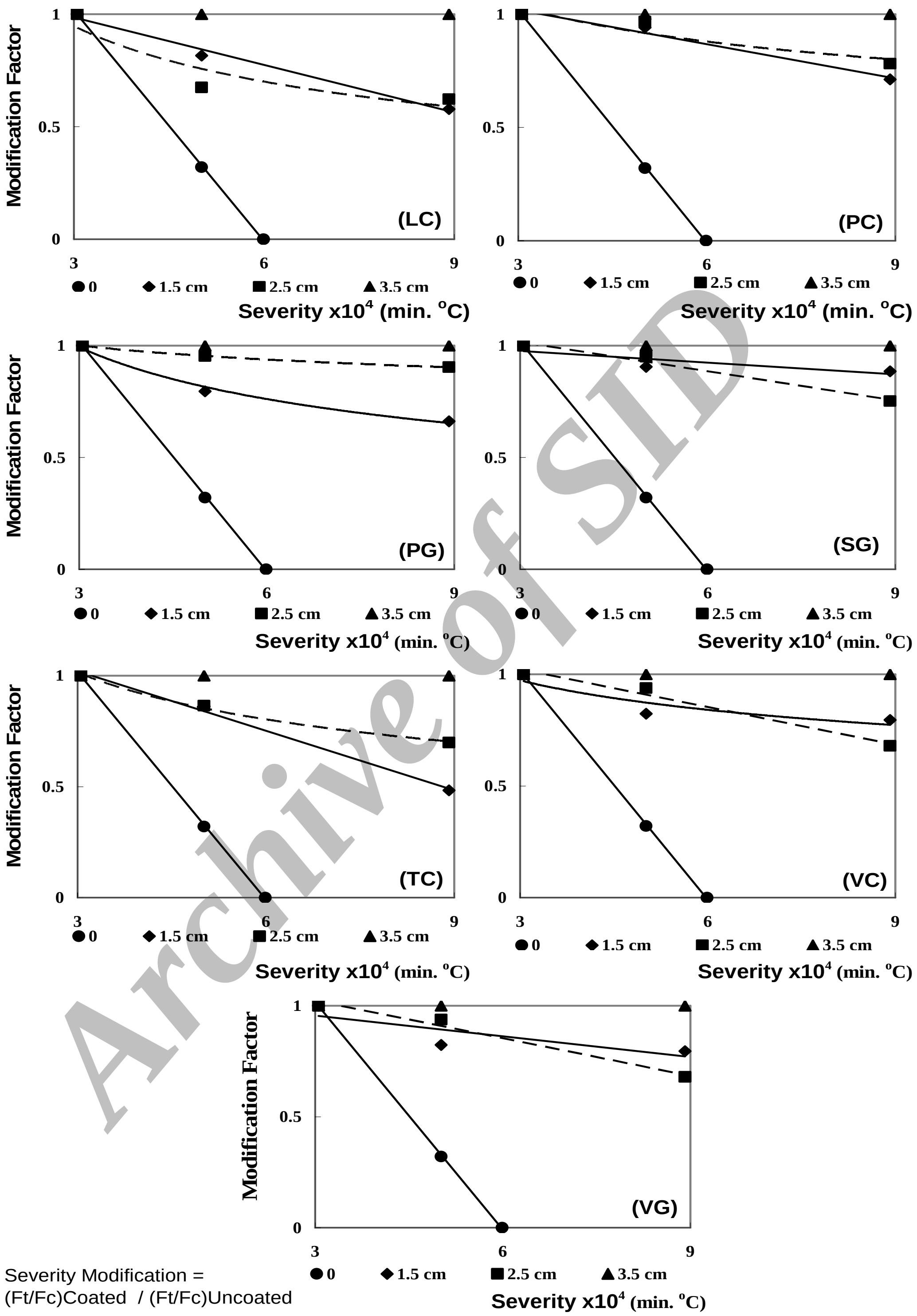


Figure 5. Modification factor considering the effect of temperature severity conditions on the residual

Table 4. Equations used to evaluate temperature severity effect on the strength

Plaster Type	Plaster Thickness	Equation	R^2
(LC)	0	R = -0.3429Sv + 2.0429	0.9998
	1.5	*R = (-0.4246Sv + 7.1989)/6.01*	0.9868
	2.5	R = (11.557Sv$^{-0.434}$)/7.59	0.8401
	3.5	R = 1	1
(PC)	1.5	*R = (-0.4126Sv + 9.5491)/8.16*	0.9811
	2.5	R = (12.902Sv$^{-0.2335}$)/9.66	0.88
	3.5	R = 1	1
(PG)	1.5	R = (13.667Sv$^{-0.3843}$)/9.02	0.9891
	2.5	R = (11.497Sv$^{-0.0943}$)/10.36	0.9997
	3.5	R = 1	1
SG)	1.5	R = (-0.6534Sv + 8.4308)/6.16	0.9658
	2.5	R = (-0.9703Sv + 11.72)/8.17	.9315
	3.5	R = 1	1
(TC)	1.5	R = (-0.4084Sv + 5.871)/4.56	0.9947
	2.5	R = (7.5702Sv$^{-0.3349}$)/5.17	0.996
	3.5	R = 1	1
(VC)	1.5	R = (7.5322Sv$^{-0.2097}$)6.15	0.8275
	2.5	R = (-0.4656Sv + 9.833)8.26	0.9779
	3.5	R = 1	1
(VG)	1.5	R = (-0.3798Sv + 6.6226)/5.47	0.9999
	2.5	R = (-0.1715Sv + 6.1488)/5.58	0.9857
	3.5	R = 1	1

Gravel Aggregate. 2 Dolomite Aggregate. 3 Bazalt Aggregate.

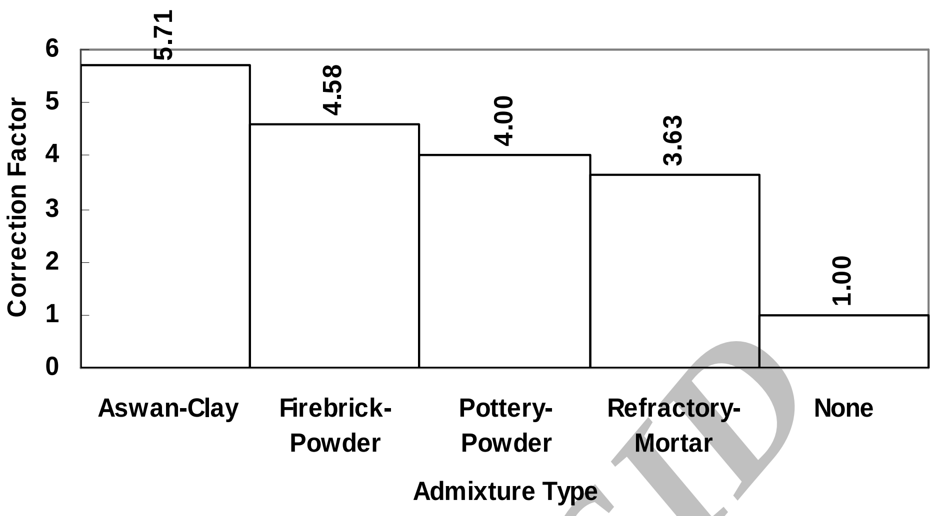


Figure 6. Modification factor consider the effect of admixture conditions on the residual strength

5. Predicting Residual Strength Using ANNs

The residual strength of heat exposed columns (RS) is a multi variant function developing an analytical model relating (RS) to the dominant variables, different column sections; and aggregate, plaster and admixtures, poses real difficulties. The obtained experimental results shall be employed in the following proposed procedure to develop the required mathematical model:

1. The effects of the aggregate type and column geometry, a/b, C/b, T/b and A_{ex}/A_{co} shall be considered in a specially designed ANN.
2. The effects of coating type and coating thickness shall be predicted using linear regression, utilizing the values of the factor (ζ).
3. The effect of varying fire severity shall be predicted using either linear or nonlinear regression, utilizing equations given in Table 4.

Thus, during the course of estimating the residual strength, a prediction of the reduction in strength due to standard elevated temperature (maximum temperature, T=650^{o}C and temperature severity=3.0653×10^{4}min.^{o}C assuming no coating or admixture exists) is obtained. This part shall be carried out adopting an artificial neural network called AGG-SEC. The next step is to modify the obtained value according to the existence of coating and admixture. Finally, modify the obtained value to account for the actual elevated temperature value.

Two types of artificial neural networks are tried to reach the best performance. The first one is the General Regression Neural Network, GRNN, and the second is the Back-propagation Neural Network, BPNN.

The used GRNN network is a three-layer network that contains one hidden neuron for each training pattern. In this ANN type, no training parameters such as learning rate and momentum, as those used in Back-propagation networks, but there is a smoothing factor is used when the network is applied to new data. The smoothing factor determines how tightly the network matches its predictions to the data in the training patterns. Although the number of neurons in the hidden layer is set automatically, it can be changed for GRNN networks. The number of hidden neurons is usually equal to the number of patterns in the training set because the hidden layer consists of one neuron for each pattern in the training set. Architecture of the developed GRNN is given in Figure 7 showing the number of neurons for each layer.

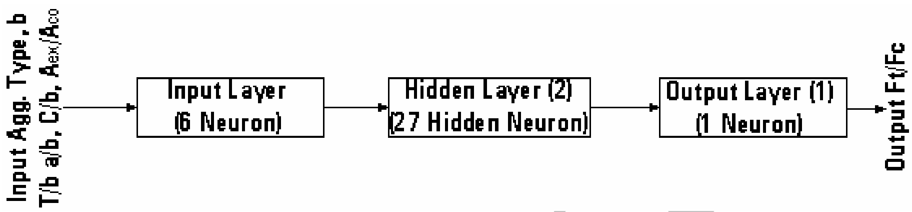


Figure 7. Configuration of general regression neural net

6. Development of the Network AGG-SEC

AGG-SEC is the network that is used to estimate residual strength in terms of aggregate type, concrete cover, section configuration and standard elevated temperature condition. For GRNN type, input-output patterns will be defined to the network. Results of residual strength, as extracted from experimental program, are fedback to the ANN to train it. Results of column strength ratios of totally 54 column samples were used. Some of the used parameters, a/b, C/b and A_{ex}/A_{co} are dimensionless. Results are clustered, tabulated, and then passed to the network for processing. Table 5 shows the data used for training and testing the proposed network, the actual output, AGG-SEC output and the difference between them. Test patterns are extracted to measure the network accuracy and training is continued until reaching a tolerated error. After that, training is stopped and weights are saved. The developed ANN doesn't consider the effect of using any protective layer of coating materials. Also, it doesn't account for changing the elevated temperature conditions from the standard ones, followed when training the AGG-SEC net. In addition, it doesn't include the effect of using admixtures. All these factors are considered separately.

7. Integrated Solution Routine

To explain how the value of the residual strength shall be predicted using the procedure introduced above, consider the case of a rectangular column with an aspect ratio is a/b, the ratio of the exposed to the cross-sectional area is A_{ex}/A_{co}, cover ratio is C/b, temperature gradient is T/b and temperature severity is S_v. If the aggregate type, coating and admixture conditions are given, thus, the solution procedure can be described as follows:

- Use the module AGG-SEC Net to get the residual strength considering standard elevated temperature condition (T=650°C, S_v=3.0653×10^4 min.°C) and no coating or admixture exists, F_{ct1}.

- Use coating modification factor, ζ, that consider the effect of coating type and coating thickness, to modify the residual strength obtained from AGG-SEC.
- Use severity modification factor, β, that consider actual temperature severity condition to modify the previous residual strength.
- Use admixture modification factor, α, that consider the admixture type to modify the last residual strength gotten.

To effectively execute this procedure, a computer program, RESIDUAL, written in Visual Basic® has been developed to perform the calculations. After finishing training of the network, AGG-SEC, run-time facilities module of the used ready-made software, NeuroShell2®, is invoked to produce a computer routine. Such routine contains all network calculation to be carried out by the network AGG-SEC. After data input (aggregate type, column dimensions, concrete cover, ...), this subroutine is called from the program RESIDUAL to perform the net calculations. Calculation will be corrected according to coating type, coating thickness, temperature severity and admixture type.

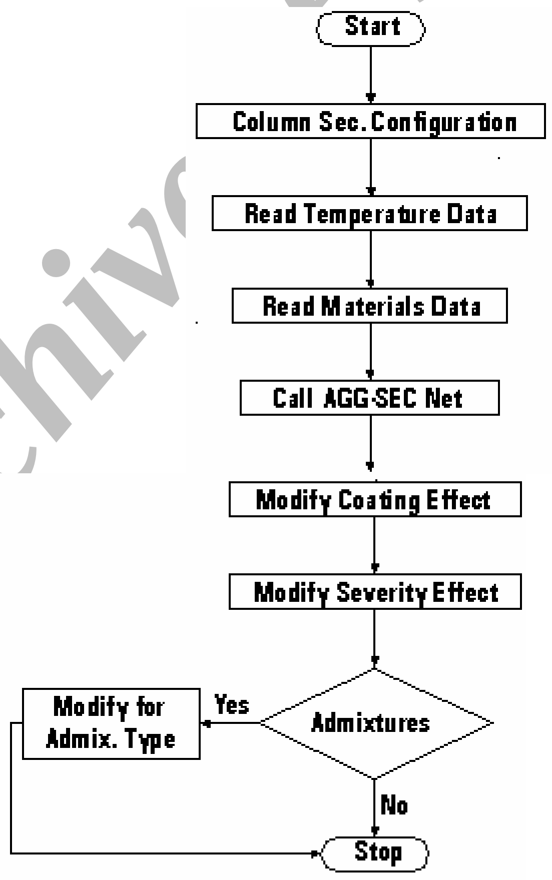


Figure 8. Flow chart of the program residual

First, RESIDUAL reads aggregate type, value of elevated temperature, column dimensions and concrete cover thickness. Consequently, parameters a/b, A_{ex}/A_{co}, C/b, and T/b are calculated. Network AGG-SEC is called to obtain the residual strength F_{ct1}. This residual strength is modified when using coating. This can be achieved using coating modification factor, ζ. The modified residual strength will be re-modified again according to the actual temperature severity. This can be achieved by using the severity modification factor, β. Finally, the last modified residual strength, F_{ct}, can be corrected using the admixture modification factor, α, if any admixture is used. Flow chart and interface of the program RESIDUAL are given in Figures 7 and 8, respectively.

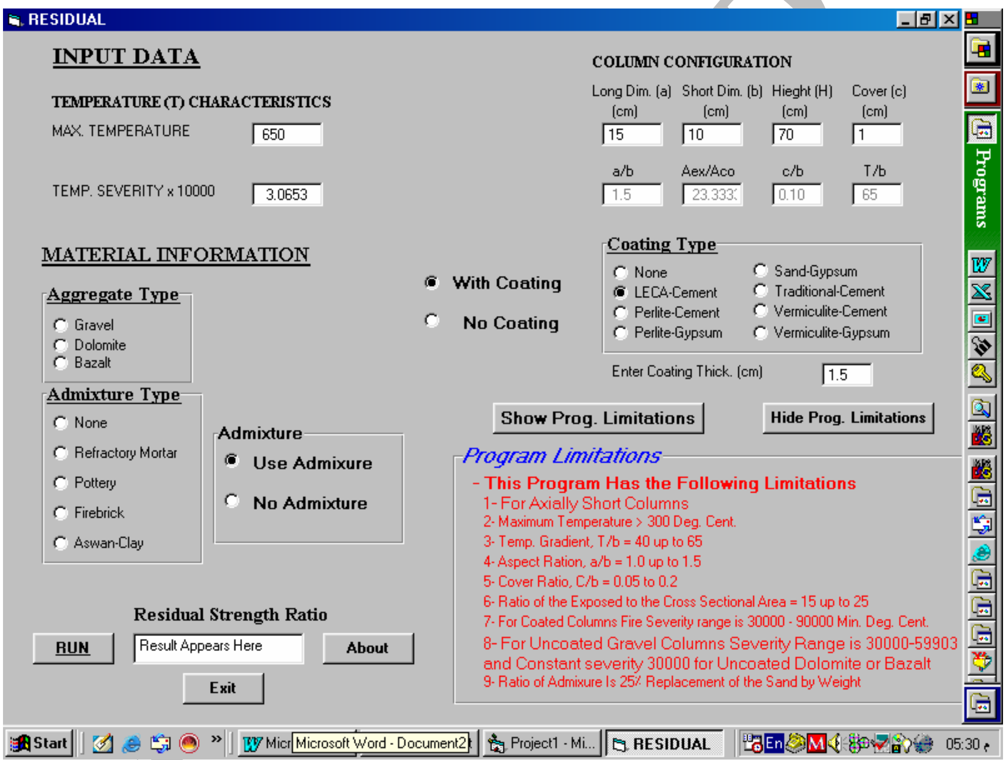


Figure 9. Interface of the program RESIDUAL

8. Conclusions

The main conclusion can be drawn from the present study:

Artificial neural networks, ANNs, can be effectively used to predict the residual strength of heated loaded RC columns. In the conducted tests, the predicted differences between the network outputs and the actual experimental results are found acceptable.

References

1. Dotreppe JC, Franssen JM, Bruls A, Baus R, Vandevelde P, Minne R, Nieuwenburg D, Lambotte H. Experimental research on the determination of the main parameters affecting the behavior of reinforced concrete columns under fire conditions, *Journal of Concrete Research*, No. 179, **49**(1997)117-27.
2. Shields TJ, Silcock GWH. Buildings and Fire, First published, 1987.
3. M Ya Roytman, *Principles of Fire Safety Standards for Building Construction*, Amerind Publishing Co. Put. Ltd, New Delhi, 1975.
4. Abrahams J, Stollard P. *Fire from First Principles*, First Edition, 1991.
5. Malhotra HL. *Design of Fire Resisting Structure*, Chapman and Hall, New York, 1982.
6. Abrams MS. Compressive Strength of Concrete at Temperature to 1600 ^{o}F, Temperature and Concrete, SP-25, American Concrete Institute, Detroit, 1971, pp. 33-58.
7. Zhou X, Zhang J. A theoretical study the effect of coatings on concrete members under fire, *Journal of Concrete Research*, No. 2, **55**(2003)143-9.
8. Basic Perlite Information and Data, The Schundler Companys' Web Site, http://www.schundler.com.
9. M Ya Roytman. *Principal of Fire Safety Standards for Building Construction*, Amerind Publishing Co. Put. Ltd, New Delhi, 1975.
10. About Vermiculite, The Vermiculite Association Web Site, *www.vermiculite.org.*
11. Chan YN, Jin P, Wang JS, Anson M. A Neural Network Model to Predict the Fire Resistance of Concrete, *International Conference on Computational Engineering Science*, Costa Rica, 1997.
12. Chan YN, Jin P, Anson M, Wang JS. Fire resistance of concrete: prediction using artificial neural networks, *Journal of Concrete Research*, No. 4, **50**(1998)353-8.
13. Tung ATY, Wang YY, Wong FS. Assessment of liquefaction Potential using Neural Networks, *Soil Mechanics and Earthquake Engineering,* **12**(1993)325-35.
14. Penumadu D, Jin-nan L, Chameau J, Arumugam S. Rate Dependent Behavior of Clays using Neural Networks", *Proceedings of the 13th ICSMFE*, New Delhi, **4**(1994)1445-48.
15. Rashad AM. Mitigating the Elevated Temperature Effects and Predicting the Residual Strength of Loaded RC Short Columns, PhD Thesis, Cairo University, Faculty of Engineering, 2005.