EFFECT OF FIRE EXTINGUISHING METHOD AND SURFACE AREA TO VOLUME RATIO ON ULTIMATE STRENGTH OF RC COLUMNS SUBJECTED TO FIRE

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Abstract— Concrete is more durable against fire than other construction materials. However, high temperature has deteriorating effects on concrete mechanical properties. Decrease of strength at higher tempera¬ture can be associated with various reasons, such as micro-and macro-cracks in concrete, volume expansion of coarse aggregates and the deterioration of calcium silicate hydrate (C-S-H) gel in the cement paste. Behavior of concrete subjected to fire depends on its mix properties, fire temperature and duration, dimensions of the structural elements, thickness of the concrete cover, fire extinguishing method (which control the rate of cooling) and the surface area to volume ratio of different structural elements. The main objective of this research is to study the effect of four different extinguishing methods on the ultimate strength of 30 reinforced concrete columns subjected to fire. The tested columns are of different surface area to volume ratios. Non-destructive tests (Core & Ultrasonic pulse velocity tests) were used to estimate the deterioration extent of concrete subjected to fire. Results of the experimental study had shown that by increasing the surface area to volume ratio or by increasing the cooling rate, the ultimate strength of RC columns decreased considerably. A mathematical model was developed to estimate the ultimate strength of RC columns subjected to fire in order to decide whether these columns deserved repair and strengthening or not. Results of the mathematical model and the obtained experimental results were compared together to evaluate the accuracy of the proposed model

Index Terms - Concrete; RC Columns; Ultimate Strength; High Temperature; Fire Duration; Cooling Scheme; Surface area to volume ratio.

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1 INTRODUCTION

Reinforced concrete is the popular material used in structures locally and all-over the world. Thus, the behavior of these structures and their failure shapes are extensively considered. The degradation of concrete strength due to fire has studied in the last few years [1-3]. The behavior of concrete subjected to fire depends on its mix properties, the nature of fire, applied loads, dimensions and kind of structure. Moreover, the failure could occur due to different causes such as loss of bending or tensile strength, reduction of shear strength, reduction of compressive strength, and more. Many years ago, various experimental and theoretical studies have been considered the degradation of RC column strength due to the short-term exposure to fire[4].

Design building codes require some instructions for structural fire-resistance to confirm building integrity for a certain time under fire conditions. Such instructions allow safe evacuation of residents and access for firemen. Most of building codes all over the world recommend minimum column dimension, minimum thickness of concrete cover based on the expected fire temperature and duration. The behavior of structure after fire, whether it is deserved to repair or not, is another point of research that needs more investigation[4]. Most of the research done in this field concentrated on the effect of fire on concrete while a limited number of articles considered the effect of fire extinguishing methods on concrete properties and concrete structural elements such as columns, beams and slabs.

In 2014 Bikhiet et al [4] had studied experimentally and theoretically the effect of concrete strength, fire duration, cooling method, applied load, reinforcement ratio, reinforcement type and bar diameter on the behavior of RC columns subjected to fire of temperature 600oC. Both the experimental and theoretical analysis showed that with increase in the fire duration up to 3 hours, the corresponding column failure load compared with the control case (case of no fire) decreased by nearly 25%. The used two cooling methods in this research were slow cooling in air in room temperature and rapid cooling using water jet. Experimental and theoretical results showed that the failure load of the rapidly cooled columns using water jet is nearly 17% less than those cooled in the room temperature. In addition, cooled columns after fire exposure in the room temperature indicated more ductile failure than those cooled by water jet.

In 2001 Balendran et al [20] had studied the effect of two cooling methods on the residual strength of high strength concrete subjected to different fire temperatures.

The experimental study in this research was carried out on concrete of four different compressive strengths (60, 90, 110 and 130 MPa) subjected to two fires of (200 & 400OC) temperatures for 4 hours duration. Two cooling methods were used slow cooling in air and rapid cooling by quenching in water. It was found that cooling method has an effect on the residual compressive strength of the high strength concrete and quick cooling causes more drop in residual strength than slow cooling and this drop is more pronounced at 400°C (drop 40% to 45% of the original compressive strength).

In 2011 Zhang et al [12] had studied the effect of type of coarse aggregates, fire temperature and cooling scheme on concrete compressive strength of standard cubes. Two types of coarse aggregates were used (siliceous granite aggregates and

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lime stone aggregates). Concrete cubes were subjected to four different temperatures (150, 350, 550 and 750oC) for 90 minutes duration and cooled by two different methods (air cooling and water cooling). The experimental results showed that the concrete mechanical properties were generally decreased with increase in temperature. The relative residual strength of calcareous aggregate concrete is higher than siliceous aggregate concrete at higher temperature. Overall speaking, the cooling schemes have minimal impact on the heated concrete strength at lower temperature (below 200oC), while they have a great influence on concrete strength at higher temperature (above 350oC).

In 2011 Mohamed Salah et al [14] had performed a finite element analysis on columns subjected to fire and cooled gradually. The analyses were performed on reinforced concrete columns subjected to the fire on three sides, with the fourth side having adiabatic conditions. This may be represents a column along the side wall of a building, with the fourth side protected from the effects of fire by the facade. The parameters taken into consideration in this finite element analysis were

1. The fire duration.
2. The effective length of the column.
3. The column cross sectional dimensions.
4. The cooling duration (which control the rate of cooling).

The main conclusion of this finite element analysis had shown that that a failure of the structure is still possible when the fire has been completely extinguished, in some cases several hours after conditions in the fire compartment have become tenable again and a first inspection of the building might be under way

In Egypt Few years ago, a reinforced concrete multistory building (basement + ground floor + 11 typical floors) was failed in Cairo because of fire in the basement floor. The reason of failure (as mentioned in the news papers at that time) was due to sudden cooling (thermal shock) of the basement floor columns using water jets. Cracking of concrete due to the thermal shock was the main cause of failure.

2 OBJECTIVE

The main objective of this research work is to study the effect of four different fire extinguishing methods on the ultimate strength of 30 reinforced concrete columns subjected to fire. The tested columns are with different surface area to volume ratios (with three different cross sections; circular, square and rectangular). Four extinguishing methods were used; three of them are uniform with different rates (rapid, slow and intermediate) while the fourth one was non-uniform. The fire extinguishing methods considered in this research are the most common used extinguishing methods in Egypt and all over the world as mentioned in the literature. Non Destructive tests (Core & Ultrasonic Pulse Velocity tests) were used to estimate the deterioration extent of concrete due to fire. A mathematical model was developed to estimate the ultimate strength of RC columns after fire exposure. Based on the results of this model we can decide if the structure needs repair and strengthening after fire exposure or not.

3 EXPERIMENTAL PROGRAM

The experimental program in this research includes preparing and testing of 30 RC columns in compression to determine their ultimate strengths. The ultimate strengths of these columns were expressed in terms of their failure loads. The descriptions of the 30 R.C. 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. Different columns cross sections were considered to account for the surface area to volume ratio as explained later.
- 24 Columns were subjected to a fire of temperature 600^{o}C for 6 hours total duration. These columns are divided into 3 groups as follows :

- 8 columns were of circular cross-section : two columns were cooled in air, two columns were cooled by water jet, two columns were cooled by CO2 extinguisher, and the last two columns were cooled by both water and air (half of the column height was cooled by water and the other half was cooled in air).

- 8 columns were of square cross section and cooled by the same four previously mentioned cooling methods.

- 8 columns were of rectangular cross-section and cooled by the same 4 previously mentioned cooling methods.

For each group of columns (8 columns as mentioned before), four cooling schemes were used, three of them are uniform with different cooling rates while the fourth one is a non-uniform cooling scheme as follows:

- Two columns were cooled uniformly using water jet (rapid rate).
- Two columns were cooled uniformly in the air in the atmospheric conditions (30^{O}C + 60% relative humidity) (intermediate rate).
- Two columns were cooled uniformly using CO2 extinguisher (slow rate).
- Two columns were cooled non-uniformly so that half of the column height was cooled rapidly using water jet and the other half was cooled in air in the atmospheric conditions. This case specifically represents the case of long columns (as in factories) where the lower half of the column height was extinguished by water (manually using water buckets) while and the upper half of the same column height was extinguished by air in the ambient temperature. Fig.1 shows the shape of columns after fire exposure. Fig.2 shows the extinguishing of columns by CO2 extinguisher.

Finally, two Non-Destructive Tests were used to evaluate the compressive strength of concrete either exposed or not exposed to fire. These two tests are : Core test and Ultrasonic pulse velocity test. Core specimens were taken from columns after the extinguishing process to measure concrete compressive strength as well as the depth of the fire affected zone. These two measurements will be used later in this research in the proposed mathematical model.

4 EXPERIMENTAL PROGRAM CONCRETE MATERIALS - TEST SPECIMENS, PROCEDURE AND RESULTS

The cement used was ordinary Portland cement that complies with the requirement of the Egyptian standard specifications ESS 4756/2007 of grade N42.5. The used coarse aggregate was crushed lime stone and the used sand was natural sand with fineness modulus of 2.73. The concrete mix was designed to achieve cube compressive strength after 28 days of 225 Kg/cm^2. Table (1) shows all the materials properties and the mix proportions for one cubic meter of concrete. The average measured 7 and 28 days cube compressive strength were 180 and 240 Kg/cm^2 respectively. The steel reinforcement used was high tensile steel with oblique ribs of grade 400/600 and 12 mm diameter. The used stirrups were plain bars of 8mm diameter and made from mild steel of grade 240/350.

The experimental program consisted of 30 reinforced concrete columns divided into three cross-sectional shapes (circular, square and rectangular). All R.C. columns have a constant cross-sectional area (45000 mm^2)

Circular columns are of 239 mm diameter - square columns are of 212x212 mm cross section - rectangular columns are of 150x300 mm cross section. The reason behind these dimensions is the capacity of the compression testing machine in the materials laboratory. Columns cross sections were designed to be failed below 135 ton (allowable capacity of the testing machine).

Surface area to volume ratios are 16x10-3 mm-1, $18x10^{-3}$ mm^{-1} and $20x10^{-3}$ mm^{-1} for circular, square and rectangular columns respectively. All columns have constant height of 1500 mm

All columns have a constant 1% percentage of steel reinforcement (4 steel bars of 12mm diameter – steel grade 400/600).

All columns have stirrups of 8mm diameter every 200mm from the column height

All columns except the reference columns (6 control columns) were subjected to fire of 600°C for 6 hours total duration (including about one hour for rising up the temperature to 600°C – so that the fire duration under 600°C was 5 hours). Fire and extinguishing of RC columns were done in an open area in El-shorouk city near Cairo.

All columns (except the 6 control columns) were subjected to fire and extinguished by the previously mentioned methods, then all columns were tested under compression until failure. Columns were tested using a hydraulic compression machine of 200 ton ultimate capacity (135 ton allowable capacity) and 0.5 ton accuracy at the Materials Laboratory - Faculty of Engineering - Ain-shams University – Cairo - Egypt. Figures 3 and 4 show the test set-up and the obtained failure mode for all columns respectively. The load was controlled manually by the testing machine and the axial & lateral deformations were measured using mechanical dial gauges located at columns mid-height every 0.5 ton load intervals. The top and bottom ends of columns were confined with bolted steel boxes made from 10 mm thick steel plates to avoid end failures.

Fig. 1 : Circular, Square and Rectangular columns

Fig. 2. Extinguishing of columns by CO2 extinguisher

TABLE 1: MATERIALS PROPERTIES AND MIX PROPORTIONS

<table>
<tr><td rowspan="2">Fine Agg.</td><td># (mm)</td><td>4.75</td><td>2.36</td><td>1.18</td><td>0.60</td><td>0.30</td><td>0.15</td></tr>
<tr><td>% passing</td><td>98.2</td><td>90.1</td><td>77.3</td><td>52.9</td><td>6.8</td><td>1.3</td></tr>
<tr><td rowspan="2">Coarse Agg.</td><td># (mm)</td><td>37.5</td><td>31.5</td><td>28.0</td><td>20.0</td><td>10.0</td><td>5.0</td></tr>
<tr><td>% passing</td><td>100</td><td>100</td><td>100</td><td>77.8</td><td>35.5</td><td>0.7</td></tr>
<tr><td colspan="2">Property</td><td colspan="3">Fine Agg.</td><td colspan="3">Coarse Agg.</td></tr>
<tr><td colspan="2">Specific gravity</td><td colspan="3">2.600</td><td colspan="3">2.660</td></tr>
<tr><td colspan="2">Unit weight (t/m3)</td><td colspan="3">1.590</td><td colspan="3">1.613</td></tr>
<tr><td colspan="2">Crushing value (Los Anglos)</td><td colspan="3">---</td><td colspan="3">22.5%</td></tr>
<tr><td colspan="2">% fine materials (by volume)</td><td colspan="3">1.78</td><td colspan="3">---</td></tr>
<tr><td colspan="2">% Absorption</td><td colspan="3">---</td><td colspan="3">1.8%</td></tr>
<tr><td colspan="2">Cement (Kg)</td><td colspan="2">Sand (Kg)</td><td colspan="2">C. Stone (Kg)</td><td colspan="2">Water (Liter)</td></tr>
<tr><td colspan="2">300</td><td colspan="2">625</td><td colspan="2">1200</td><td colspan="2">200</td></tr>
</table>

Fig. 3. Test set-up

Fig. 4. Typical column failure

Table 2 shows the failure loads of all the tested columns. Tables 3 and 4 shows the core test results and the ultrasonic pulse velocity test results respectively of all columns (core compressive strength was converted to the equivalent standard cube compressive strength). Fig. 4 shows core test specimen taken from square column after fire exposure.

Fig. 5. Core specimen cut from square column

TABLE 2: FAILURE LOADS FOR ALL COLUMNS

Fire	Cooling scheme	Shape	Ultimate load (ton)	Average (ton)	% From circular	% From control	S.A./volume ratio x 10^{-3} (mm^{-1})
No Fire (Control)	----	Circular	96	92	100%	100%	16
			94				
		Square	97				18
			88				
		Rect.	92				20
			86				
Fire 600° C 6 Hrs.	CO2	Circular	64	63	100%	68%	16
			62				
		Square	62	62	98.4%	67%	18
			62				
		Rect.	63	61.5	97.6%	67%	20
			60				
	Air	Circular	58	57.5	100%	63%	16
			57				
		Square	57	56	97.3%	61%	18
			55				
		Rect.	60	55	95.6%	60%	20
			50				
	water	Circular	57	54.5	100%	59%	16
			52				
		Square	54	54	99%	59%	18
			54				
		Rect.	50	49	89.9%	53%	20
			48				
	Mix	Circular	52	50	100%	54%	16
			48				
		Square	50	49	98%	53%	18
			48				
		Rect.	45	42.5	85%	46%	20
			40				

TABLE 3 : CORE TEST RESULTS FOR ALL COLUMNS

Fire		Shape	Equivalent standard cube strength (kg/cm²)		% from Circular	% from Control	S.A./volume ratio x10⁻³ (mm⁻¹)
No fire (con-trol)		Circular	243 240 239	Av. 241	100%	100%	16
		Square					18
		Rect.					20
Fire 600oC 6 Hrs.	CO2	Circular	190		100%	79%	16
		Square	172		90.5%	71%	18
		Rect.	163		85.7%	68%	20
	Air	Circular	175		100%	73%	16
		Square	162		92.5%	67%	18
		Rect.	157		89.7%	65%	20
	water	Circular	164		100%	68%	16
		Square	160		97.5%	66%	18
		Rect.	153		93.2%	63%	20
	Mix	Circular	159		100%	66%	16
		Square	148		93%	61%	18
		Rect.	148		93%	61%	20

TABLE 4 : ULTRASONIC PULSE VELOCITY TEST RESULTS FOR ALL COLUMNS

Fire		Shape	Ultrasonic Ve-locity (m/s)		% from circular	% from control	S.A./volume Ratio x10⁻³ (mm⁻¹)
No fire (con-trol)		Circular	3800 3660 3650	Av. 3700	100%	100%	16
		Square					18
		Rect.					20
Fire 600° C 6 Hrs.	CO2	Circular	3347.5		100%	91%	16
		Square	3155		94.2%	85%	18
		Rect.	2950		88.1%	80%	20
	Air	Circular	3335		100%	90%	16
		Square	3132.5		93.9%	85%	18
		Rect.	2555		76.6%	69%	20
	wa-ter	Circular	3330		100%	90%	16
		Square	3120		93.6%	84%	18
		Rect.	2540		76.2%	69%	20
	Mix	Circular	3262.5		100%	88%	16
		Square	3015		92.4%	81%	18
		Rect.	2385		73.1%	64%	20

5 DISCUSSION THE EFFECT OF (SURFACE AREA / VOLUME) RATIO

Test results given by Figure (6) and table (2) show that by increasing the surface area to volume ratio from 16 to 20 (x10-3)mm-1, the failure loads of columns decreased by about 3% for columns cooled by CO2, by 5% for columns cooled by air, by 11% for columns cooled by water and by 15% for columns cooled by the Air/water. Note that the circular column is the reference for each extinguishing method since it has the lowest SA/Vol. ratio. Generally, the degree of deterioration and spreading of cracks caused by fire increase by increasing the surface area to volume ratio for all columns. Reduction of columns ultimate strength can be attributed to the reduction of concrete compressive strength due to increasing the concrete surface area exposed to fire (i.e. more area for spreading of cracks). Core test results (Table 3) show that concrete compressive strength decreased for the same cooling scheme due to increasing the surface area subjected to fire with percentages up to 14%. On the other hand, Ultra-Sonic tests results (Table 4) show a drop about 27%.

Core test results agree to a better degree with the columns failure loads more than ultrasonic test results. This is because part of the micro-cracks caused by fire affect the ultrasonic test results without affecting, by the same level, the core test results or columns failure loads. That is why we will depend mainly on core test results to develop a mathematical model to estimate the ultimate loads of columns subjected to fire later in this research. Comparing the test results (failure loads results– core results – ultrasonic results) of columns subjected to fire with those of control columns (not subjected to fire), it can be noticed that the max. drop in failure load is 54%, the max. drop in core compressive strength is 39% and the max. drop in ultrasonic pulse velocity is 36%. These values indicate the level of danger for structures subjected to fire and the need for a model to estimate the degradation level with an acceptable accuracy.

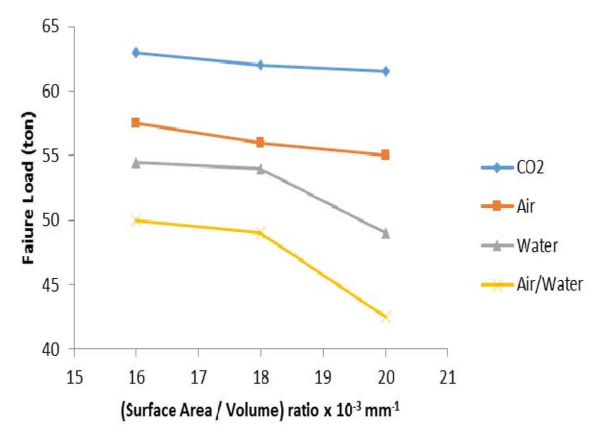


Fig. 6. Effect of (Surface area/Volume) ratio on ultimate Load

6 DISCUSSION THE EFFECT OF COOLING SCHEME

Effect of cooling scheme on columns failure loads is shown in Fig. (7) and Table (5). For the case of circular columns, it can be noticed that by using the cooling schemes (CO2, air, water, air/water), the ultimate strength of columns (expressed in terms of failure loads) decreased by about (34%, 40%, 43%, 48%) respectively compared to the control columns.

For the case of square columns, it can be noticed that by using the cooling schemes (CO2, air, water, air/water), the ultimate strength of columns (expressed in terms of ultimate load) decreased by about (33%, 40%, 42%, 48%) respectively when compared to control columns.

For the case of rectangular columns, it can be noticed that by using the cooling schemes (CO2, air, water, mix), the ultimate strength of columns (expressed in terms of ultimate load) decreased by about (31%, 39%, 45%, 52%) respectively when compared to control columns.

Generally, it can be noticed that the failure loads of columns decreased by increasing the rate of cooling. For the three cases of uniform cooling methods with different rates, it can be noticed from the test results that the slow rate (case of CO2 extinguishing) is better than case of intermediate rate (air extinguishing in atmospheric conditions), which is better than rapid cooling rate (case of water extinguishing).

An average decrease of 34%, 40% and 43% in ultimate loads occurred for cases of CO2, air, water respectively for all columns cross sections.

Core test results (Table 6) show an average drop in concrete compressive strength for the same cross section for uniform cooling schemes of about 27%, 32%, and 34% for CO2, air, water extinguishing schemes respectively.

Increasing the rate of cooling will increase the cracks due to increasing the temperature difference between the concrete surface layer and the internal concrete zone. Sudden cooling of columns (columns cooled by water) will cause a thermal shock in concrete. Water cooling is considered the method of the most rapid rate. Intermediate and slow cooling rates (Air and CO_2 respectively) will cause a temperature gradient across the column cross-section without a thermal shock. That is why the maximum drop in column strength is due to water cooling (for uniform schemes).

Non-uniform cooling scheme (Air/Water method) is considered the worst extinguishing method; the max. reduction in failure loads occurred by using this method. Reduction in failure loads of about 48% occurred in cases of circular and square columns where a reduction of 53% occurred in cases of rectangular columns. Core test results show a drop of about 40% in the case of non-uniform cooling scheme (Air/Water). Here, the thermal shock occurs not only across the column cross-section but also along the column height.

Ultrasonic test results (Table 7) show a reduction ranging from 12 to 18% for all cooling schemes for circular and square columns. This reduction is far from failure loads reduction values. On the other hand for rectangular columns, the reduction values were 20%, 30%, 40% and 45% for CO2, Air, water and Air/Water cooling schemes respectively which is not far from failure load reduction values. Effect of fire and cooling scheme on rectangular columns is more severe than that on circular and square columns. This is due to the minimum dimension of rectangular column is affected more strongly by fire than bigger dimensions of circular and square cross-sections. That is why most of the building codes require minimum dimensions for rectangular columns based on the expected fire temperature and duration. Core test results agree to a better degree with the columns failure loads test results more than ultrasonic test results. That is why we will depend mainly on core results to develop a mathematical model later in this research.

TABLE 5: EFFECT OF THE COOLING SCHEME ON ULTIMATE LOAD

Cross Section	Fire	Cooling scheme	Ultimate load (Pu) (ton)	Average (ton)	Percentage
Circular	No fire (control)	--------	96	95	100%
			94		
	Fire 600° C 6 Hrs.	CO2	64	63	66.3%
			62		
		Air	58	57.5	60.5%
			57		
		Water	57	54.5	57.3%
			52		
		Mix	52	50	52.6%
			48		
Square	No fire (control)	--------	97	92.5	100%
			88		
	Fire 600° C 6 Hrs.	CO2	62	62	67%
			62		
		Air	57	56	60.5%
			55		
		Water	54	54	58.3%
			54		
		Mix	50	49	52.9%
			48		
Rect.	No fire (control)	--------	92	89	100%
			86		
	Fire 600° C 6 Hrs.	CO2	63	61.5	69.1%
			60		
		Air	60	55	61.7%
			50		
		Water	50	49	55%
			48		
		Mix	45	42.5	47.7%
			40		

TABLE 6: EFFECT OF COOLING SCHEME ON CORE TEST RESULTS

Cross section	Fire	Cooling scheme	Equivalent standard cube strength (kg/cm^2)	Percentage
Circular	No fire (control)	------------	243	100%
	Fire 600oC 6 Hrs.	CO2	190	78.1%
		Air	175	72%
		Water	164	67.4%
		Mix	159	65.4%
Square	No fire (control)	------------	240	100%
	Fire 600oC 6 Hrs.	CO2	172	71.6%
		Air	162	67.5%
		Water	160	66.7%
		Mix	148	61.6%
Rect.	No fire (control)	------------	239	100%
	Fire 600oC 6 Hrs.	CO2	163	68.2%
		Air	157	65.6%
		Water	153	64%
		Mix	148	61.9%

TABLE 7: EFFECT OF COOLING SCHEME ON ULTRA-SONIC TEST RESULTS

Cross section	Fire	Cooling scheme	Ultrasonic Velocity (m/s)	Percentage
Circular	No fire (control)	------------	3800	100%
	Fire 600°C 6 Hrs.	CO2	3347.5	88%
		Air	3335	87.7%
		Water	3330	87.6%
		Mix	3262.5	85.8%
Square	No fire (control)	------------	3660	100%
	Fire 600°C 6 Hrs.	CO2	3155	86.2%
		Air	3132.5	85.5%
		Water	3120	85.2%
		Mix	3015	82.3%
Rect.	No fire (control)	------------	3650	100%
	Fire 600oC 6 Hrs.	CO2	2950	80.8%
		Air	2555	70%
		Water	2540	69.5%
		Mix	2385	65.3%

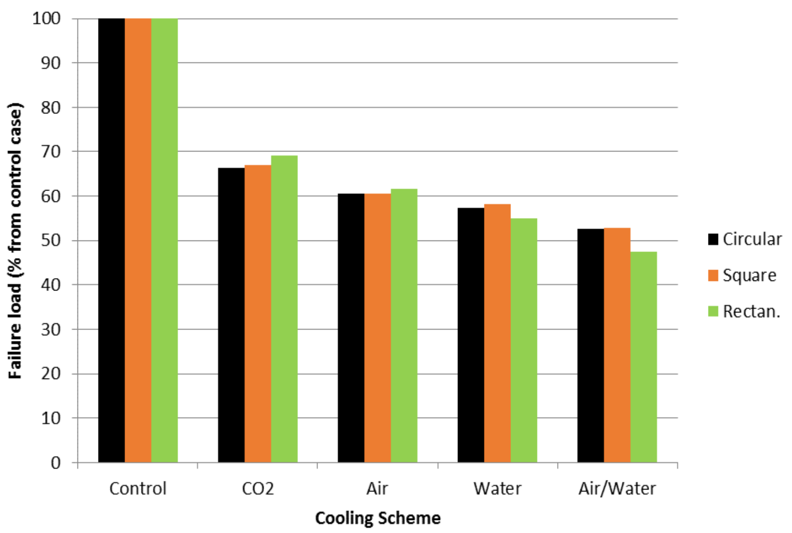


Fig. 7. Effect of the cooling scheme on failure load (Failure load is a % from the control case)

7 DEVELOPED MATHEMATICAL MODEL

The proposed mathematical model will be used to estimate the ultimate (failure) loads of columns after exposure to fire. This model and its calculations are based mainly on two important measurements taken from the core specimens. The first measurement is the compressive strength of core specimens (converted into the equivalent standard cube compressive strength) and the second measurement is the depth of the fire affected zone. Calculations will depend on the following three assumptions :

- The heat affected layer (the outer layer of concrete) does not share in resisting the compression load. Basically, this layer does not exist in many locations due to the spalling of concrete cover.
- The inner part of concrete (after subtracting the fire affected layer) will resist the full applied compression load. Its compressive strength is determined from the core specimens taken from the column after the extinguishing process. After extracting the core specimen, the fire affected layer (if still existing on the concrete surface) was cut and removed from the core specimen before capping the core specimens followed by the compression test.
- Neglecting the effect of the 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 column. Losses of bond between steel bars and concrete due to high temperature will support this assumption strongly.

The proposed model depends mainly on compressive strength obtained from core tests as well as the measured depth of the fire affected zone. The depth of the fire affected zone was measured from the sides of the core specimens. Several values were measured and the average depth was calculated. Fire affected zone has a different color (darker) than unaffected concrete and can be measured easily.

Calculated ultimate load for each column equals the measured core compressive strength multiplied by the cross sectional area of the columns after subtracting the fire affected area from the column cross section.

$Pu = (fc)(A1-A2)$

Pu : Ultimate (failure) load of the column

fc : Core compressive strength (equivalent standard cube strength) after removing (cutting) the fire affected layer from the core specimen.

A1 : Total cross sectional area of the column.

A2 : Cross sectional area of the fire affected zone which calculated from the measured average depth of the fire affected zone.

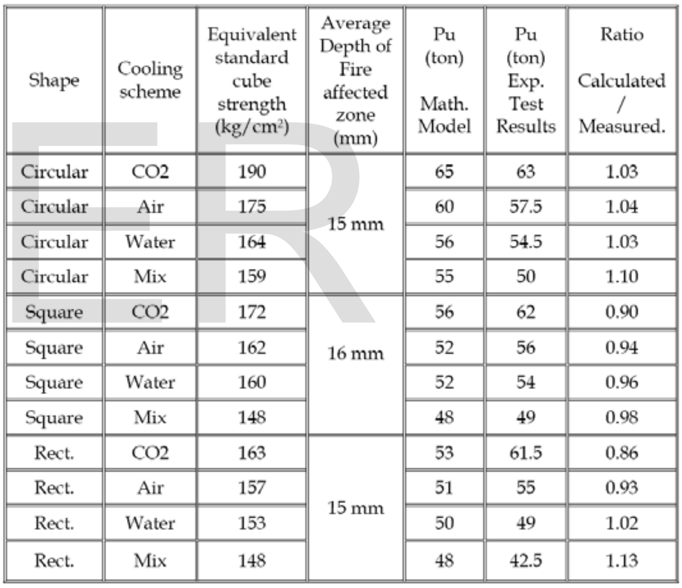
For example for square columns cooled by air :

- Original area of column cross section = A1 = $[212]^2$ = 44944 mm^2
- Area without the heat affected zone =A1-A2 = $[(212- (2x16)]^2$ = 32400 mm^2
- Core compressive strength (equivalent standard cube strength) = 162 kg/cm^2
- Calculated ultimate load = 324 cm^2 x 162 Kg/cm^2 = 52489 Kg
- Measured ultimate load = 56000 Kg
- Ratio bet. calculated and measured ultimate load = 0.94
- Percentage of error (referred to the measured value) = -6%

It can be noticed from Table 8 that the calculated ultimate load from the aforementioned model represents 86% to 113% from the experimentally measured failure loads. The percentage of error (ranging from -14% to +13%) can be considered acceptable if we consider the variability of reinforced concrete properties specially after exposure to fire.

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

TABLE 8: COMPARISON BETWEEN CALCULATED ULTIMATE LOADS FROM THE PROPOSED
MODEL AND THE EXPERIMENTALLY MEASURED ULTIMATE LOADS



Shape	Cooling scheme	Equivalent standard cube strength (kg/cm^2)	Average Depth of Fire affected zone (mm)	Pu (ton) Math. Model	Pu (ton) Exp. Test Results	Ratio Calculated / Measured.
Circular	CO2	190	15 mm	65	63	1.03
Circular	Air	175		60	57.5	1.04
Circular	Water	164		56	54.5	1.03
Circular	Mix	159		55	50	1.10
Square	CO2	172	16 mm	56	62	0.90
Square	Air	162		52	56	0.94
Square	Water	160		52	54	0.96
Square	Mix	148		48	49	0.98
Rect.	CO2	163	15 mm	53	61.5	0.86
Rect.	Air	157		51	55	0.93
Rect.	Water	153		50	49	1.02
Rect.	Mix	148		48	42.5	1.13

8 CONCLUSION

Based on the results of the experimental study and the results of the proposed model, the following points can be concluded :

- R.C columns subjected to 600°C for 6 hours duration losses 46% to 68% from its original failure loads for all columns cross sections and all extinguishing methods.
- For uniform extinguishing schemes; rapid rate of cooling (by water jet) causes 45% drop in failure loads of R.C columns while slow and intermediate rates of cooling (by CO2 and air) causes an average drop of 35%.
- The non-uniform cooling rates (air/water) is much more severe on the ultimate strength of R.C columns than uniform cooling rates. It causes an average drop of 50% in failure loads of R.C columns

- Effect of fire is much more severe on rectangular columns than columns of other cross sections because of the minimum dimension of the rectangular column.
- Increasing surface area to volume ratio will decrease the ultimate strength of R.C columns subjected to fire. The circular column has the minimum strength loss then square column followed by rectangular column.
- Calculated failure loads from the proposed mathematical model represents 86% to 113% from the experimentally measured loads. The percentage of error ranging from -14% to +13% can be considered acceptable.

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