Journal of Engineering and Sustainable Development
http://jeasd.uomustansiriyah.edu.iq/index.php
https://doi.org/10.31272/jeasd.26.2.5

Vol. 26, No. 02, March 2022
ISSN 2520-0917

PUNCHING SHEAR BEHAVIOR OF A SELF-COMPACTED BUBBLE DECK SLAB SUBJECTED TO FIRE AND WATER COOLED

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Received 18/8/2021 ***Accepted in revised form 10/10/2021*** ***Published 1/3/2022***

Abstract: In this research the punching shear behavior of Self-Compacted bubble RC slab was investigated after burning it in real fire test until reach 300 C° and cooling it by air and water Experiment results show that using self-compacted concrete improves the cracking pattern and punching failure zone due to improvements in the microstructure of the concrete and how it fills voids and makes contact with the plastic ball. The ultimate load increased by (13) % when using SCC with the same fć, and the effect of water cooling was reduced compared to its effect on normal concrete due to SCC's lower permeability, but the effect of spalling made self-compacted concrete more sensitive to high temperatures.

Keywords: *bubble slab, self-compacted concrete, water cooling, punching shear force, high temperature*.

1. Introduction

Punching shear strength for RC structures are important not just to cover their service life but, rather often, to rehabilitate them after they have been damaged during special events, for example earthquakes, fires etc.

Due to the fact that some damages, such as warping and shrinkage, would be caused to the concrete structure during the high temperature, this might lead to deterioration in the stability of the concrete structure. This could lead to a loss of bearing capacity and cracking of the components. After being exposed to fire, concrete will lose its strength, certain visible damage will form, etc. Other major issues involve declining steel reinforcement and the weakening of concrete [1]. Laboratory studies indicate that the concrete's strength and performance is to be reduced at high temperatures. The formation of micro-structure cracks, as well as changes in volume of concrete caused by thermal stresses, are directly on building stiffness [2]. The influence related to fire on structural members be governed by different aspects such as the temperature rate, duration and distribution of fire loading as well as the cooling method (gradually or suddenly). Also, the fire source either standard fire or real fire flame.

Due to the fact that slab acts as a deadener and a joist, it a key structural member that is imperative for building construction [3]. The building's system requires to be designed not only to withstand dead and live loads, but is also designed to withstand the fire resistance. The fire resistance associated with the reinforced concrete slab is expressed in terms of fire resistance as determined by the standard

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fire tests. After the fire is brought to the desired intensity, the slab is scheduled to be overcome in a specified time frame. The standard ASTM E-119 [4] method of floor slab fire tests specifies that if "the temperature rise of the unexposed area is less than 120 ° C, the fire test is considered to be successfully performed. In order to produce this product, regulations have specified that the steel must not be heated to over 540°C in the fire endurance phase.

Once the span increases, the amount of deflection also increases. Therefore, the thickness of the slab should be increased. With the added thickness of the slab, the roof will be heavier and the foundation thickness and column cross section are both increased. Buildings also consume more materials such as reinforcement steel and concrete.

For the purpose of avoiding such drawbacks, Bubbled Reinforced Concrete Slab System (also referred to as Voided Slab System), was lately used in Europe. It has been developed via Jorgen Breuning (Danish engineer). The system contains hollow plastic spheres cast in concrete for creating grid related to the void forms in slab. RC bubble slab generally consists from bottom reinforcing mesh, plastic balls and top reinforcing mesh [5]. Checking the failure of the punching shear and the strength of the slab-column connections is one of the critical analyzes that must be carried out if bubbled slab is to be used. This type of failure occurs at a load path below the flexural capacity as the transverse shear stress concentrates around the column slab connections [6]. Fig.1 indicates a "RC" bubble slab system.

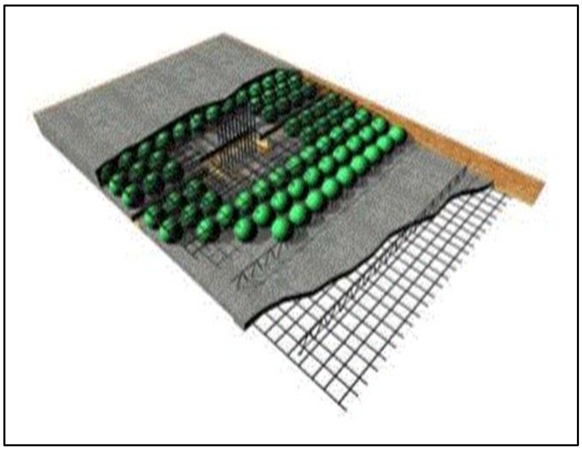


Figure 1. Demonstrates the RC Bubble Slab System

Recent years have seen an increase in the development and use of high-performance concretes such as high strength concrete (HSC) and self-compacting concrete (SCC). Additionally, research and development of high-strength self-compacting concrete for pre- and post-tensioned components are ongoing. Not only the mechanical behavior of buildings made of these materials at room temperature is critical in this development, but also understanding of their performance during fire exposure. In the case of traditional concrete, standards such as Eurocode, EC2 1992-1-2 [7] contain material models for heat transmission and mechanical properties. In the Eurocode 2 the validity of the material models for SCC and HSC has not yet been verified (in general) although some recent studies show that some aspects of traditional concrete and SCC are similar [8]. Concrete that does not require any energy for compacting in order to cover the reinforcement or fill out the mould has attracted a great deal of interest. The technique has also been introduced for dwelling houses, tunnels and office buildings. SCC today covers 11% of the concrete production market in Sweden for example [8].

2. Previous Studies

Salem et al in 2012 [9] experimentally studied the impact of fire on the punching strength of solid slabs. Experimental program, that consists of 14 one-third scale specimens which have been pre-exposed to the fire on their tension side, also they have been tested in concentric punching. The major studied parameters are cooling approach, duration of exposure to fire, and concrete cover. The specimens have been exposed to direct flame for 1, 2 and 3 hours. The concrete covers which have the sizes of 25mm and 10mm have been applied for the test specimens. There are 2 cooling approach used; sudden cooling with water and gradual cooling in air utilized directly to slabs' heated surface. It has been indicated that exposing the slabs to fire will lead to decrease of up to 18.3 percent and 43 percent in the cracking loads and ultimate punching loads, respectively. The concrete cover has been indicated to have considerable impact on temperature's level in the reinforcement of tension. Decrease in the punching strength of up to 14 percent has been identified in specimens with three hours exposure to fire in comparison to those of 1 hour exposure. Sudden cooling has been indicated to decrease the punching strength by 25 percent in comparison to the specimens which have been gradually cooled.

Ali et al in 2020 [10] investigated the behavior of a self-compacted bubble deck slab. In his research paper investigation was carried out to study the shear strength behavior of one-way bubble deck slab using self-compacting reinforced concrete. The experimental program consists of testing thirteen one-way slabs with dimensions of (1700 length, 700 width and 150 thick) mm. One of the tested slabs is a solid slab (without balls) is used as a reference, the remaining twelve bubbled slabs with ball diameter (73, 60) mm were divided into five groups according to the parameters of the experimental work, the parameters of the experimental work include: type of slab (bubble and solid slabs), ball diameter (73, 60) mm, shear reinforcement and spacing between balls. The results showed that compared to solid slabs, bubbled slabs have a lower ultimate load and a higher deflection at ultimate load, but the first crack load is lower by 15.3 to 42.4 percent due to lower moment of inertia. Also, the results showed that the bubbled slabs withe shear reinforcement (multi-leg) have an increase in the ultimate load as compared to solid slab by about 35.4% to 57.3% and an increase in the deflection at ultimate load by about 1% to 15%, at the same time the first crack load decreases by about 2.8% to 27.4% as compared to solid slab.

A study was done by **Sakin** [11] in 2014 to investigate the punching shear capacity of 5 normal and self-consolidating concrete (SCC) slabs. Three of them where Bubble Decks consist plastic voids of diameter of (40 mm) and the rest were solid slabs. In this study, critical perimeter (at distance of 2d from column's faces) was strengthened by using steel fiber added by (0.8 and 1 %) by volume fraction of the concrete. The test results indicated a decrease in ultimate load of voided slabs (without steel fiber) by about 15% compared with that of the reference solid slab, while this reduction is about (9 and 13 %) in voided slabs reinforced with (1 and 0.8 %) of steel fiber, respectively.

3. Experimental Work

3.1. General

Ten RC slabs have been cast in the Structural Engineering Laboratory of College of Engineering in Mustansiriyah University. The examined slabs in this research were all square in shape and modeled according to "Bubble Deck Span Guide" durability and fire resistance requirements [12], with dimensions of (450x450) mm and 70 mm thickness and concrete cover was 15 mm. They were clearly supported around their four edges using steel frame and loaded centrally with a steel cube of (40x40x40) mm.

Bubble diameter was (40) mm with a spacing between bubbles (60) mm center to center and the reinforcement in both bottom and top layer is ϕ3 @ 25 mm (wire mesh). As shown in fig. 2.

Figure 2. Plywood mold with steel reinforcement

3.2. Materials

All used materials are described in table (1).

Table 1. Materials properties and description

Material*	Descriptions
Cement	Ordinary Portland Cement (Type I).
Fine aggregate (Sand)	Natural sand of (4.75mm) maximum size.
Coarse aggregate (Gravel)	Crushed gravel of (14 mm) maximum size.
Limestone powder	Fine limestone powder of Iraqi origin.
Superplasticizer	Viscocrete - 5930 - L produced by Sika.
Water	Tap water

*All local materials were conforming to applicable Iraqi standards and specifications.

3.3. Concrete Mix Design

The mix proportions of (NC 30 MPa fć) used in this study are mentioned in table (2), based on previous studies [13]. And the mixture modeling approach for SCC proposed and used in this research is based on a method established by Nan Su in Taiwan [14]. The main goal of this approach is to calculate the sum of paste needed to cover the gap between loosely piled aggregate. The measures in this process done by Jasim [15] and proportions are as shown in table (3).

Table 2. Properties of Concrete Mix (NC)

Mix notation	NC
Average Nominal Compressive Strength fć (MPa)	30
w/c	0.45
Cement kg/m^3	400
Water (L)	180
Sand kg/m^3	600
Gravel kg/m^3	1200

Table 3. Mix Proportions of (SCC)

Mix notation	SCC
Average Nominal Compressive Strength Fć (MPa)	30
w/b	0.40
Cement kg/m^3	350
Water Liter	178
Sand kg/m^3	983
Gravel kg/m^3	766
SP Liter	9
Limestone powder kg/m^3	96

Prior to beginning to blend NC, it was sufficient to keep the mixer clean and moist although devoid of water. To begin, the mixer was filled with gravel and sand, following that, apply one-third of the mixing water to moisten both for (1 min). At this point, cement is added and mixed for (0.5 minute), followed by one-third of the combination water and blended for one minute, and then the remaining water is gradually applied and mixed for (1.5 min). The total time needed for mixing is (4 min). A measured amount of coarse and fine aggregate was laid out on an impervious concrete surface. Repeat the mixing process before color uniformity is achieved; the mixing period should be about 10-15 minutes. Because of the need for effective dispersion of fine particles used to achieve a homogeneous and durable blend, mixing time is increased as opposed to standard concrete. Furthermore, the need for an accurate overall moisture content of the blend necessitates a thorough understanding of the properties of the products being used. It is important that the material source maintains consistency in moisture content and particle size distribution. The grading of the sand and the moisture content are especially significant. Fig. 3 shows the casted slabs.

Figure 3. Bubbled reinforced concrete slabs casting

3.4. Curing Procedure

24 hours later, the samples and specimens used as controls (cubes, cylinders, and prisms) are removed from their formworks and put in a tank filled with water to reach the 28-day curing time according to ASTM C31/C31M-12 [16].

3.5. Test Procedure

After allowing adequate curing time for the slabs (28 day), all specimens were cleaned and ready for the next step. The first phase in the testing process is to burn 8 slabs and hold 2 slabs as references for comparison. Following the completion of the burning test, slabs were cooled in 4 methods and subjected to a punching shear load test.

3.5.1 Burning Slabs

The bubble RC slab specimens were exposed to fire flame by the burners represented in Fig. 4. The fire flame is subjected to the tension side of the slab, the distance between the slab and the fire flame is 20 cm. A steel frame was used to present the true state of burning; the frame was sealed on all sides with one opening as depicted on the Fig. 5.

Figure 4. The Burner

Figure 5. Steel frame with burner

An infrared thermometer with a temperature range of (-32 to 550) °C was used to calculate the fire intensity on the slab's bottom face. The temperature measuring unit is depicted in Fig. 6.

Figure 6. Infrared thermometer

The specimens which were burnt at a temperature of 300 °C for 30 minutes, with the face exposed to the fire being tested every 5 minutes to determine the temperature of the concrete and to guarantee that it stayed within the 300 °C cap as shown in Fig. 7. The average temperature on the other face was also measured to determine how heat is transmitted through the concrete.

Figure 7. Taking average temperature for concrete

3.5.2 Cooling Slabs

After the burning stage of the specimen is finished, it is moved to the cooling stage, which is in four forms. The first method is to leave the model to cool down at room temperature, the second method is to immerse it in water for 15 minutes as in Fig. 8, and the third and fourth methods are to spray the model with water for 5 and 10 minutes, respectively as in Fig. 9. The immersion was performed in one of the basins, which is the same temperature as tap water used in spraying which is about 15 °C.

Figure 8. Quenching slab in water

Figure 9. Spraying water on slabs

3.5.3 Punching Shear Test

The slab was labeled carefully and then they were placed on a rigid support with a clear span of (0.45x0.45) m. The point load was applied at the center of the slab and a 0.01mm dial gauge was positioned directly under the middle of each slab. To measure the central deflection.

All slabs were tested using a hydraulic universal testing machine of the type (EPP300MFL system) with a capacity of (3000 kN) available in the structural Laboratory in Civil Engineering Department, College of Engineering, Mustansiriyah University.

The load was applied progressively in 2.5 kN increments. Throughout the test, the number of loads and subsequent deflections are recorded, providing an accurate reflection of the slab's structural behavior. Both the load at the first crack and the ultimate punching shear load, as well as their subsequent deflections at the slab center, were detected and recorded.

As seen in Fig. 10, a solid square steel cube with dimensions (40X40X40) mm was positioned over the middle of the slab to provide concentrated load.

(a)

(b)

(c)

Figure 10. Punching Shear Test of specimens Slab

4. Results

4.1. Cracking and Ultimate Load

The main objective of this study is to determine the ultimate load capacity of reinforced concrete bubbled slab for punching shear because ultimate load is an important factor that makes indication of structural behavior. The observed failure loads of the tested slabs for each group are as bellow:

4.1.1 Group-one (Normal Strength Concrete)

This group is consisting of five normal Strength concrete specimens' slab with (30) MPa fć. First one is reference slab which was tested without expositing to fire and the four other specimens were burned to 300 C° and cooled in air, spraying water for 5 and 10 min and by using quenching in water for 15 min.

The tests show that the ultimate punching shear load for specimen NC-R is (28) kN and the first crack appears at (10) kN which is (35.71 %) of the ultimate load. After burn other slabs NC-A the one which cooled with air failed at (23) kN which is (82.14) % of the ultimate load for reference slab because of the heat effect on tension face of the concrete slab and the first crack appear at (7.5) kN which is lower than that in reference slab by (75) % and for the same reason. The results are comparable to those of Thaar [17]. The cement paste expands when heated, but from 300ºC, a contraction occurs, associated with water loss. At this stage, aggregates continue to expand, and the resulting internal stresses can lead to loss of strength, cracking and flaking.

By moving to water cooling method spraying water on tension face for 5 and 10 min bring the load of specimen NC-W5 and NC-W10 down to (21 and 20) kN which is lower than that in control slab at (75 and 71.42) % and first crack appears at (6.5 and 6) kN which is less than the reference at (65 and 60) % and the reason of that decrease in ultimate load and first crack load is the fast and deeper deterioration caused by water and the effect of sudden cooling is show clearly in the last cooling method which is quenching the burned slab into water tank for 15 min and that made the ultimate load of NC-Q decrease to (66.07) % of the ultimate load for reference slab at (18.5) kN and the first crack is (50) % from first crack load of the reference slab at (5) kN . First crack load varies from (27 to 35.71) % of the ultimate load of all specimen. The results are close to what was observed by **Wouter** and **Robby** [18] in their research where quenching the specimens after heating results in the highest possible strength loss compared to spraying water and cooled the specimens gradually and that loss could reach 38% for 350 Cº of heating. **Annerel** [19] and **Bingöl et al.** [20] showed the same results and this reduction is mainly attributed to the formation of microcracks caused by high thermal stress. Table (4) and Figure (11) show the results.

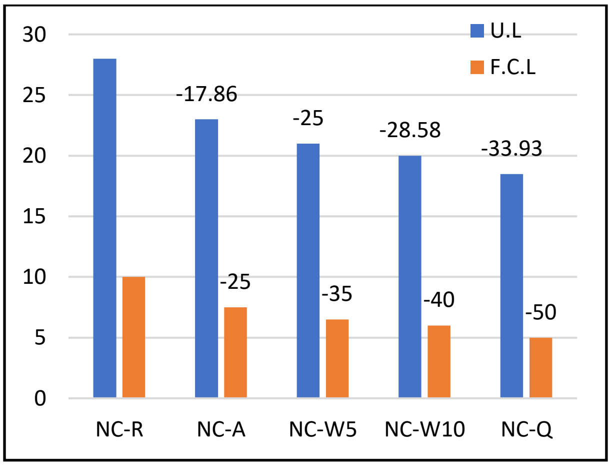


Figure 11. Ultimate Load results for Normal Strength concrete

Table 4. Ultimate Load test results for group-one

Group name	Labeling	First Crack load (F.C.L) (kN)	Ultimate load (U.L) (kN)	$\frac{F.C.L}{U.L}$ (%)	$\frac{F.C.L}{(F.C.L)R}$ (%)	$\frac{U.L}{(U.L)R}$ %
	NC-R	10	28	35.71		
	NC-Air	7.5	23	32.6	75	82.14
G1	NC-W5	6.5	21	30.95	65	75
	NC-W10	6	20	30	60	71.42
	NC-Q	5	18.5	27	50	66.07

4.1.2 Group-two (Self-Compacted Concrete)

The ultimate punching shear load attained after 28 days of curing was (33) MPa at room temperature of 26˚C for specimen SCC-R and the first crack appears at (12.5) kN which is (37.9 %) of the ultimate load .

After burn other slabs, SCC-A the one which cooled with air failed at (28) kN which is (80.3) % of the ultimate load of reference slab SCC-R and the first crack appears at (9) kN which is lower than that in reference slab SCC-R by (72) % because above 110 ˚C, the chemically bound water from calcium silicate hydrate (C-S-H) was started to release, and the intermolecular stress was increased due to thermal expansion of aggregate [21] [22]. When subjected to elevated temperature, the strength of concrete structure started to decrease from 300 ˚C due to the evaporation of chemically bound water and dehydration of $Ca(OH)_2$ into free lime leading to the formation of micro-cracks inside the concrete [23] [24]. The strength of concrete is greatly affected due to the expansion of lime during the cooling period [23]. By using water cooling method, spraying water on the burned face for 5 and 10 min bring the ultimate load of SCC-W5 and SCC-W10 down to (25 and 24) kN which is lower than that in control slab at (75.75 and 72.72) % and first crack show at (8.5 and 8.1) kN which is less than the reference at (68 and 64.8) % of the reference slab SCC-R respectively and the reason of that decrease in ultimate load and first crack load is the fast and deeper deterioration caused by thermal shock which cause thermal stresses and the effect of sudden cooling shows clearly in the last cooling method which is quenching the burned slab into water tank for 15 min and that made the ultimate load of SCC-Q decrease to (65.15) % of the reference slab ultimate load at (21.5) kN and the first crack is (59.2) % from first crack load of the reference slab at (7.4) kN .

For both mixtures designed to be at the same fć, self-compacted concrete shows more strength where ultimate load increase by (17.8) % in reference specimens and (21.7) % at slabs cooled with air and shows more resistant to water cooling effect due to its properties at about (19, 20, 16) % comparing to normal Strength concrete specimens. All the above difference in behavior of the self-compacted slab is rely on its low permeability and minimum voids ratio in its micro structure which causes more spalling in early burn time [24] [25] [26]. Table (5) and figure (12) show the results.

Table 5. Ultimate Load test results for group-two

Group name	Labeling	First Crack load (F.C.L) (kN)	Ultimate load (U.L) (kN)	$\frac{F.C.L}{(U.L)R}$ (%)	$\frac{F.C.L}{(F.C.L)R}$ (%)	$\frac{U.L}{(U.L)R}$ %
G2	SCC-R	12.5	33	37.9		
	SCC-Air	9	26.5	33.9	72	80.3
	SCC-W5	8.5	25	34	68	75.75
	SCC-W10	8.1	24	33.5	64.8	72.72
	SCC-Q	7.4	21.5	34.4	59.2	65.15

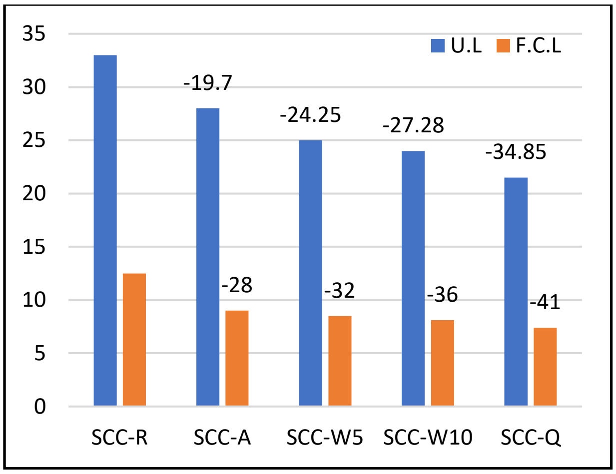
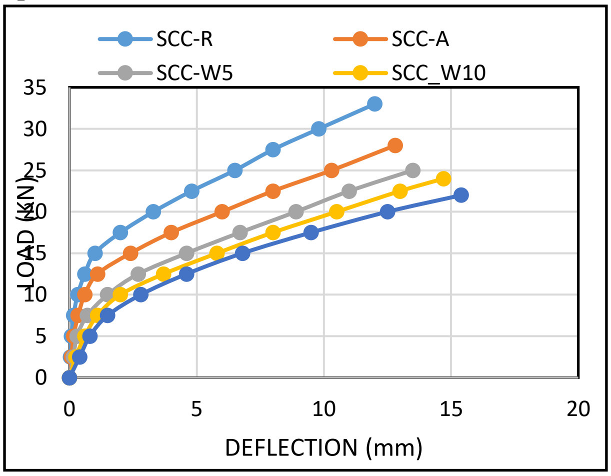


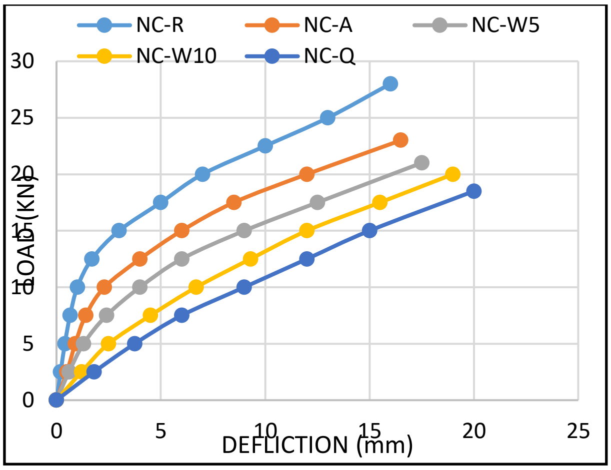
Figure 12. Ultimate Load results for Self-Compacted concrete

4.2 Load-Deflection Relationship

The deflection was measured at the center of slabs using a (0.01mm) dial gage with a load increment of 2.5 kN, and the readings for these gages were recorded for each load increment. When a reinforced concrete slab is gradually loaded, the deflection increases linearly in an elastic manner. Once cracks begin to form, the slab's deflection increases at a faster rate. After the slab develops cracks, the load-deflection curve is nearly linear until the flexural reinforcement begins to yield, at which point the deflection continues to increase without an appreciable increase in load. Fig. 13 illustrate the load-deflection relationship for all specimens.



(a) Group-one



(b) Group-two

Figure 13. Load-Deflection relation

It can be detected that the load deflection reaction can be distributed into two stages of behavior. The first limited stage was described by an approximately linear relationship between the load and deflection. During this stage of behavior, the section was un-cracked and both the concrete and steel behave essentially elastic. The second stage denotes the behavior post initial cracking of the composite section where the stiffness of the slab was decreased as indicated by the reduced slope of the load versus deflection curve.

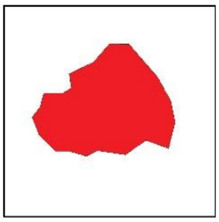
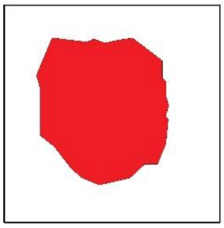
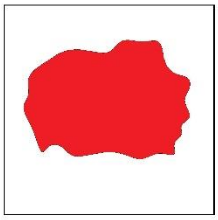
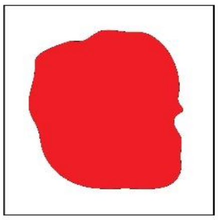
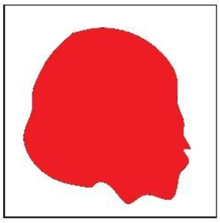
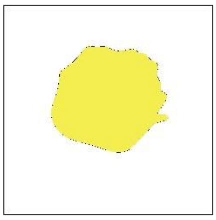
4.3. Crack Pattern and Punching Zone

The difference in crack pattern between self-compacted and normal concrete specimens was clearly shown due to the nature of the two materials, with SCC being stiffer as shown in fig. (15) and (16).

Punching zone was measured using Auto CAD by exporting a clear straight image to the program and draw over the punching area and using the command Area to calculate the actual area. The punching zone provides an indication of specimen strength during a punching shear test, as demonstrated by the results, which show that the punching zone was smaller in reference specimens, larger in gradually air-cooled specimens, and even larger in water cooling slabs, demonstrating the true effect of water cooling on bubble concrete slabs.

Table (6) show the punching area for each specimen

Table 6. Perimeters and Failure Zone Area for all specimens

Specimen	Perimeter Measured by Auto Cad (m)	Measured Area (m^2) by Auto Cad	$\frac{\text{Punching Area}}{\text{Total Area}}$ (%)	Zone of Failure
NC-R	0.9064	0.0488	24.1	
NC-A	0.9844	0.0677	33.4	
NC-W5	1.0725	0.0711	35.1	
NC-W10	1.1466	0.0945	46.7	
NC-Q	1.2075	0.0983	48.5	
SCC-R	0.8047	0.0429	21.2	

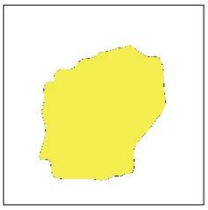
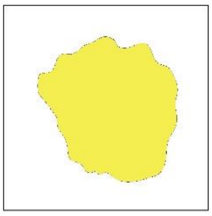
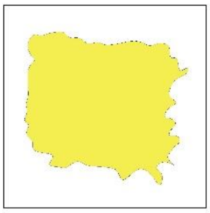
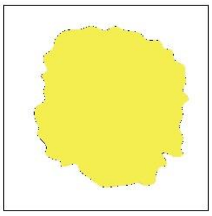
SCC-A	1.0052	0.0644	31.8	
SSC-W5	1.0314	0.0704	34.7	
SCC-W10	1.4404	0.0896	44.2	
SCC-Q	1.2557	0.0935	46.2	

Fig. (14) Indicates the punching shear behavior associated to simply supported reinforced concrete slabs which are exposed to fire from beneath. The slabs' ends can rotate freely, also the slab can elongate freely (thermally un-restrained). Steel reinforcement contains straight bars which are positioned close to slab's bottom. As the slab's underside is exposed to fire, bottom will be expanding more than top, the subsequent curvature makes the slab deflecting downwards. In the case when the reinforcement's strength decreases less than that needed for supporting slabs and any superposed load, the punching or flexural and punching failure is going to occur.

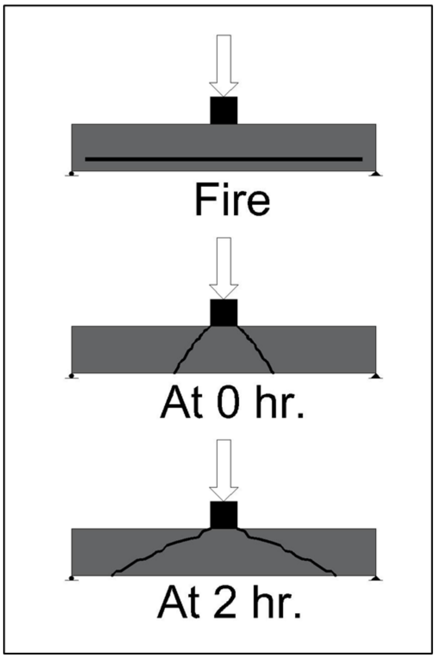
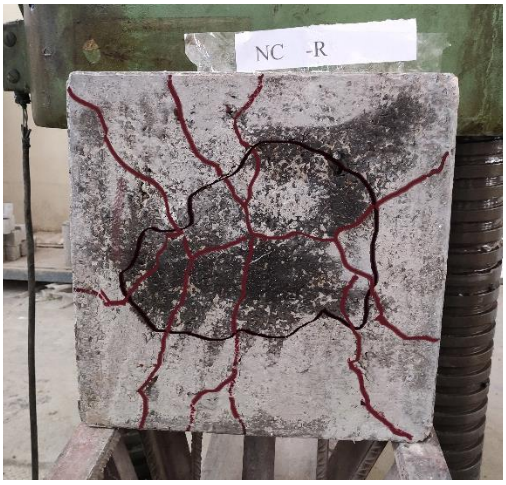


Figure 14. The Impact of Fire on punching shear of Simply Supported Reinforced Concrete Slab.

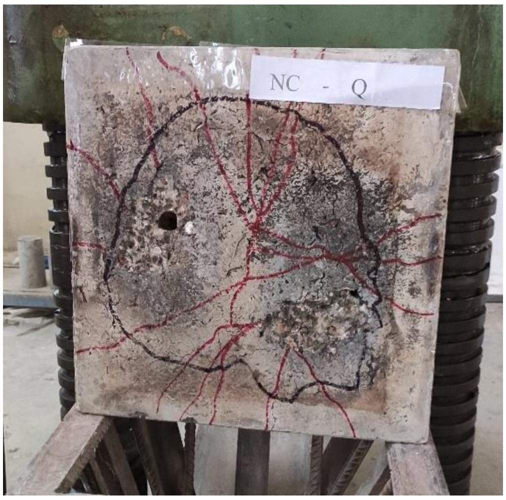


(a) NC-R

(b) NC-A

(c) NC-W5

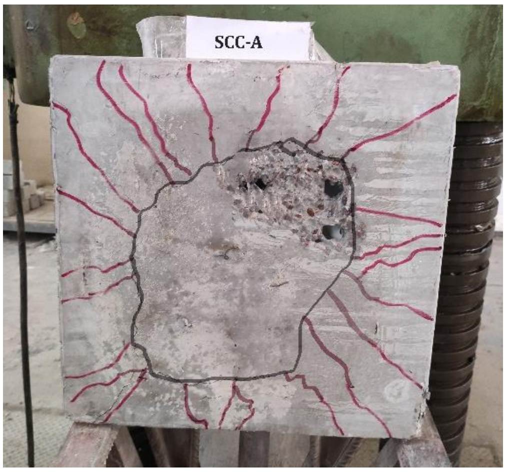
(d) NC-W10



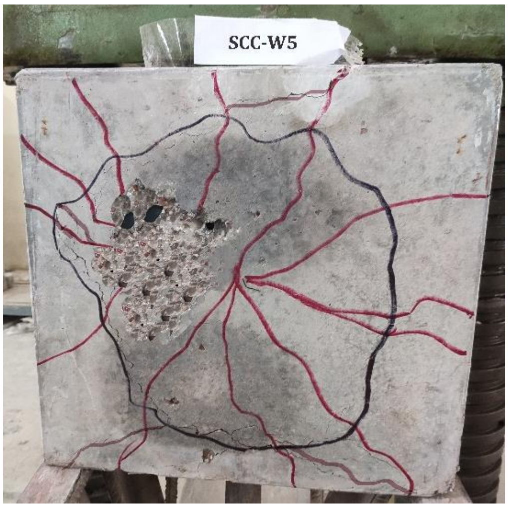
(e) NC-Q

Figure 15. Crack Pattern and Punching Zone of normal concrete

(a) SCC-R



(b) SCC-A



(c) SCC-W5

(d) SCC-W10

(e) SCC-Q

Figure 16. Crack Pattern and Punching Zone of Self-Compacted concrete

5. Conclusions

- Using SCC increase the Ultimate load of reference specimens (13) % comparing to NC in bubbled slab.
- Spalling was higher in SCC specimens.
- Effect of water cooling on SCC was less than that in NC because of low permeability surface in SCC.
- Punching shear area increase depending on cooling method.
- Crack pattern and failure mode in SCC tends to be punching failure mode and normal concrete tends to be punching and flexural failure mode.
- SCC more sensitive when expose to fire flame.

Conflict of interest

The authors confirm that the publication of this article causes no conflict of interest.

6. Abbreviations

SCC	self-compacted concrete
NC	Normal strength concrete
R	Reference specimen
A	Air cooled specimen
W5	Sprayed with water for 5 min

W10	Sprayed with water for 10 min
Q	Quenching in water or 15 min

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