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EFFECT OF FIRE TEMPERATURE & DURATION ON ULTIMATE STRENGTH OF R.C. COLUMNS WITH DIFFERENT CROSS SECTIONAL SHAPES

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Abstract— Deterioration of reinforced concrete structures can be happened due to many reasons; fire is considered one of the most important deterioration reasons that can lead to a complete and a catastrophic failure. In order to evaluate the degradation level of a RC structures exposed to fire, a number of factors should be considered. These factors are: fire duration, fire peak temperature, dimensions of member, humidity and age of concrete, type of coarse aggre¬gate, chemical composition of cement, water-cement ratio, and the loading conditions of the structural member.(3,4). The main goal of this research is to study the effect of two fires with two different temperatures and durations on the ultimate strength of 18 reinforced concrete columns. The first 6 columns were subjected to a fire of 300^{o}C for 3 hours, 6 columns were subjected to a fire of 600^{o}C for 6 hours and the last 6 columns were used as control (reference) columns without fire exposure and used for comparison. The tested 18 columns are of different cross sectional shapes (circular, square and rectangular) to account for the effect of surface area to volume ratio. Core tests were used to estimate the concrete compressive strength and the depth of the fire affected layer. A mathematical model was proposed to estimate the failure load of RC columns subjected to fire to decide if the structure needs repair and strengthening or not. Results of the mathematical model and the measured experimental results were compared together.

ndex Terms— RC Columns; compressive Strength; Fire Temperature; Fire Duration; Surface area to volume ratio,

1 Introduction

Fire is considered a significant threat to the structural integrity of reinforced concrete buildings. Depending on fire temperature and duration, structural members may lose strength and stiffness eventually leading to collapse [7]. During exposure to high temperatures, reinforced concrete undergoes changes in its chemical composition and physical properties. These chemical and physical changes primarily occur in the hardened cement paste. The resulting physical changes and chemical decomposition of major concrete constituents are demonstrated by cracks, explosive spalling of concrete cover or both [6].

2 Objectives

The main aim of this research is to investigate the effect of fire on ultimate strength of RC columns (ultimate strength of columns is expressed in terms of failure loads) considering the following important parameters:
1. Fire temperature and duration.
2. Surface area to volume ratio of columns.

The tested columns are of different surface area to volume ratios (with three different cross sections; circular, square and rectangular) as shown in fig. (1). Two different fire temperatures and durations were considered (Fire A : 300^{o}C for 3 Hours & Fire B : 600^{o}C for 6 Hours). Compression test on core specimens was used to estimate the deterioration extent of fire on concrete compressive strength.

Fig. 1 : Circular, Square and Rectangular columns

3 Program of experimental study

The experimental program includes preparing and testing of 18 RC columns in compression to determine the ultimate strength. Ultimate strength of these columns was expressed in

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terms of the failure loads. The descriptions of the 18 columns are as follows:

- 6 Columns were used as control specimens for comparison purposes. These 6 columns were not subjected to any fire. Two columns of circular cross section, two columns of square cross section and the last two columns were of rectangular cross section.
- 6 Columns were subjected to a fire of Temperature 300°C for 3 hours duration as shown in fig. (2). The columns cross sections are exactly like the aforementioned 6 columns.
- 6 Columns were subjected to a fire of Temperature 600°C for 6 hours duration. The columns cross sections are exactly like the aforementioned 6 columns.

All columns have the same cross sectional area, same height and the same steel reinforcement. Finally, Core Test was used to evaluate the compressive strength of concrete and the depth of the fire affected layer.

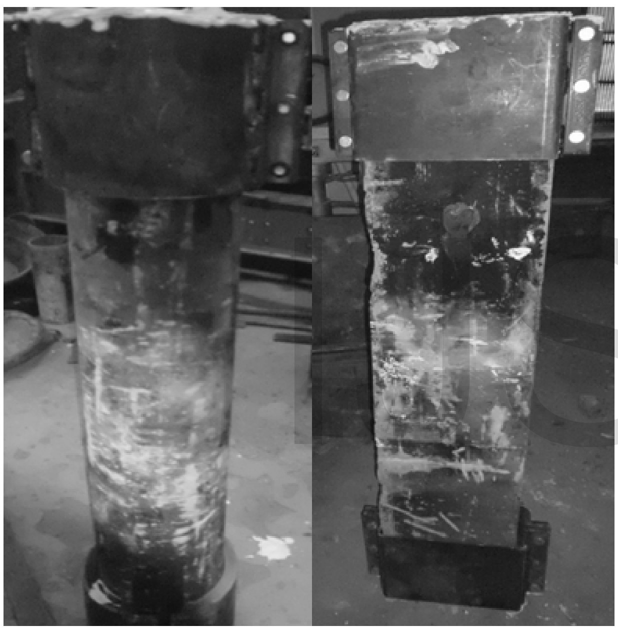

Fig. 2 : Columns after fire exposure

4 Materials and Test Specimens

Ordinary Portland cement was used that complies with the requirement of the ESS 4756/2007 of cement grade N42.5. Crushed stone and natural sand were used as coarse and fine aggregates respectively. The concrete mix was designed to achieve cube compressive strength of 225 Kg/cm^2 after 28 days. The steel reinforcement used was high tensile steel with oblique ribs of grade 400/600 (N/mm^2) and of nominal diameter 12 mm. The used stirrups were plain bars of 8mm diameter and made from mild steel of grade 240/350 (N/mm^2). All concrete materials properties are given in table (1).

18 reinforced concrete columns were prepared using the mix proportions given in table (1). Six columns are of circular cross section of diameter 239mm. Six columns are of square cross section of dimensions 212x212 mm. The last six columns are of rectangular cross section of dimensions 150x300 mm. All the 18 columns are of the same height and cross sectional area. Height of all columns are 150 cm where the cross sectional are A= 450 cm^2. All columns have constant 1% percentage of steel reinforcement (4 bars of diameter12mm) made from high tensile steel of grade 400/600. Stirrups were five every one meter of the column height (i.e. stirrup every 20 cm); stirrups are of 8 mm diameter and made from mild steel of grade 240/350.

TABLE 1
Concrete materials Properties

Fine Aggregate	Sieve size (mm)	4.75	2.36	1.18	0.60	0.30	0.15
	% passing	98.2	90.1	77.3	52.9	6.8	1.3
Coarse Aggregate	Sieve size (mm)	37.5	31.5	28.0	20.0	10.0	5.0
	% passing	100	100	100	77.8	35.5	0.7

Test results of fine & coarse aggregates

Property	Fine Aggregates	Coarse Aggregates
Specific gravity	2.60	2.66
Unit weight (t/m^3)	1.590	1.613
Crushing value (Los Anglos)	---	22.5%
% fine materials (by volume)	1.78	---
% Absorption	---	1.8%

Mix proportions (By weight) of One cubic meter of concrete

Cement (OPC) (Kg)	Sand (Kg)	Crushed Stone (Kg)	Water (Liter)
300	625	1200	200

5 Test Procedure and Results

Six columns were not exposed to fire and used as control (reference) columns for comparison purposes as mentioned earlier. All the other 12 columns were exposed to fire and cooled in air. Six of them were exposed to fire of 300 °C for 3 hours while the other six columns were exposed to fire of & 600 °C for 6 hours. The two fires were at a desert clear site in new Cairo city.

All the 18 columns were tested under compression until failure. The columns were placed in a compression testing machine manually by using a lever crane. The compression testing machine was a hydraulic machine of 200 ton capacity and 0.5 ton accuracy as shown in fig. (3) at the materials laboratory – Faculty of Engineering - Ain-shams University. The load was controlled manually through the testing machine and the axial & lateral strains were measured using dial gages at the column mid-height every 5.0-ton intervals. The top and bottom ends of columns were confined with steel boxes made from 10 mm thickness steel plates of 250 mm height to avoid ends failure. Table (2) show the failure load results of all columns and table (3) show the core test results. Fig. (4) shows the typical crushing failure mode of all columns and fig. (5) shows the shape of core specimen cut from a circular column.

Fig. 3 : Test set up

Fig. 4 : Typical crushing failure mode of columns

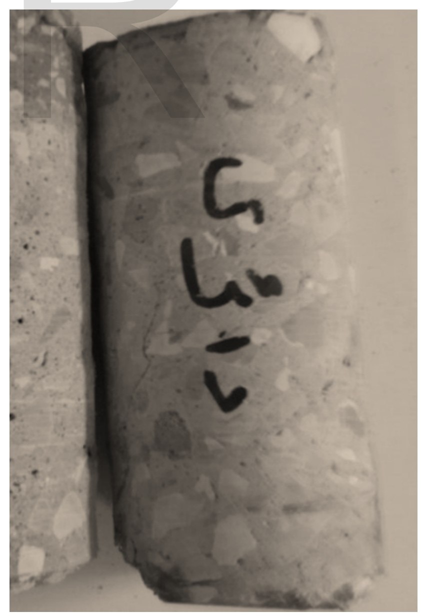

Fig. 5 : Core specimen cut from a circular column

TABLE 2
FAILURE LOADS OF ALL COLUMNS

Fire	Shape	Surface area/volume ratio x10^{-3} (mm^{-1})	Failure Load (ton)	Average (ton)	% from control	Average %
No Fire Control Columns	Circular	16	96	92.2	100	100
			94			
	Square	18	97			
			88			
	Rect.	20	92			
			86			
Fire A 300 ^{0}C 3 Hours	Circular	16	80	78.5	85.1	80
			77			
	Square	18	78	74.0	80.3	
			70			
	Rect.	20	70	69.0	74.8	
			68			
Fire B 600 ^{0}C 6 Hours	Circular	16	58	57.5	62.4	61
			57			
	Square	18	57	56.0	60.7	
			55			
	Rect.	20	60	55.0	59.7	
			50			

TABLE 3
COMPRESSIVE STRENGTH OF CORE SPECIMENS

Fire	Shape	Surface area/volume ratio x10^{-3} (mm^{-1})	Core Equivalent Standard Cube Strength (kg/cm^2)	Depth of fire affected layer (mm)	Average (kg/cm^2)	% from control	Average %
No Fire Control Columns	Circular	16	243	No Fire	240.7	100	100
	Square	18	240				
	Rect.	20	239				
Fire A 300 ^{0}C 3 Hours	Circular	16	212	11	212	88.1	86.4
	Square	18	207	13	207	86.0	
	Rect.	20	205	13	205	85.2	
Fire B 600 ^{0}C 6 Hours	Circular	16	175	15	175	72.7	68.4
	Square	18	162	16	162	67.3	
	Rect.	20	157	15	157	65.2	

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6 Discution of Test Results

6.1 Effect of Fire Temperature & Duration

- As shown from table (2) : as a general attitude, by increasing the fire temperature and duration, ultimate strength of columns (expressed in terms of failure loads) will decrease.
- **For fire "A"** of 300^oC for 3 hours duration, the ultimate strength of circular columns decreased 14.9%, ultimate strength of square columns decreased 19.7% and ultimate strength of rectangular columns decreased 25.2%. **An average drop of 20%** is happened for all columns with different cross sections compared to reference columns (not exposed to fire). Fig. (6) shows the Percentage of failure loads from control columns.
- Losses in compressive strength (from core test results) are 11.9%, 14% and 14.8% for circular, square and rectangular columns respectively. **An average decrease of 13.6%** is happened for all core specimens compared to reference core specimens (not exposed to fire). Fig. (7) shows the Percentage of core compressive strength from control specimens.
- **For fire "B"** of 600^oC for 6 hours duration, the ultimate strength of circular columns decreased 37.6%, ultimate strength of square columns decreased 39.3% and ultimate strength of rectangular columns decreased 40.3%. **An average drop of 39%** is happened for all columns with different cross sections compared to the reference columns. Fig. (6) shows the Percentage of failure loads from control columns.
- Losses in compressive strength (from core test results) are 27.3%, 32.7% and 34.8% for circular, square and rectangular columns respectively. **An average drop of 31.6%** is happened for all core specimens compared to reference core specimens. Fig. (7) shows the percentage of core compressive strength from control specimens.
- Reduction in concrete compressive strength by increasing fire temperature and duration is attributed to micro-and macro-cracks in concrete, volume expansion of coarse aggregates and the deterioration of calcium silicate hydrate (C-S-H) gels in the cement paste.
- In addition of that spalling of concrete cover and losses of bond strength between reinforcing steel and concrete will increase the reduction percentage of failure loads. That is why the reduction of failure loads are higher than that of concrete compressive strength for both fires "A&B".
- Figures 6 and 7 shows the effect of fire temperature & duration on Failure loads and compressive strength respectively.

6.2 Effect of Surface Area/Volume Ratio

- **Fire A :** For columns subjected to fire (A) (300^o C – 3 hrs duration), table (4) shows that by increasing the surface area to volume ratio from 16 to 18 (x10-3)mm^{-1}, the failure loads of columns decreased by about 5.7%. By increasing the surface area to volume ratio from 16 to 20 (x10^{-3})mm^{-1}, the failure loads of columns decreased by about 12.1%. Note that the circular columns here are the references since they have the lowest SA/Vol ratio. Generally, degree of deterioration caused by fire increases by increasing the SA/Volume ratio for all columns. Reduction of columns ultimate strength can be attributed to the reduction of concrete compressive strength due to increasing the surface area exposed to fire (i.e. more cracks, more volume expansion of coarse aggregates, more deterioration of calcium silicate hydrate (C-S-H) gels, more spalling of concrete cover and more losses of bond strength between reinforcing bars and concrete).
- **Fire B :** For columns subjected to fire (B) (600^o – 6 hrs duration), table (4) shows that by increasing the surface area to volume ratio from 16 to 18 (x10^{-3})mm^{-1}, the failure loads of columns decreased by about 2.6%. By increasing the surface area to volume ratio from 16 to 20 (x10^{-3})mm^{-1}, the failure loads of columns decreased by about 4.4%. Note that the circular columns here are the references as mentioned before. But here, we have to notice that the effect of SA/V ratio is very small compared with fire "A" and can be neglected. The major effect in this case is the fire temperature and duration not the S/V ratio. This means that for heavy fires (fires of higher temperatures and durations like fire "B"), the drop in ultimate strength is due to fire temperature and duration regardless the column cross sectional shape (i.e. regardless the S/V ratio).

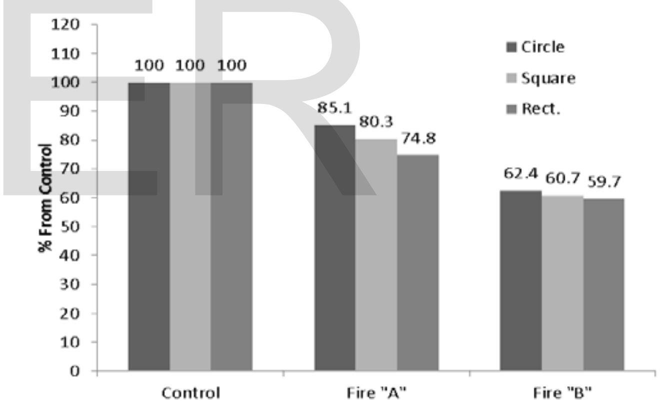

Fig. 6 : Percentage of failure loads from control columns

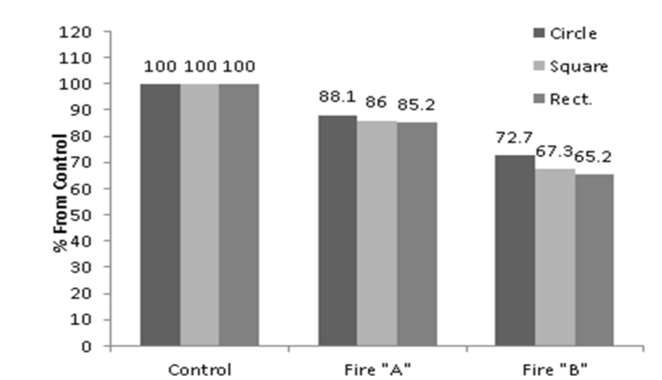

Fig. 7 : Percentage of core compressive strength from control specimens

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TABLE 4
EFFECT OF SA/VOL RATIO (% FROM CIRCULAR COLUMNS)

Fire	Shape	Surface area/volume ratio x10^{-3} (mm^{-1})	Failure Load (ton)	Average (ton)	% from circular columns
Fire A 300 ^{0}C 3 Hours	Circular	16	80	78.5	100
			77		
	Square	18	78	74.0	94.3
			70		
	Rect.	20	70	69.0	87.9
			68		
Fire B 600 ^{0}C 6 Hours	Circular	16	58	57.5	100
			57		
	Square	18	57	56.0	97.4
			55		
	Rect.	20	60	55.0	95.6
			50		

7 PROOSED MATHEMATICAL MODEL

Practically, the most important decision should be taken after the fire exposure is if the structural members need repair and strengthening or not. The answer of this question depends mainly on : to how extent the fire affected the ultimate strength of the structural members?.

Of course, after fire exposure, buildings need a visual inspection and non destructive tests (like Core, Schmidt hammer, Ultrasonic, …etc)to estimate the degradation level.

The proposed mathematical model will be used to calculate the ultimate (failure) loads of columns after fire exposure. The model is based on the measured core compressive strength and measured depth of the fire affected layer. Both measurements are taken from core specimens. Calculations will depend on the following three assumptions :

1) Neglecting the effect of the fire affected layer (outer layer with different color) in resisting the applied compression loads. Basically, this layer does not exist in many locations due to the spalling of the concrete cover.

2) The inner part of concrete (after subtracting the fire affected zone) will resist the full applied loads. Its compressive strength is determined from the core specimens taken from the column after fire exposure. After extracting the core specimens, the fire affected layer (if still existing on the concrete surface) was cut and removed from the core specimen before capping the specimens followed by the compression test.

3) Neglecting the effect of steel reinforcement in calculating the column capacity without a significant error since the steel area does not exceed 1% from the total cross sectional area of the columns. Losses of bond between steel bars and concrete due to high temperature will support strongly this assumption.

The proposed model depends mainly on compressive strength obtained from core tests as well as the measured depth of the fire affected zone as given in table (3). Depth of the heat affected zone was measured from the sides of the core specimens; several values were taken and the average depth was calculated. Fire affected zone (outer layer) has a different color (more dark) than the inner concrete.

Ultimate load for each column equals the measured core compressive strength (of the inner part) multiplied by the cross sectional area of the columns after subtracting the fire affected area from the total cross sectional area of the column as follows :

$$\mathbf{P_u = (f_c)}\ x\ \mathbf{(A\text{-}a)} \qquad (1)$$

Pu : Ultimate (failure) load of the column
fc : Core compressive strength after removing (cutting) the fire affected layer from the core specimen.
A : Total cross sectional area of the column.
a : Cross sectional area of the fire affected zone which calculated from the measured average depth of the fire affected zone.

For example for square columns exposed to fire "A" (300^{o}C for 3 hours):

-Total area of column cross section (A)
= $[212]^2$ = 44944 mm^2
-Area without the heat affected zone (A-a)
=$[(212- (2x13)]^2$ =34596 mm^2
- Core equivalent standard cube strength (fc) = 207 kg/cm^2
- Calculated ultimate load (Pu)
=345.96 cm^2 x 207 Kg/cm^2 = 71613 Kg
- Measured ultimate load = 74000 Kg
- Ratio bet. Calculated /Measured ultimate load
=0.97 (i.e. -3.2% error)

It can be noticed from table (5) that the calculated ultimate load from the proposed mathematical model represents about 92.5% to116% from the measured failure loads. The percentage of error ranging from -7.5% to +16% can be considered acceptable if we consider the variability of reinforced concrete properties and the fire parameters.

Based on this proposed model, we can estimate the ultimate load for a RC column subjected to fire by extracting core specimens from concrete after fire exposure and measure both compressive strength and fire affected depth. Estimation of column ultimate load is of great importance to decide repair and strengthening steps based on the level of danger (degradation level) after fire exposure.

TABLE 5
COMPARISON BETWEEN CALCULATED AND MEASURED ULTIMATE LOADS

Fire	Shape	Equivalent standard cube strength (kg/cm^2)	Depth of heat affected zone (mm)	Average (kg/cm^2)	Pu (ton) Math. Model	Pu (ton) Test	Ratio Mode / Test
No Fire Control Columns	Circular	243	0	240.7	107	92.2	16%
	Square	240					
	Rect.	239					
Fire A 300 ^{0}C 3 Hours	Circular	212	11	212	78.4	78.5	-0.13%
	Square	207	13	207	71.6	74	-3.2 %
	Rect.	205	13	205	69.5	69	0.72%
Fire B 600 ^{0}C 6 Hours	Circular	175	15	175	60	57.5	4.3%
	Square	162	16	162	52.4	56	-6.4%
	Rect.	157	15	157	50.9	55	-7.5%

8 CONCLUSIONS

From the above discussion, it can be concluded that:

1. R.C columns exposed to 300°C for 3 hrs duration losses in average between 15% to 25% from its original ultimate strength depending on the surface area to volume ratio (i.e. column cross sectional shape).
2. R.C columns subjected to 600°C for 6 hrs duration losses near about 40% from its original failure loads regardless the surface area to volume ratios.
3. Increasing surface area to volume ratio will decrease the ultimate strength of R.C columns. Circular column is the best (minimum strength loss) then Square column followed by Rectangular column.
4. Rectangular columns are affected by heavy fire (600°C for 6 hrs) more than square or circular columns because of the minimum dimension of the rectangular column.
5. Calculated ultimate loads from the proposed mathematical model represents 86% to116% from the measured loads. This percentage of error ranging from -7.5% to +16% can be considered acceptable.

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REFERENCES

[1] Jensen E, "Assessment of Concrete Deformation and Failure Behavior during a Standard Fire Test and a Controlled Heating Rate Test", ACI Spring Convention, April 2015.

[2] Technical Note, Izbicki T, McDonald, David B,"Fire Resistance of Reinforced Concrete Buildings", Concrete reinforcing steel institute, No. 52, 2015.

[3] Arel H. S, Yazıcı S, "Effect of Different Parameters on Concrete-Bar Bond under High Temperature", ACI MATERIALS JOURNAL, V. 111, No. 6, November-December 2014.

[4] Bikhiet M.M, El-Shafey N.F *, El-Hashimy H.M, "Behavior of reinforced concrete short columns exposed to fire", Alexandria Engineering Journal, May 2014.

[5] Xiao J, Hou Y, Huang Z, "Beam test on bond behavior between high-grade rebar and high-strength concrete after elevated temperatures", Fire Safety Journal, V.69, 2014.

[6] Lublóy É, György B.L, "TEMPERATURE EFFECTS ON BOND BETWEEN CONCRETE AND REINFORCING STEEL", JOURNAL OF FACULTY OF CIVIL ENGINEERING, V.26, 2014.

[7] Emberley R. L, Leonard D. A, "A Study into the Behavior of Reinforced-Concrete Columns under Fire Exposures using a Spreadsheet-Based Numerical Model", Thesis, WORCESTER POLYTECHNIC INSTITUTE, May 2013.

[8] Jansson R, "Fire Spalling of Concrete theoretical and experimental studies", stockholm, Sweden, 2013.

[9] Yehia S, Kashwani G, "Performance of Structures Exposed to Extreme High Temperature—An Overview", Open Journal of Civil Engineering, 2013.

[10] Sebaaly J, "Fire effects on concrete", Technical Note , Fellow constructor, 2014.

[11] Pothisiri T, Panedpojaman P, "Modeling of bonding between steel rebar and concrete at elevated temperatures", Construction and Building Materials, V.27, 2012.

[12] Zhang Q, Yuan G, Dong Y, "Influence of Cooling Methods and Standing Time on Different Aggregate Concrete Strengths after Elevated Temperature", Advanced Materials Research, ISSN: 1662-8985, Vols. 250-253, pp 155-159, 2011.

[13] Raut N, Kodur V.R, "Response of Reinforced Concrete Columns under Fire-Induced Biaxial Bending", Aci Structural Journal, September 2011.

[14] Dimia M .S, Guenfoud M, Gernay T, Franssen J-M, "Collapse of concrete columns during and after the cooling phase of a fire", Journal of Fire Protection Engineering, 21(4) 245–263, 2011.

[15] Fawzi N. M, Essa M. S, Kadhum M. M, "BEHAVIOUR OF FIRE EXPOSED REINFORCED CONCRETE COLUMNS", Journal of Engineering, Number 3, Volume 17, June 2011.

[16] Nassar K. M, Shihada S, "Improving Fire Resistance of Reinforced Concrete Columns", Thesis, Islamic University of Gaza, 2011.

[17] Henry M, Suzuki M, Kato Y, "Behavior of fire-Damaged Mortar Under Variable Re-Curing Conditions", ACI Materials Journal, V.108, 2011.

[18] Yaqub M, Bailey C.G, "Repair of fire damaged circular reinforced concrete columns with FRP composites", Construction and Building Materials, 25, 2011.

[19] TECHNICAL NOTE, "Fire Damaged Reinforced Concrete–Investigation, Assessment And Repair", Vic Roads, April 2011.

[20] Varona F.B, Baeza F.J, Ivorra S, Bru D, "EXPERIMENTAL ANALYSIS OF THE LOSS OF BOND BETWEEN REBARS AND CONCRETE EXPOSED TO HIGH TEMPERATURES", BUILDING TECHNOLOGY Concrete, 2011.

[21] Haddad R.H, AL-Mekhlafy N, Ashteyat A.M, "Repair of heat-damaged reinforced concrete slabs using fibrous composite materials", Construction and Building Materials, 25 - 1213–1221, 2011.

[22] Wu B, Li Y-H*, Chen S-L, "Effect of Heating and Cooling on Axially Restrained RC Columns with Special-Shaped Cross Section", Fire Technology, 46, 231–249, 2010.

[23] Liu Q, Zhang P, Zhao T, Zhang J, Liu Z, "INFLUENCE OF ELEVATED TEMPERATURE ON MECHANICAL PROPERTIES AND DURABILITY OF CONCRETE", National Basic Research Programof China (no. 2015CB655100), 2010.

[24] Culfik M.S, Ozturan T, "Mechanical properties of normal and high strength concretes subjected to high temperatures and using image analysis to detect bond deteriorations", Construction and Building Materials, V.24, 2010.