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Structural Performance of Short Square Self Compacting Concrete Columns in Fire

Dr. Mohammed Mansour Kadhum Alkafaji
Engineering College, Babylon University/ Babil.
E-mail: Moh_alkafaji@yahoo.com

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ABSTRACT:

This paper represents an experimental program on the behavior of SCC columns under fire. The research includes testing reinforced SCC columns subjected to various loading levels and heating rates. Nine columns were tested under concentric and eccentric loading and two burning rates are (400 and 700^{o}C) for 1.5 hour period of exposure at 60 days age. The paper represents the main results including the residual ultimate load carrying capacity, maximum crack width, axial deformation, crack pattern, the measured concrete and steel temperatures and axial displacements. It was found that the predicted load carrying capacity of SCC columns by the three codes which are (ACI-318/08, BS-8110/97 and Canadian/84), was unstable after burning except for the BS Code equation which was able to predict load capacity after exposing to high fire temperature levels. Valuable conclusions on the effect of loads and heating on concrete explosive spalling are shown in the paper.

Keywords: Fire, Burning, Spalling, SCC Columns, Load Carrying Capacity

الاداء الانشائي للاعمدة القصيرة المربعة المصنوعة من الخرسانة الذاتية الرص والمعرضة للحريق

الخلاصة

يمثل هذا البحث البرنامج العملي لسلوك الاعمدة الخرسانية الذاتية الرص SCC والمعرضة للحريق. يتضمن البحث فحص نماذج الاعمدة المسلحة والمعرضة الى مستويات احمال وحرارة مختلفة. تم فحص تسعة من نماذج الاعمدة تحت محورية التحميل او لامحورية بلا تمركزية وعرضت الى لهب النار بمستويات حرارة مختلفة (400 و 700) درجة مئوية ولفترة تعرض ساعة ونصف وبعمر 60 يوم. من خلال الفحوصات والاعمال المختبرية تم دراسة مقاومة الاحمال المتبقية، عرض الشق الاقصى، التشوه المحوري وانماط التشقق قبل وبعد التعرض الى لهب النار المباشر وتم تسجيل وعرض ومناقشة النتائج. لقد وجدت النتائج العملية ان معادلات المدونات (الامريكي، البريطاني، الكندي) غير قادرة للتنبؤ بمقاومة الحمل بعد التعرض للحريق ما عدا معادلة المدونة البريطانية تكون قادرة لتخمين الحمل الاقصى بعد التعرض للحريق وبدرجات الحرارة العالية.

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ومن الاستنتاجات الثمينة ايضاً لهذا البحث لوحظ تشضي القطع الخرسانية لاعمدة الخرسانة الذاتية الرص SCC والمعرضة للتأير المزدوج الحمل والحرارة سوية.

INTRODUCTION

Self Compacting Concrete is a material used in the construction where it is suitable for placing the concrete in difficult conditions and in structures with congested reinforcement without vibration. In case of unexpected fire, the concrete elements such as beams, columns etc. will be subjected to extreme temperatures and need for assessment of their performance after the fire. Hence, it is important to understand the change in the concrete strength properties due to the extreme temperature exposure.

When concrete columns are exposed to the fire, the material properties of concrete and the reinforcing steel changed as a result of the temperature increases. The decreases in yield strength and modulus of elasticity reduce the overall strength of the column. Once the column strength decreases lower than the applied load, the column will fail either by crushing or by flexural buckling. In structural fire performance testing, a column is placed in a furnace and subjected to a controlled fire while being loaded with a prescribed force. The period of time from the beginning of exposing fire to the failure is the fire resistance rating of a column.

Many investigations on self-consolidating concrete (SCC) have been carried out in the last several years and the mechanical behaviour of this type of concrete are well understood by now. The fire behaviour of this specialized concrete, however, is not fully understood.

Concrete columns are considered to be an important structural element in reinforced concrete structures because they support the structure and transfer the loads to the supports or foundation, so any failure or damage which occurs in the column may cause a partial or complete failure of the structure by perhaps chain action [1]. Thus, the aim of this experimental study was to evaluate the effect of fire flame exposure on the behaviour of SCC columns.

RESEARCH SIGNIFICANCE

When used in buildings, structural members must be designed to satisfy appropriate fire resistance requirements in addition to load carrying requirements. These fire resistance requirements can be attributed to the fact that, when other measures of controlling the fire fail, structural integrity is the last line of defense.

Many researchers studied the effect of fire on concrete; reinforced concrete members are concentrated on exposing such members to high temperatures in special ovens. They worked on the strength and deformation properties at elevated temperatures. Such conditions do not represent the effects due to real fires, whereas, subjecting these members to direct fire flame is assumed to simulate the conditions happening in real fires. However, very little work was done on load carrying capacity of SCC columns exposed to direct fire flame. In order to simulate this problem to practical site conditions, reduced scale column models were cast and they were as close as possible to practical circumstances. Hence, the study is focused on the structural behaviour of SCC square columns under burning As a part of this research project, proposes reduced-scale fire resistance tests have been conducted on square RC columns to investigate the behaviour of loaded RC columns under exposure to real fire flame. Simulation of real fires in laboratory using a set of methane burners which subjecting the column specimens to real fire flame. The paper includes the fire endurance experiment, main results, conclusions and measured parameters which include temperatures and axial displacement of SCC columns.

RESEARCH BACKGROUND

Several studies evaluating structural performance in fire have been conducted on concrete structures in recent years. Background topics include: SCC properties, column behaviour at normal and elevated temperatures, time-temperature curves, and structural analysis of reinforced-concrete columns. The following is a brief review of these studies.

Self-compacting concrete

SCC is defined so that no additional inner or outer vibration is necessary for compaction. It is compacting itself due to its own weight and is de-aerated almost completely while flowing in the formwork [2]. In structural members with high percentage of reinforcement it also fills completely all voids and gaps. SCC consists of the same components as conventionally normal concrete, which are hydraulic cement, fine and coarse aggregates plus appreciable amount of additives and/or admixtures (fillers and superplasticizers). The high amount of superplasticizer is for reducing the water demand and highly enhancing flowability and overall workability. The high powder content, as well as the use of viscosity modifying agents is to increase plasticity and viscosity of the SCC mix [3].

Su K. et al. 2002, [4] studied the effect of sand ratio (S/A = fine aggregate volume to total aggregate volume) on the elastic modulus of SCC. They found that the flow ability of SCC increases with the increase in S/A ratio, meanwhile the modulus of elasticity of SCC is not significantly affected by this ratio when the total aggregate volume is kept constant.

Several test methods are used to evaluate filling ability (flowability), passing ability (passibility), and segregation resistance (stability) of fresh SCC. Among these test methods are the followings:

- Slump flow and T50cm test to evaluate flowability and stability.
- L-box test to assess flowability and passing ability.
- U-box test to measure the filling ability.
- V-funnel test to determine the filling ability.

The effect of fire on reinforced concrete structure

The load capacity of a reinforced-concrete column will deteriorate based on the reduction of the modulus of elasticity and strength of both the concrete and the reinforcing steel. These losses are a result of the increasing cross-section temperature due to fire exposure (Society of Fire Protection Engineers, 2008).

Kodaira et al., 2004, [5] studied the behaviour of composite beams composed of rolled steel profile concreted between flanges during a fire by conducting a fire resistance test with different cross sections and load ratios, by numerical analysis. The results they obtained are as follows:

1) In steel-concrete composite beams which were simply supported and to which positive bending moment was applied, deformations were downward in the early period of fire, and then the deformation rate decreased once but increased again as heating was continued, leading to the limit of fire resistance.

2) The fire resistance of steel-concrete composite beams increased when the applied bending moment ratio decreased. The fire resistance time was affected by the size of the cross-section, whether steel-concrete composite beams were connected to the reinforced concrete floor or not, as well as by the applied bending moment ratio.

Annerel, 2007, [6] studied the residual strength of concrete members after fire exposure. From a batch of traditional (TC = NSC) and self-compacting (SCC) concrete, two cubes were heated for each of the examined temperature levels till 800°C. The heating rate was 3.5°C/min and the target temperature was kept constant for 750 minutes. The cubes were cooled in ambient air after removal from the oven. Figure 1 shows the mean residual compressive strength immediately after cooling was 20°C for TC and 105°C for SCC. Both curves were situated around the Euro code curves for normal siliceous concrete (E_c).

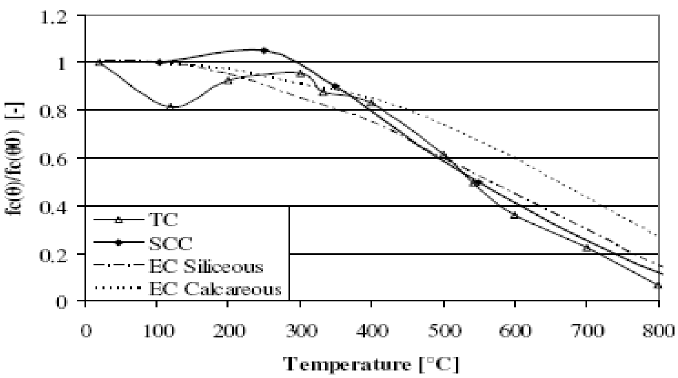


Figure (1): The residual compressive strength [8].

Chen et al. 2009, [7] studied an experimental research on the effect of fire exposure time on the post-fire behaviour of reinforced concrete columns. Nine reinforced concrete columns (45 mm x 30 mm x 300 mm) with two longitudinal reinforcement ratios (1.4% and 2.3%) were exposed to fire for 2 and 4 hours with a constant preload. One month after cooling, the specimens were tested under axial load combined with uniaxial or biaxial bending. The test results showed that the residual load-bearing capacity decreased with increasing fire exposure time. This deterioration in strength which is followed by an increase in fire exposure time can be slowed down by the strength recovery of hot rolled reinforcing bars after cooling. In addition, the reduction in residual stiffness was higher than that in ultimate load; consequently, much attention should be given to the deformation and stress redistribution of the reinforced concrete buildings subject to earthquakes after afire.

EXPERIMENTAL PROCEDURE

Materials and mixes

Introduction

The properties of materials used in any structure are of considerable importance [9, 10]. The American Society for Testing and Materials (ASTM) and Iraqi specifications IQS standard tests were conducted to determine the properties of materials used in the current study .

Materials

Tasluga-Bazian Ordinary Portland cement (O.P.C) (ASTM Type I), was used in this study. This cement conforms to the Iraqi specification (IQS, No.5:1984 and ASTM C150-05) [10, 11]. Kerbala sand brought from Al-Akhaidher region was used as fine aggregate in the present study through sieve size (9.5 mm) to separate the aggregate particles of diameter greater than 9.5mm. Rounded coarse aggregate of maximum size (14 mm) from Al-Nebai region was used. The sand and gravel were then washed and cleaned with water several times, and then they were spread out and left to dry in air, to be ready for using. Deformed steel bars of diameters (Ø8 mm and Ø10 mm) were used as reinforcement.

A liquid superplasticizer commercially known as [Ura-plast SP] was added to the concrete mix to obtain high workability and fluidity. This superplasticizer can be classified as class F and G according to ASTM C494-99 as it has the capability of obtaining more than 12% reduction in mixing water for a given consistency, and it has a retarding effect to setting [12]. According to trials it was found that the most suitable dose of Ura-plast SP is (4 liters per 100kg of cement). The typical properties of this superplasticizer are listed in Table (1).

Table (1): Properties of Ura-plast superplasticizer.

Form	**Color**	**Relative density**	**Viscosity**	**pH value**
Viscous liquid	Dark brown	1.1 at 20°C	128 + 3 cps at 20°C	6.6

Limestone powder (LSP) named locally as "Ghobra" was used filler to increase the amount of powder content (cement + filler) to produce SCC mixes in the present work. The fineness of limestone powder was measured by Blaine method and found to be 1500 cm^2/g. The particle size which is less than 0.125mm acts to increase workability and density of the SCC. This filler conforms to BS 8500-2, 4.4 specifications. The chemical composition of the used limestone powder is given in Table (2).

Table (2): Chemical composition of limestone powder.

Oxide	CaO	SiO_2	$Al2O_3$	Fe_2O_3	MgO	SO_3	L.O.I
%	52.76	1.40	0.70	0.17	0.10	2.91	40.60

Mix design and proportions

The Japanese mix design procedure (cited by EFNARC 2005) [14] was followed to design the mix proportions of SCC. Many trials were made to fix the proportions so as to obtain SCC mix maintaining the ranges and limits of fresh SCC. Table (3) shows the mix proportions of the SCC mix used in the present study.

Table (3): Mix proportions of the SCC mix.

Mix proportions of specimen materials, (kg/m^3)						
W/P ratio	Water	Cement	Sand	Gravel	LSP	SP % by wt. of cement

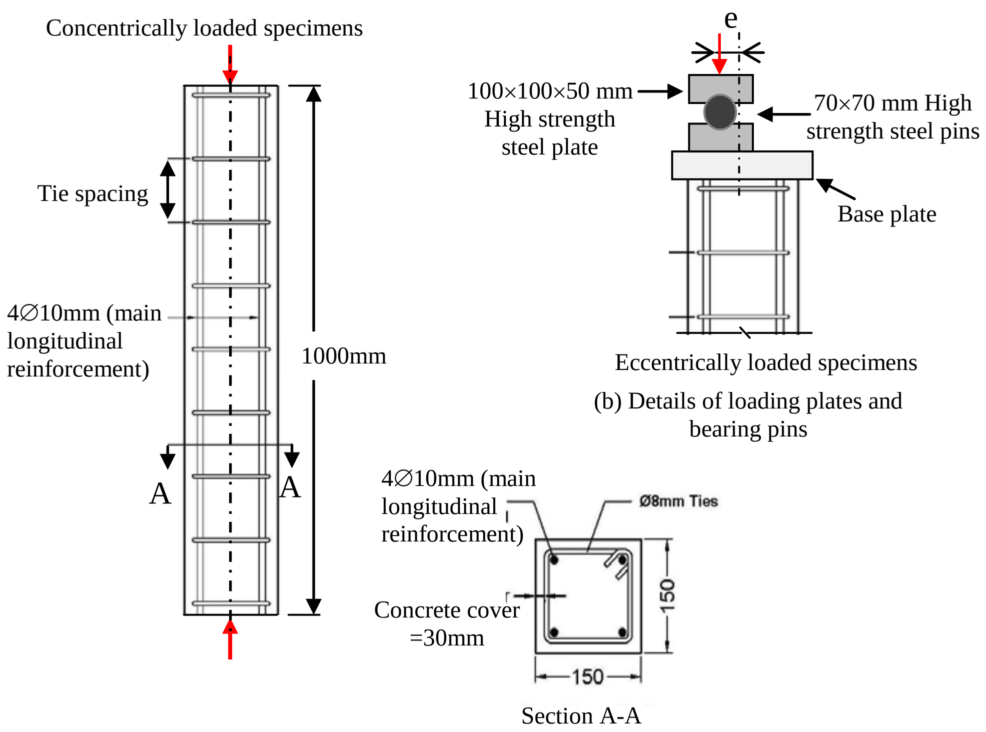
0.33	200	480	760	844	120	6

The fresh properties of SCC

The fresh properties of SCC were tested by the procedure of European Guidelines. Four characteristics were achieving by conducting three tests which were flowability, was achieved by slump flow test, passibility which was achieved by L box tests, viscosity which was achieved by T50 and V funnel tests, and segregation resistance which was achieved by no halo shape in slump flow test, no visible segregation during handling or testing, and by controlled the average separated diameter of slump to not exceeded the segregation border in slump flow test.

Column specimen preparation

The dependent dimensions of the specimens of SCC columns were selected to be (150×150×1000 mm). The mold included: base, sides and sectors for ends. They were made of plywood with a thickness of (18 mm) to reduce the water effect during the casting process. Reinforcing steel used as longitudinal bars and lateral ties in reinforced SCC columns which met the ASTM A615 requirements [14]. The longitudinal and lateral ties reinforcement was deformed steel bars of Ø10mm and Ø8 mm respectively. The specimen dimensions, reinforcement arrangements and loading plate arrangement are presented in Figure (2). Table (4) shows the description and the notation of column specimens.



(a) Specimen dimensions and reinforcement details

Figure (2): Specimen details and loading plate arrangement.

Table (4): Description of column test specimens.

Column notation	C1	C2	C3	C4	C5	C6	C7	C8	C9
Temperature stage (ºC)		25			400			700	
Eccentricity (e) of applied load (mm)	0	25	50	0	25	50	0	25	50

Nine of the SCC column specimens were cast and cured under laboratory conditions. The casting and curing of the columns were carried out during four months from the first of May to the first of September 2013. All specimens were cured in the same method. Polyethylene sheets were used to cover the columns and control specimens in order to avoid plastic shrinkage cracks within 24 hours and then burlap sacks were placed over the columns and water was sprayed on them continuously for fourteen days. Finally, the columns were dried out in uncontrolled laboratory conditions until 60 days which is the time of testing.

Fire processing was achieved by subjecting the SCC column specimens to direct fire flame from a network of methane burner. (Mohamadbhai, 1986 and Castillo, 1990) [15, 16] stated that the maximum temperatures reached during fires of buildings ranging from of 1000 to 1200^{o}C although such high temperatures occur only at the surface of the exposed members. Since the modeling of the specimens is small size, it was decided to limit the temperature of the study to two levels of (400 and 700^{o}C). The dimensions of this burner network are. (1000×100 mm) (length × width respectively) as shown in Figure (3).

When the target temperature was reached, the temperature of concrete and steel reinforcement was measured at different depths by continuously applying Infrared ray thermometer from about approximately 3 meters from the concrete exposed to fire. The measurement device is shown in Figure (4).

Figure (3): Network methane burners.

Figure (4): Temperature measurement device.

Testing procedure

All the SCC column specimens were white painted to facilitate detection of cracks. The column specimens were tested vertically in a stiff testing frame. For the eccentrically loaded tested, high strength steel pins and bearing plates were placed at the desired eccentrically at each column end to allow free rotation of the ends and to distribute the load (see Figure 3b). While the concentrically loaded columns, the rotational pins were removed from the test setup. The columns were tested using a load cell of maximum capacity of (150 Tons) at the age of (60 days). At each test, the first cracking load, midheight lateral deflection, axial deformation, maximum crack width and ultimate load were recorded. The load was applied gradually and the readings were recorded manually. When the first crack appeared on the column surface, the load was applied in small increments up to failure. The specimens were concentrically and eccentrically loaded by eccentricity of (25mm and 50mm).

Two dial gauges were fixed at distance 25 mm from the nearest edges of these columns to measure the deformation at these edges due to burning. Also, another one was fixed at the centerline of column specimens to measure the axial deformation due to concentric load. The dial gauge was used to measured axial deformation of the specimen having a minimum graduation of 0.001 mm and a maximum needle length of 50 mm mounted at the bottom face of the specimens. Figure (5) shows the setup of axial deformation measurements mentioned above. The positions of the visual cracks in the concrete and the loads, at which these cracks were formed, were recorded. The reading of the lateral deflections versus loads was recorded simultaneously for each load increment. The SCC column specimens which were subjected to fire flame under loading are shown in Figure (6). The specified (target) fire temperature was reached the fire burners which are controlled by a sliding arm to decide the fire distance and fire intensity to the surface of the column specimens, and also by monitoring the through controlling the methane gas pressure in the burners. The temperature was measured by infrared rays thermometer continuously till reaching the specified (target) fire temperature. Then, the sliding arm and gas pressure were kept at this position along the period of burning (1.5 hour).

Figure (5): Testing measurement of axial deformation.

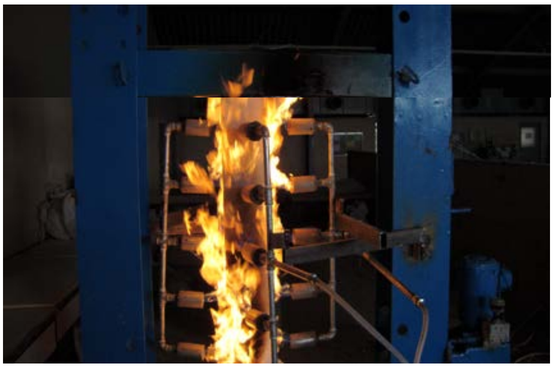


Figure (6): Testing of SCC column under 15% of ultimate load with exposure burning.

During the fabrication of the specimens, three thermocouples were installed within the concrete and on the internal reinforcing steel at column midheight for measuring temperatures at various locations across the cross section. Two of them were positioned at 25mm and mid-depth of the cross-section of reinforced concrete columns, and another one was touching the steel reinforcement of the column. The layout of the thermocouples is shown in Figure (7).

The lateral deflection of the column specimens exposed to fire is resulting from loading to 20% of ultimate load before burning, loading 20% and applied fire flame, and loading after burning until failure. While, for specimens without burning the lateral deflection is resulting from applied load only.

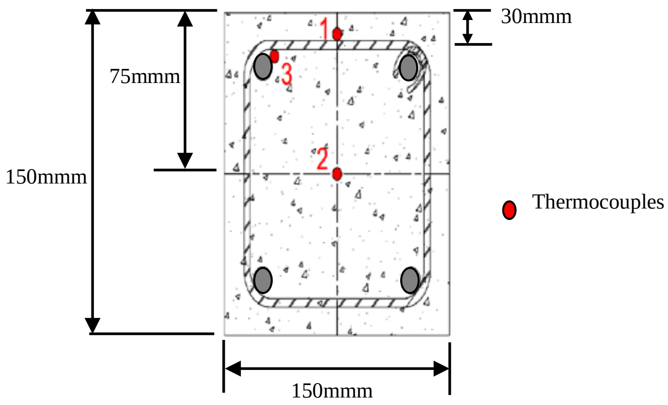


Figure (7): Thermocouples locations at midheight section in model SC columns.

RESULTS AND DISCUSSIN

Fresh concrete test results

Table (5) gives the experimental results obtained from Slump flow, T50cm, L-box, and V-funnel tests that were conducted throughout the present work. It can be seen that the test results are within the limits of self-compacting concrete results established in EFNARC 2005 [13]. This means that the designed concrete mix in the present work conforms to the specifications of SCC.

Table (5): Results of fresh properties for SCC.

Type of test	Flow, (mm)	T50cm, (sec.)	V-time, sec.	L-box (H2/H1)%
Values	770	3.1	6.8	0.93
Limits of EFNARC,2005	650–800	2–5	6–12	0.8–1

Compressive strength results

Table (6) presents cube compressive strength test results for the SCC mix before and after exposure to fire flame at the ages 28, 60 and 90 days. Compressive strength test was conducted by using a standard cubes of dimensions (150×150×150 mm). Each test result represents the mean value of the compressive strength of three cubes. Figure (8) reveals the relation between compressive strength and fire temperature. It is obvious from the results that the compressive strength decreases significantly with exposure to fire flame.

The percentage of residual compressive strength after burning at 400ºC fire temperature was (84%), while the percentage of the remaining compressive strength was (42%) at (700ºC) Fire temperature. In addition, it can be noted that the test results of the residual compressive strength after burning show that, the reduction at 28 days age was more than the reduction at 60 and 90 days. This may be attributed to the fact that hydration of cement paste is more complete at later ages.

Table (6): Test values of cube compressive strength before and after burning.

Age at exposure (days)	Cube compressive strength (MPa)			(fcua/fcub) Ratio	
	Temperature (ºC)			b/a	c/a
	25 (a)	400 (b)	700 (c)		
28	42	35.3	17.6	0.84	0.42
60	46	40.0	19.8	0.87	0.48
90	48	42.2	24.5	0.88	0.51

fcua: Cube compressive strength after burning
fcub : Cube compressive strength before burning

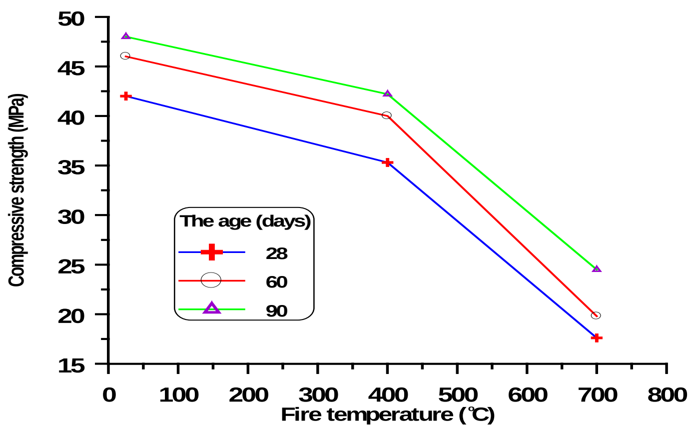


Figure (8): Effect of fire temperature on the compressive strength.

First crack load and ultimate load for columns exposed to fire flame

The ultimate load values were recorded for all columns which were tested with or without exposing to the fire flame. Table (7) provides the results of the first crack load and ultimate load values for all columns specimens. From this Table, it can be seen that the values of ultimate load decreases when the column specimen is exposed to fire flame.

At burning temperature (400 and 700°C), the residual ultimate loads were (86 and 26 %) for concentric loads respectively, while (87, 113.8%) and (28, 39%) for reinforced concrete SCC column specimens loaded at eccentricity of (25, 50mm) respectively.

First crack load which was recorded in this study was represented, the load which caused the visible first crack in the face of column which parallel with the direction of the fire flame and caused by loading operation with respect to the columns which were not exposed to the fire and, which were exposed to fire. Where, the last columns (fired columns) were precracked before the loading operation. From these results, it can be concluded that the first crack load of the reference SCC column specimens decreased when the amount of eccentricity was increased. It is important to note that, clearly from the results, first crack load was more sensitive to fire flame than the ultimate load. This is according to the effect of fire intensity on the outer layers of the columns in which first cracks occur. Where these layers were subjected to temperature more severe than the interior layers. As the loss in tensile strength in these layers the first crack rapidly occurs of.

Figure (9) reveals the effect of fire flame on residual ultimate load carrying capacity with different amount of eccentricities (25 and 50 mm). From this Figure, it can be noted that the residual ultimate load capacity had increased in the eccentric column C6. This can be explained by the low reduction percentages in tensile and compressive strength of the concrete member at low fire temperature exposure. On the other hand the expansion happened due to fire exposure can cause an increase in the axial compressive stress affecting on the eccentric (e=50 mm) loaded column C6 which raises the moment capacity of the column and consequently the load capacity.

The fire flame temperature applied to concrete column causes evaporation of the free moisture in concrete with continual exposure to fire. The temperature inside the specimen increases and the strength of concrete decreases. This can be attributed to hydration of free lime and deformation of $Ca(OH)_2$ due to absorption of moisture by the effect of fire flame, so expansion takes place, which causes cracking and reduces the ultimate load capacity.

Table (7) Test results of the first crack load, ultimate load, axial deformation and maximum deflection for reference columns and columns exposed to fire flame.

Column notation	Temperature level°C	First Crack load(kN)	Ultimate load (kN)	Percentage residual ultimate load (%)	Axial deformation (mm) at centerline	Maximum deflection at midheight (mm)
C1		182.5	978	100	3.2	----
C2		144.0	658	100	----	5.83
C3	25	47.5	232	100	----	8.72
C4		Precracking	842	86	4.4	----
C5		Precracking	574	87	----	6.3
C6	400	Precracking	264	113.8	----	9.20
C7		Precracking	256	26	6.18	----
C8		Precracking	187	28	----	6.9
C9	700	Precracking	91	39	----	8.9

--- No measured value

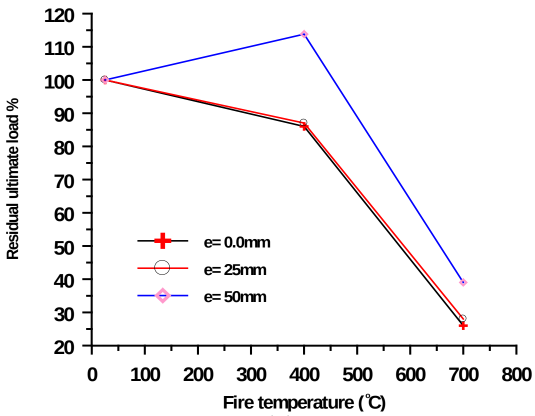


Figure (9): Effect of fire temperature on the residual load capacity of SCC column.

The data of axial deformation was recorded up to 95% of the ultimate load because the final axial deformation at ultimate load cannot be measured due to the immediate type of failure of concrete column specimens. Figures (10 and 11) present the effect of fire flame temperature on the characteristics of axial deformation of the column specimens. From these Figures, it can be seen that the concentric SCC column specimens exhibited a small contraction when loaded to 20% of the ultimate load during 25minutes then remain constant for the later period of this applied load, and then the columns exhibit a sudden increase in contraction which was identified as failure after applied residual load. While, for column specimens exposed to fire flame temperature (400 and 700°C) also exhibited a small contraction when loaded to 20% of the ultimate load during 25 minutes then remain constant for the later period of this load, thereon noticed a large elongation at the left and right edge of column specimens when exposed to burning, then a sudden contraction was observed when applying the residual load until 95% of ultimate load. As it is shown in Figure (11) the axial deformation development of columns (C4 and C7) have a similar trend but the maximum axial deformation value of 6.18 mm was reached at ultimate load of 256 kN. Also, it is important to point out here that the higher value axial deformation was recorded in case of high fire exposure temperature. The deformation during fire exposure results from several factors, such as load, thermal expansion, and creep. The initial expansion of the column was mainly due to the thermal expansion of concrete and steel. While the effect of load and thermal expansion is significant in the intermediate stages, the effect of creep becomes pronounced in the later stages due to the high fire temperature. The later contraction of the column in the exposure is mainly due to the loss of strength and stiffness of the concrete and steel as the internal temperatures increase.

Finally, these Figures present the variation in fire exposure time with the vertical displacements in y-direction (expansion or contraction) for column specimens at different stages during burning and loading.

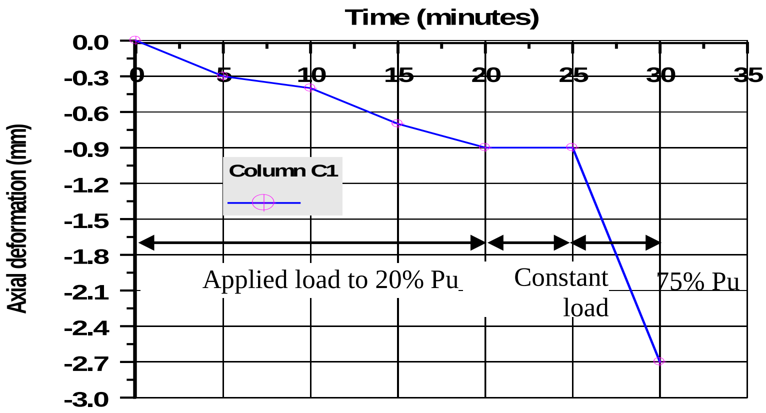


Figure (10): Axial deformation recorded at centerline of column specimen before burning.

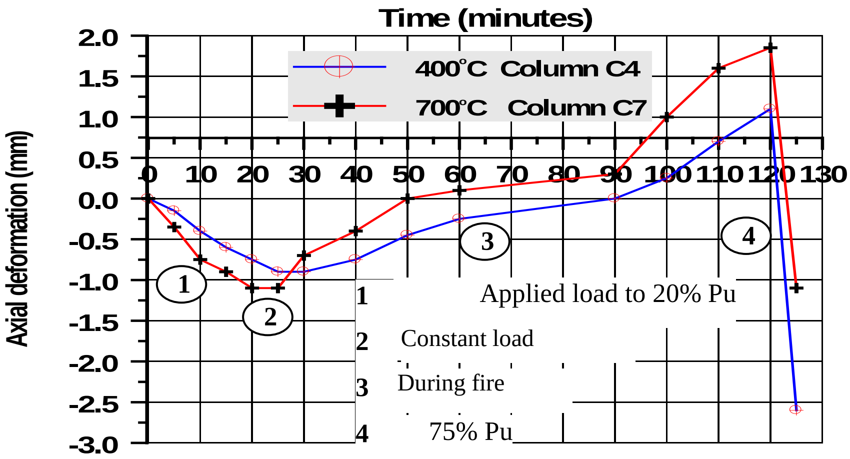


Figure (11): Axial deformation recorded at 50 mm from the centerline of column specimen before, during and after burning.

Effect of fire flame on load-deflection relationship

The midheight lateral deflection of the column specimens which were loaded and exposed to fire flame at the same time was measured during this process. Each column specimen was loaded to 20% of the ultimate load before burning for 25 minutes; then it was exposed to fire flame temperatures of (400 and 700°C) thereon; the residual ultimate load was applied until failure. Figure (12) showed the load-midheight lateral deflection relationships for columns before and after the exposure to the fire flame where columns which exposed to higher fire temperature, gave approximately, the lesser curvature compared with those of the control column specimens and lower burning temperature. This can be attributed to the reduction in modulus of elasticity of concrete and increase in the amount of cracks formation. These Figures reveal that the load-deflection relation of the column specimens is almost linearly proportional to the two eccentricities (25 and 50mm) and for temperature exposure 700°C. In addition, it can be noted that the increase in the fire temperature decreases the load carrying capacity and increases lateral deflection in column specimens.

When the fire flame temperature increases to 700°C, the load carrying capacity decreases, but the deflection values increases rapidly for the same load and eccentricity as shown in these Figures. This can be attributed to the weaker bond strength between the concrete and steel reinforcement. This de-bonding is resulted due to the cracks that formed at surface. They were at locations close to the steel reinforcement. As these cracks propagated and widened, the fire penetrated into the inner part of the column specimens and the steel reinforcement through the "crack opening".

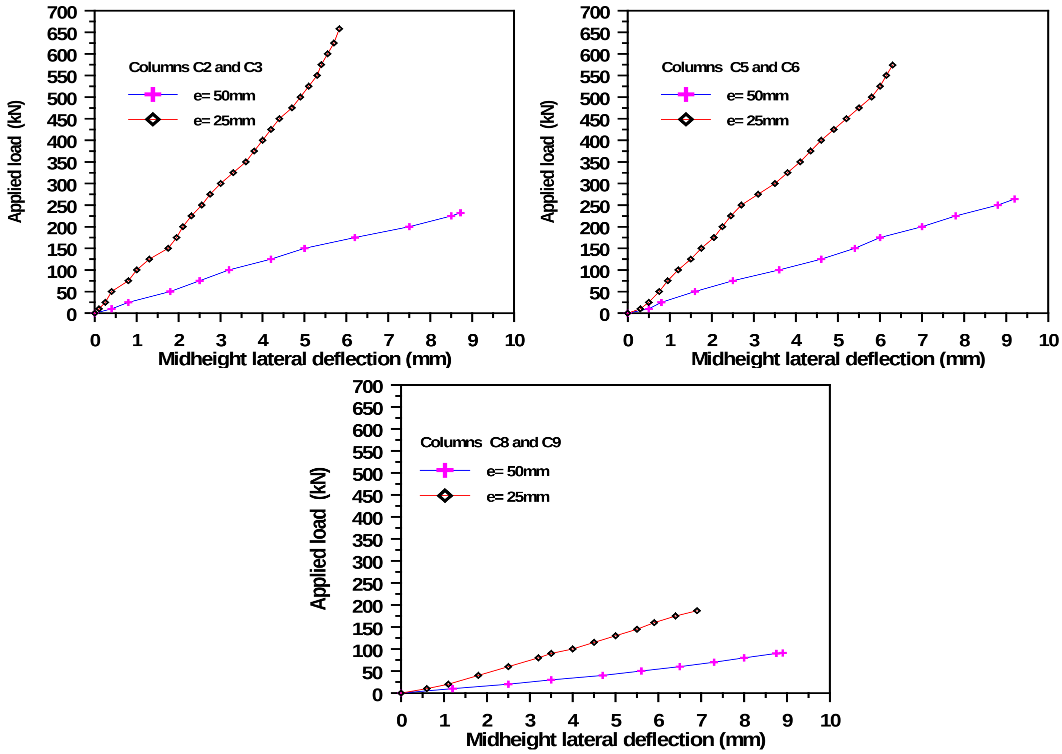


Figure (12): Comparison of eccentric load-midheight deflection curves of SCC columns.

Test observations and mode of failure

During testing the SCC column specimens up to failure, it was observed that the cracks appeared on the concentric columns nearly vertical, hairline cracks appeared at the middle portion of columns. More cracks (mostly vertical) continued to appear on the column faces. Concrete spalling was approximately observed at the first twenty five minutes of burning at temperature 700°C. Scabbing occurred prior to the column failure due to the crushing of the concrete and subsequent buckling of the main reinforcement at later stage. Cracks appeared for columns loaded at eccentricity 25 and 50mm on the surface from the tension zone towards the compression zone. Further, flexural cracks were formed progressively and widened as the loading increased. Nearly some of short vertical, hairline cracks were detected on the middle third of the columns.

Longitudinal cracks appeared and propagated on all faces of the columns tested which were as long as to fire flames continued. Transverse cracks during burning, which appeared at locations of ties can also be distinguished. Figures (13 and 14) show these cracks. As loading increased, the cracks widened and extended to join and form triangular-shaped cracks of (115-135 mm) length and (25-35 mm) width as shown in Figure (15).

At the first few minutes, it was noticed that runoff water from all surfaces of column specimens. This phenomenon was observed at about 12-16 minutes and continued for approximately 11 minutes for all burning temperatures 400 and 700^{o}C, Figure (16) shows this behaviour. This can be attributed to the increase in vapor pressure generated by fire exposure inside the saturated voids which makes the water to escape out from the cracks on the surface. Different modes of failure were observed:

- Compression failure for concentric loaded column specimens.
- Combined flexural and compression failure for eccentric loaded column specimens.

The columns burned at 400^{o}C, the type of failure for concentric and eccentric loaded specimens remained without changes. While the columns burned at 700^{o}C, the type of failure also remained constant but scabbing occurred in the concrete cover. This can be attributed to the vapor pressure of the runoff water which exerts internal pressure stresses on the surface layers of concrete which were unconfined by the tie reinforcement resulting in scabbing of these layers.

Figure (13): SCC column exposure to fire 400°C and concentric loading.

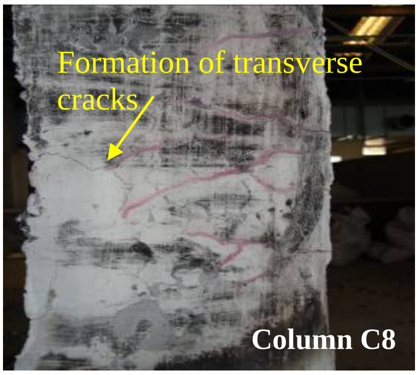


Figure (14): SCC column exposure to fire 700°C and eccentric loading.

Figure (15): SCC column exposure to fire 700°C and eccentric loading prior to failure.

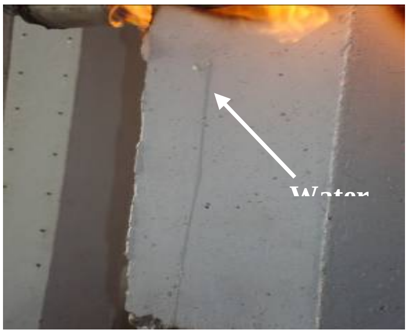


Figure (16): Runoff water from SCC column specimen.

General behaviour and verification of building code provisions of axially loaded column specimens

The test results were used to verify the recommendations and design simplifications of the various Building Codes pertaining to axial load capacity (Pn) design. Some comments are made on the accuracy of strength predictions. These equations are selected and used in this study for comparison with the results of the experimental work. They are outlined in Table (8). Table (9) presents the comparison between the experimental results with (ACI, B.S and Canadian) Codes. To utilize these equations after exposure to fire flame temperatures, the relative axial load capacity values (Pu test/Pn calculated) were calculated for the SCC column specimens. The relationship between fire temperature with residual axial load capacity and ultimate load carrying capacity were illustrated in Figure (17).

Table (8): Summary of formulas for predicting axial load column capacity.

Method	Equation	EQ. NO.
ACI-318M-08 Code	$P_n = 0.85f'_c A_n + f_y A_{st}$	1
B.S 8110-97 Code	$P_n = 0.4f_{cu} A_n + 0.75f_y A_{st}$	2
Canadian Code-1984	$P_n = 0.51f'_c A_n + f_y A_{st}$	3

Table (9): Comparison of the load carrying capacity test results with that obtained from (ACI, B.S and Canadian) codes of SCC column specimens at age of 60 days.

Column notation	Compressive strength (MPa)		Steel yield stress (GPa)	Ultimate load (kN)				$\frac{P_{u\,test}}{P_{n\,ACI}}$	$\frac{P_{u\,test}}{P_{n\,B.S}}$	$\frac{P_{u\,test}}{P_{n\,Cand.}}$
	Cube	Cylinder		Test	B.S	ACI	Canady			
C1	42.0	35.7	540	978	500.3	843.3	547.5	1.16	1.96	1.78
C4	35.3	30.0	540	842	440.8	735.8	484.0	1.14	1.91	1.74
C7	17.6	14.96	453	256	260.8	421.6	308.8	0.61	0.98	0.83

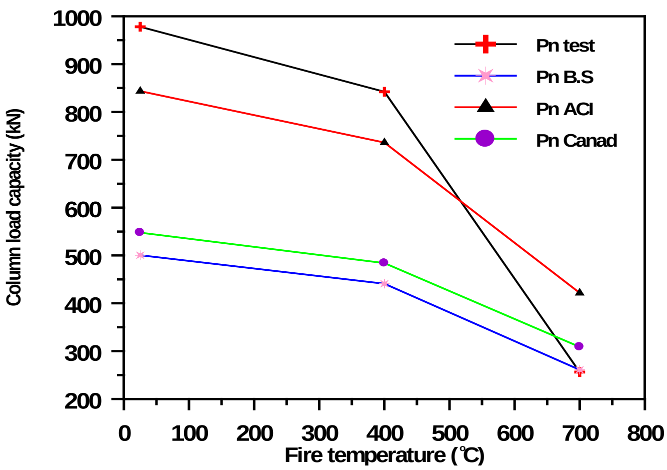


Figure (17): Effect of fire temperature on the axial load capacity of SCC column specimens.

At burning temperature (400°C), the ACI Building Code gave reasonable results to predict axial load capacity, while the (B.S and Canadian) codes gave very conservative values of column capacity. The ratios between the measured and (ACI, B.S and Canadian) [18, 19, 20] predicted values were (1.14, 1.91 and 1.74%) respectively.

At burning temperature (700°C), the ACI Code became unable to predict axial load capacity, while the B.S Building codes gave close results, whereas, the Canadian code gave overestimated results to predict column load capacity to predict column capacity. The ratios between the measured and (ACI, B.S and Canadian) predicted values were (0.61, 0.98 and 0.83%) respectively.

From the results, it is clear that the predicted ultimate axial load capacity obtained from ACI Code provisions is lower than that obtained from the experimental work at burning temperature up to (400°C). While, at burning temperature above (400°C) the predicted ultimate axial load capacity obtained from ACI Code provisions is greater than that obtained from the experimental work. This can be attributed to the precracking which happens upon burning.

While, B.S-8110 gave results lower than that obtained from experimental results at burning temperatures up to 700°C. The predicted ultimate axial load capacity obtained from Canadian Code provisions is lower than that obtained from the experimental work at burning temperature up to (400°C), while at burning above (400°C) the Canadian Code provisions slightly overestimate ultimate axial load capacity.

From previous Table (9), it is clear that the yield tensile stress at fire temperature of 400˚C, both burning and subsequent cooling did not affect on it, but the effect was observed in case of burning temperature at 700˚C. The percentage of residual yield tensile stress was (83.9%) for the longitudinal bars reinforcement. The modulus of elasticity was not affected by burning and cooling. Similar behaviour was observed by other investigators [20, 21].

Temperature Behaviour

The temperature results for Column C4 and Column C7 at midheight for horizontally positioned thermocouples are given in Figure (18). The readings for temperature measurement were for the concrete surface, steel reinforcement, in the concrete at 30 mm from surface and internal to the concrete. The experimental results clearly indicate that the temperature of the surface which is near to the fire is higher and decreases towards the center of the column. (Lie and Celikol, 1991) have shown that this temperature behaviour is due to the thermally-induced migration of moisture toward the center of the column [21]. The influence of moisture migration is the highest at the center of the column.

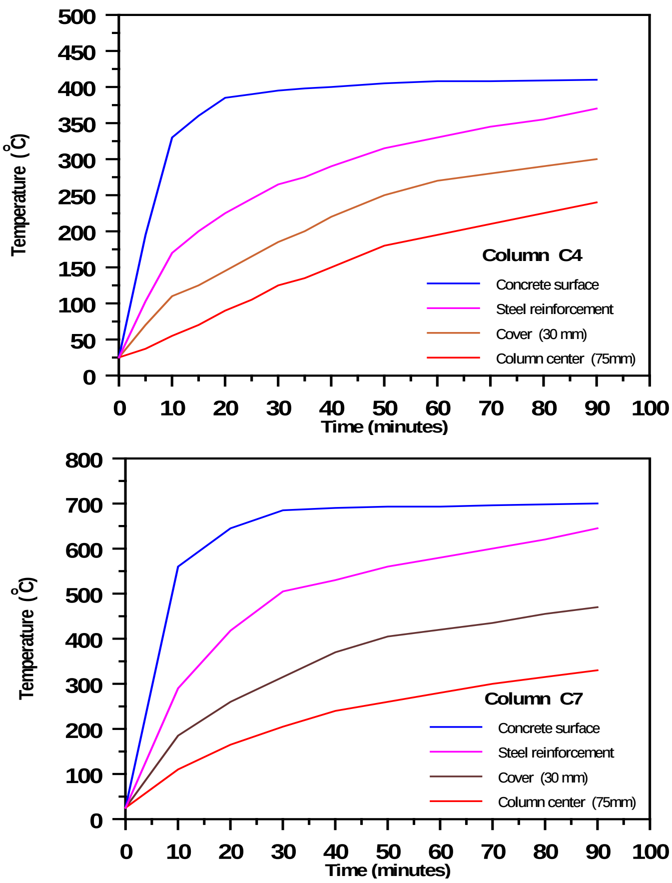


Figure (18): Temperature recorded at midheight in columns C4 and C7 as a function of time.

CONCLUSIONS

Based on the results obtained from this work, the following investigation can be made:

1. The residual compressive strength ranged (84-88%) at 400ºC, and (42- 51%) at 700ºC burning temperature.
2. In this study, it is observed that the value of longitudinal crack width is less than flexure transverse crack width for columns with or without burning.
3. It is found that the residual ultimate load capacity of SCC column specimens decreases significantly when subjected to burning by fire flame.

- After exposure to fire temperature 400^{o}C, the percentage residual ultimate load is 86% for concentric loaded, while 87% and 113.8% for eccentric at 25 and 50 mm loaded column specimens respectively.
- After exposure to fire temperature 700^{o}C, the percentage residual ultimate load is 26% for concentric loaded, while 28% and 39% for eccentric at (25 and 50 mm) loaded column specimens respectively.

4. The experimental results clearly indicate that the crack width in reinforced concrete columns that are subjected to fire flame are higher than the columns that are not burned at identical loads.
5. In this study, it is noticed that the load-deflection relation of rigid beam specimens exposed to fire flame temperature around 700^{o}C are more leveled indicating softer load-deflection behaviour than that of the control beams. This can be attributed to the early cracks and lower modulus of elasticity.
6. Columns tested under high exposure fire temperature showed less fire resistance.
7. The Canadian/84 and ACI Codes predict ultimate load carrying capacity after exposure to 400^{o}C fire flame temperature conservatively.
8. B.S-8110/97 Code gives close results to predict ultimate load carrying capacity after exposure to 400^{o}C fire flame temperature.
9. It was noticed that the spalling occurs in a period up for 33 minutes when exposed to temperature 700^{o}C. While, low burning temperature minimized the risk of explosive spalling.

REFERENCES

[1] Sakai, K., and Sheikh, S. A., "What Do We Know about Confinement in Reinforced Concrete Columns," ACI Structural Journal, V. 86, No. 2, Mach-April, pp. 192-207, 1989.

[2] Campion, M., and Jost, P., "SCC: Expanding the Possibilities of Concrete Design and Placement," Concrete International, No. 4, April, pp. 31-34, 2000.

[3] Frank J. and Fritz H., "Ecological Performance of SCC," The Swiss Society of Engineering and Architects, pp. 1-8, 2001.

[4] Su, K.; Cho, W.; Yang, C.; and Huang, R., "Effect of Sand Ratio on the Elastic Modulus of SCC," Journal of Marine Science and Technology, V. 10, No. 1, pp. 8-13, 2002.

[5] Kodaira, A.; Fujinaka, H.; Ohashi, H.; and Nishimura, T., "Fire Resistance of Composite Beams Composed of Rolled Steel Profile Concreted between Flanges," Fire Science and Technology 23(3), pp. 192-208, 2004.

[6] Annerel, E., "Residual strength of concrete members after fire Exposure," Department of Structural Engineering, Ghent University, 2 pp., 2007.

[7] Chen .B, Li.C, Chen .L, "Experimental Study of Mechanical Properties of Normal-Strength Concrete Exposed to High Temperatures at an Early Age", Fire Safety Journal 44, pp. 997–1002, 2009.

[8] Neville, A. M., "Properties of Concrete," Longman Group, Ltd., 4th and Final Edition, pp. 388, 1995.

[9] ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI211.1-91)," American Concrete Institute, Michigan, U.S.A., 1997.

[10] Iraqi Organization of Standards, IOS 5, for Portland cement, 1984.
[11] ASTM C150, "Standard Specification for Portland Cement," Annual Book of ASTM, Standards American Society for Testing and Materials, 2005.
[12] ASTM C 494/C494M-99, "Standard Specification for Chemical Admixture for Concrete," Annual Book of ASTM Standards, American Society for Testing and Materials, V.04.02, 1999.
[13] European Research Project, "Measurements of Properties of Fresh Self Compacting Concrete," Guidelines for Testing Fresh Self Compacting Concrete, Principle Author; G.DE SCHUTTER, September, 2005.
[14] ASTM A615/615M-5a,"Standard Specification for Deformed and Plain Carbon Structural Steel Bars for Concrete requirement," Annual Book of ASTM Standards, V.01.02, 2005.
[15] Mohamadbhai, G., T., "Effect of Exposure Time and Rates of Heating and Cooling on Residual Strength of Heated Concrete," Magazine of Concrete Research, V. 136, September, pp. 151-158, 1986.
[16] Castillo, C., and Durrani, A., J., "Effect of Transient High Temperature on High Strength Concrete," ACI Materials Journal, V. 87, No. 1, January-February, pp. 47-53, 1990.
[17] ACI 318-08, "Building Code Requirements for Reinforced Concrete", American Concrete Institute, Detroit, 2008.
[18] Canadian Standards Association, "Design of Concrete Structures for Buildings CAN.3-A23.3-M84," National Standard of Canada, Rexdale, Canada, 1984.
[19] Harada, T., Takeda, J., Vamane, S., and Furumura, F., "Strength, Elasticity and Thermal Properties of Concrete Subjected to Elevated Temperatures", ACI Special Publication, SP-34, V.1, pp.377-401, 1972.
[20] Nuri, D., "The Effect of Temperature on Some Properties of Concrete", M.Sc. Thesis, Submitted to The Building and Construction Department, University of Technology, September, 116PP, 1983.
[21] Lie, T. T., and Celikkol, B., "Method to Calculate the Fire Resistance of Circular Reinforced Concrete Columns", ACI Materials Journal, pp.84-91, 1991.