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STRUCTURAL BEHAVIOR OF SUSTAINABLE LIGHTWEIGHT HOLLOW-CORE SLABS REINFORCED WITH FIBERS

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ABSTRACT

A hollow Core Slab (HCS) is a concrete component with holes that distribute throughout the slab's span, intending to reduce weight and expense and provide a lateral advantage that can be used in electrical or mechanical systems, in addition to good thermal and acoustic insulation properties. This study's main objective is to study the structural behavior of HCS produced from sustainable lightweight aggregate concrete (LWAC) reinforced with chopped carbon fiber (CF) under symmetrical two-point loads. Five Hollow Core Slabs containing crushed pumice stone as coarse Lightweight Aggregate (LWA) were casted including, three HCS specimens with CF as a variable; the first is a normal HCS specimen with 0% CF, the second HCS specimen is reinforced with 0.5% carbon fiber, and the third is HCS specimen reinforced with 1.0% CF, while the remaining two HCS specimens containing replacement of a Percentage of sand with a fine lightweight aggregate (RE) as a variable and 0.5% CF, one is HCS specimen with 10% RE and the other is HCS specimen with 30% RE. Load-deflection Relationship, the first cracking and the ultimate loads, and the ductility ratio of hollow Core Slabs were studied. The results indicate that the ductility ratio of the HCS specimen with 1% carbon fiber increased by 131.5% and also the deflection at ultimate load grew by 42.5% compared with the nonfibrous specimen. At the same time, the deflection at the ultimate load is increased by using the lightweight fine aggregate (LWFA) as a replacement with a percentage (10% and 30%) of sand by 21.23% and 36.1% respectively, as compared to HCS specimen without replacement and reinforced with 0.5% CF.

KEYWORDS

Chopped carbon fiber; natural Pumice Aggregate; Sustainable concrete; a hollow core slab.

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PAPER INDEX

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1. INTRODUCTION

Recently, HCS have been employed as the major flooring systems for various of structures, including high-rise buildings, hotels, commercial buildings, educational, hospital, factory, and residential buildings. Hollow core slabs have various benefits in addition to their structural advantages and capacity to span wide distances, including their relatively light weight, ease of construction, good heat and noise insulation and high fire resistance [1]. Also, this system reduces the number of workers on the job site and uses continuous holes in the slab to conduct electrical cables, water taps, and sewage pipes [2]. Finding new ways to build with natural lightweight volcanic materials (such as pumice and ash) is becoming widespread. Lightweight aggregate (LWA) decreases the weight of different structural members, which results in reducing the load transmitted to the foundations The presence of gaps and holes in lightweight aggregate offers excellent thermal and sound insulation as well as better fire safety. Lightweight structural Concrete (SLWC) has good fire resistance, thermal, and sound insulation due to the presence of voids and pores in LWA [3]. The pumice stone is one of the oldest volcanic LWAs utilized in construction. Pumice has a porous structure because of the gases released from cooling magma during volcanic activity. LWAC demonstrate brittle behavior. LWAC's brittleness can be solved by adding fibers to concrete, which enhances its characteristics by bridging cracks and preventing them from widening [4].

There are some researches on studies the using of LWA in hollow concrete slabs [5, 6, and 7]. But a thorough study to produce HCS containing pumice stone is not yet accessible. as lightweight aggregate and reinforced with carbon fibers

1.1. RESEARCHES SIGNIFICANT

1. Producing sustainable hollow core concrete slab specimens containing pumice stone as coarse lightweight aggregate and studying their structural behavior.

2. Studying the effect of two parameters (the volume percentage of carbon fibers (Vf) and the replacement of a proportion of sand with a fine lightweight aggregate (RE)) on the hollow core LWC slabs' structural behavior.

2. EXPERIMENTAL PROGRAM

2.1. MATERIALS

2.1.1. CEMENT

Ordinary Portland cement (Type I) from Lafarge Company Sulaymaniyah governorate in Iraq. According to the test results, the selected cement complies with Iraqi Specification No. 5/1984 [8]. Tables 1 and 2 demonstrate the results of tests of the physical and chemical properties of cement.

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Table 1. Cement Chemical Composition

Oxides Composition	Abbreviation	Content (% by weight)	Limits of Iraqi Specification No. 5/1984
Lime	CaO	60.74	---
Silica Dioxide	SiO_2	18.14	---
Alumina Trioxide	Al_2O_3	6.71	---
Iron oxide	Fe_2O_3	2.9	---
Magnesia Oxide	MgO	1.28	≤ 5 %.
Sulphate	SO_3	2.09	≤ 2.8 %
Loss on Ignition	L.O.I	2.25	≤ 4 %
----	Total	94.11	---
Insoluble material	I.R.	1.25	≤ 1.5 %
Lime Saturation Factor	L.S.F	0.92	0.66-1.02

Table 2. Cement's Physical Properties

Physical Properties	Test Results	Limit of Iraqi Specification No. 5/1984
Specific surface area (Blaine method), (cm^2 /g)	4678	≥ 2300
Setting time (vicats method) Initial setting, (hrs. : min: sec) Final setting, (hrs. : min)	0:1:25 3:50	≥ 45 min ≤ 10 hrs.
Compressive strength (MPa) For 3-days or 7-days	25 43	≥ 15 MPA ≥23 MPA

2.1.2. FINE AGGREGATE

Local Iraqi sand was employed as a fine aggregate with a maximum particle diameter of 4.75 mm in this experimental work. The sand came from Al-Ukhaidir, as the sand's gradient and its physical characteristics and chemical characteristics are explained in the tables 3 and 4, respectively. According to test results, the sand's gradient and its physical and chemical characteristics are meet Iraqi Specifications No. 45/1984 [9].

Table 3. Fine Aggregate Sieve Analysis

Sieve Size (mm)	Cumulative Passing (% by weight)		Limits of Iraqi Specification No.45/1984 (zone 2)
	sand	Pumice	
4.75	90	100	90 - 100
2.36	75	90	75 - 100
1.18	59.7	80	55 - 90
0.6	39.3	50	35 - 59
0.3	12.4	30	8 - 30
0.15	2.28	10	0 - 10

Table 4. Physical and Chemical characteristics of Fine Aggregate

Properties	Test Result		Limits of Specification
	sand	pumice	
Bulk Specific Gravity	2.6	1.32	---
Absorption %	1.92	17.2	---
Dry loose unit weight, (kg/m^3)	1620	965	---
Sulphate content (SO^3), %	0.114	0.17	≤ 0.5 %*
Material finer than 0.075 mm sieve, %	3.6	----	≤ 5 %*

* (I.Q.S.) NO.45-84[9].

2.1.3. LIGHTWEIGHT COARSE AGGREGATE (PUMICE)

The crushed pumice stone is located in northern Iraq, specifically in the Sulaymaniyah governorate and it was prepared as a lightweight aggregate. The pumice stone was crushed by a crusher machine with variable size (14-2.36) mm as shown in Figure 1. The grades and physical characteristics of lightweight coarse aggregate complies with Iraqi Specification No. 45/1984, as shown in Tables 5 and 6.

Table 5. Coarse Aggregate Sieve Analysis

Sieve Size (mm)	Cumulative Passing (% by weight)	Limits of Iraqi Specification No. 45/1984 (20-5mm)
20	100	95-100
10	50	30-60
5	10	0-10

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Table 6. Physical Properties of Coarse Aggregate*

Properties	Test Result	Limits of Specification
Bulk Specific Gravity	0.93	---
Absorption %	28.6	---
Dry loose unit weight, (kg/m^3)	672	---
Sulphate content (SO^3), %	0.17	0.1 %**
Material finer than 0.075 mm sieve, %	----	3**

* Physical analysis was conducted by National Center for Construction Laboratories and Researches (NCCLR).

** (I.Q.S.) NO.45-84[9].

Figure 1. Pumice Stone preparation steps.

2.1.4. HIGH RANGE WATER REDUCING ADMIXTURE (HRWRA)

A Chemical mixture based on edited polycarboxylic ether was used, known commercially as (Sika 5930). This superplasticizer that meets satisfies ASTM C494M/04 kinds F [10].

2.1.5. CARBON FIBER

The chopped Carbon fibers (CF) with 600 mm width and 0.167mm thickness were used as concrete reinforcement, which was called (Sika warp-300c). The carbon fibers were sliced with a length of 5 mm as depicted in Figure 2. Its dry density was 1.82 g/$cm^3$and tensile strength of 4000 Mpa According to the manufacturer.

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Figure 2. Carbon Fiber

2.1.6. STEEL REINFORCEMENT

Steel reinforcement with a nominal diameter (Ø6 mm) was used. The steel bars were tied by steel wire with dimensions (150*180) mm according to the design to form the slab reinforcing mesh. The steel reinforcement of HCS specimens were designed in accordance with ACI 318M-14 [11]. The average ultimate strength is 578 Mpa. The test results met ASTM A496 [12] requirements.

2.2. CONCRETE MIXES

ACI committee 211-2 [62] designed experimental concrete mixtures to obtain a compressive strength of 21 MPa after 28 days of curing. The dry density of sustainable LWC should be less than 2000 kg/m3 and the compressive strength greater than 40 MPa. The mixing ratio used in this research by weight is 1:1.18:0.72 (Cement to Sand to Aggregate) and with the cement content of 550kg per m3 and w/c ratio of 0.44. Many mixes have been tried to find the right amount of superplasticizer (HRWRA) that gives concrete suitable flowability to get LWAC. A suitably chosen mixture (the reference mixture) contains 1.1 liter superplasticizer per 100kg of cement and with a w/c ratio of 0.28 and without fiber. The details about the concrete mixes analyzed in this work are depicted in Table 7. Group one includes three LWAC mixes, the variable in this group is the volume fraction of carbon fibers (MPAF), as each mix contains a volume fraction of carbon fibers (0.0%, 0.5%, and 1%). Group two contains two LWAC mixes, the variable in this group is replacing a percentage of the natural sand used with LWFAs (MPARE), as each mix in this group contains a percentage of LWFAs (10%, and 30%) as a replacement with natural sand.

Table 7. Details of Concrete Mixes

Group No.	Hollow core slab symbol	Carbon fibers % by volume*	Replacement of sand % by weight
Group 1	SRPA	0.5	0
	SPAF-0.0	0.0	0
	SPAF-1.0	1.0	0
Group 2	SPARE-10	0.5	10
	SPARE-30	0.5	30

*Percent of mix volume.

2.3. PREPARATION, CASTING, CURING, AND TESTING OF SPECIMENS

In this investigation, five hollow core slab specimens with sizes of 1000 x 450 x 100 mm are produced and tested. Steel mesh was used to reinforce these slabs, and an appropriate cover was applied from the base of the mold to the tension face. Figures 3 and 4 illustrate the mold and the hollow core slab's dimensions. Before testing, all slab specimens were lifted from the water basin and let to dry after 28 days of curing. The slabs were kept clean and sprayed white to allow for easier detection of the first cracks that arise during testing. All slabs are tested until failure using a mechanical testing device type ELE with a 150 KN capacity and increase the load applied in incremental increases of (5) KN for all specimens. The specimens are simply supported in a two-point load test with a clear span of (900) mm and a clear spacing between the point loads of (300) mm as shown in Figure-5. All important ultimate and initial crack load readings was recorded throughout the investigations. Three dial gauges were used to measure slab deflections below the two loading locations and at the middle of the slabs. As demonstrated in Figure-6, these dial gauges have a 0.01 mm precision and a capacity of (30) mm. The gauges were fixed to a frame made of steel that was in touch With the slabs' bottom faces. The deflections were measured for every 5 KN of the applied load.

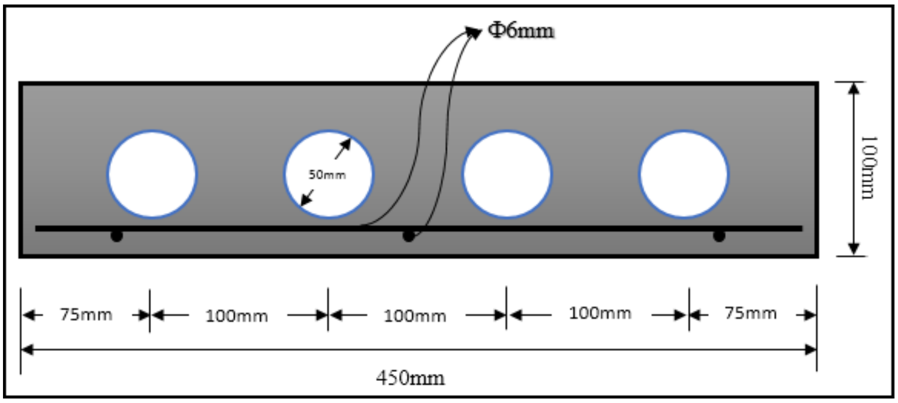

Figure 3. Hollow Slab with steel mesh.

Figure 4. The mold of HCS.

Figure 5. Testing of Slab Specimen.

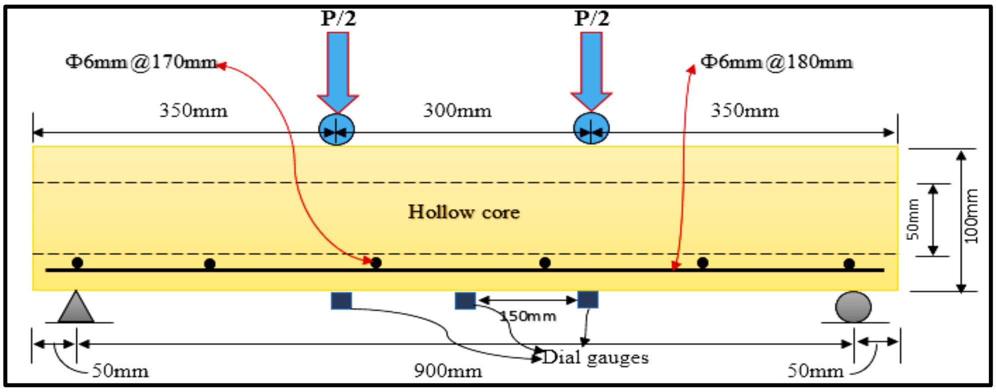

Figure 6. Details of the Slab Test.

3. RESULTS AND DISCUSSIONS

Five Hollow core slabs were casted in this study as shown in Figure-7.

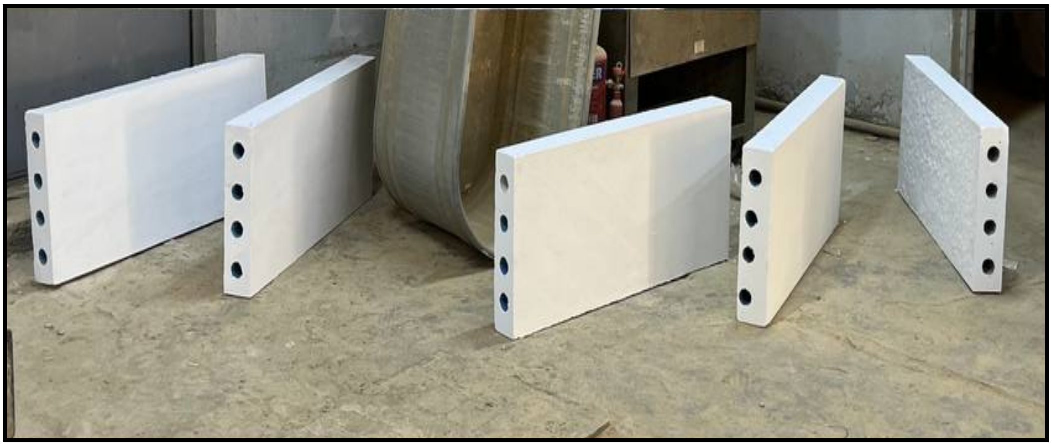

Figure 7. Slabs Specimens.

3.1. THE FIRST CRACKING AND THE ULTIMATE LOADS

The test results of the flexural cracking loads and the ultimate flexural strengths of all specimens are shown in Table-8. Table-8 shows that by raising the volume percentage of fiber from 0.0% in SPAF-0.0 to 0.5% in SRPA and 1.0% in SPAF-1.0 the first cracking load Pcr increased from 17.37kN to 19kN and 20.81kN respectively representing an increase of 9.6% and 19.8% compared with the nonfibrous slab SPAF-0.0. Also when the volume fraction of fibers increased at the same rate, the ultimate load Pu increased from 37.45kN for SPAF-0.0 to 43.72kN for SRPA and 48.77kN for SPAF-1.0 representing an increase of 16.7% and 30.2%, respectively. This is attributable to two points as follows: the presence of the fibers firstly restricts the propagation of the flexural cracks and secondly transfers the tensile stresses uniformly to the concrete medium surrounding the crack rather than concentrating at its tip.

Also, the results demonstrated that the increment in the ratio of lightweight fine aggregate as a replacement with a percentage of sand (RE) caused a decrease in the flexural strength of the LWAC hollow core slab, as seen in Table-8. it was observed that by increasing (RE) from 0% for SRPA to 10% for SPARE-10 and 30% for SPARE-30 decreased Pcr from 19kN to 18.21kN and 17kN representing a decrease of 4.11% for SPARE-10 and 10.5% for SPARE-30 compared with SRPA (without RE). Also, for the same increase in the RE, the ultimate load Pu decreased from 43.72kN to 40.82kN and 37kN representing a decrease of 6.63% and 15.36%, respectively. The main reason is that adding fine pumice aggregate by a certain proportion to LWA concrete increases the water required for the mix to get suitable workability. As a result, the strength decreases and the load carrying capacity of concrete.

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3.2. LOAD - DEFLECTION RELATIONSHIP

In this investigation, the load-deflection curves of the tested LWAC hollow core slabs are plotted in two groups as shown in Figure 8 and 9. These curves make it obvious that the load-deflection relationship in HCSs reinforced with fibers typically goes through three stages. The first phase is the phase of elastic behavior, where when the load is increased gradually on the specimens, the deflection increases linearly with the load. As a result, up until the first crack, the curve is linear at this stage and has a constant slope. In second phase, the vertically flexural cracks are spread in tensile area of the slab at the maximum bending moment region of the slab. Those cracks develop as the loading increases, thus, moment of inertia of the cracked section continuously decreases. The relationship turns from linearly to non-linearly because at this phase the rate of increment in deflection increases continuously when the load goes up. Then, in third phase, in flexure, the slab approaches its maximal strength, and the deflection of the slab keeps increasing with no noticeable increase in the load applied therefore, the load-deflection curve becomes nearly horizontal up to failure.

Group one shows the effect of the volume fraction of carbon fibers (Vf) on the load-mid-span deflection relationship of LWAC hollow core slabs, SPAF-0.0 (Vf = 0.0%), SRPA (Vf = 0.5 %), and SPAF-1.0 (Vf = 1.0 %). The figure clearly shows that during the initial loading stages, the deflection reduces when the ratio of fibers raised. This behavior could be ascribed to the improved stiffness of LWC hollow core slabs and enhanced mechanical characteristics of LWA concrete (the modulus of the elasticity, the flexural strength, the compressive strength and the tensile strength). The deflection (Δ_u) at the ultimate load was increased by the presence of carbon fibers, as shown in Table-8 and Figure-8. The addition of carbon fibers to LWAC hollow core slabs at volume fractions of 0.5% in SRPA and 1.0% in SPAF-1.0 increased the value of Δ_u by 13.6 % and 42.5%, respectively, as compared to Δ_u of the SPAF-0.0 specimen. The effectiveness of the carbon fibers in stopping the spread and limiting the size of the vertical cracks inside the concrete slab as they cross each other typically explains this. The slab hence could withstand greater loads and deflection before failure.

Group two illustrates at the same applied load, the deflection increases with the increment of using the lightweight fine aggregate (pumice) as a replacement with a percentage of sand (RE), as shown in Figure-9. By comparison the load-deflection behavior of hollow core slabs SRPA (RE= 0.0%), SPARE-10 (RE=10%), and SPARE-30 (RE= 30%), an increase in deflection with rising RE values are indicated. The deflection (Δ_u) at the ultimate load was increased by increasing RE, as shown in Table-8 and Figure-9. The increase in RE in LWAC hollow core slabs from 0.0 in SRPA to 10% in SPARE-10 and 30% in SPARE-30 increased the value of Δ_u by 21.23% and 36.1%, respectively, as compared to Δ_u of SRPA specimen. This can be attributed to the fine pumice aggregate having a lower air-dry density than that of sand; thus, the slabs become more brittle.

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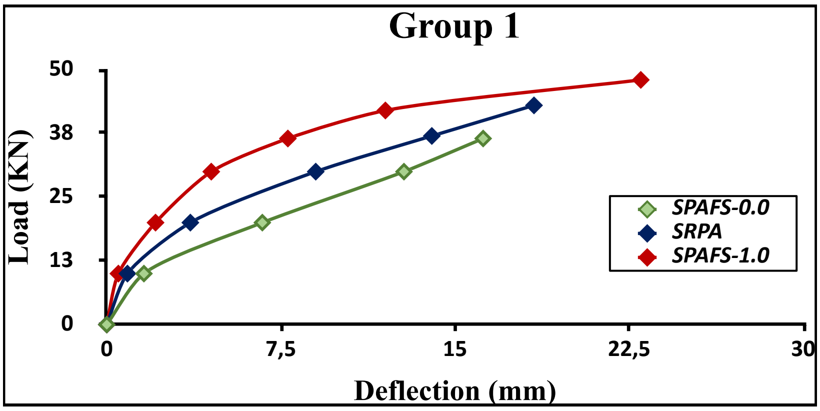

Figure 8. Effect of volume fraction of carbon fibers on Load-Deflection Curves of HCS specimens.

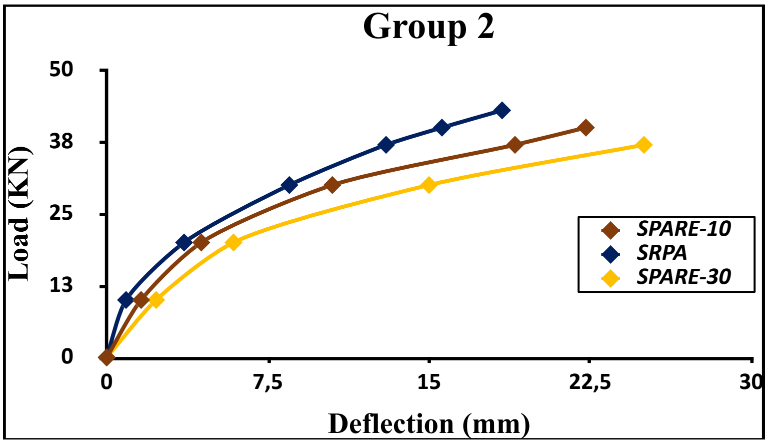

Figure 9. Effect of lightweight fine aggregate as a replacement with a percentage of sand on Load-Deflection Curves of HCS specimens.

3.3. DUCTILITY RATIO

The deflection at the ultimate load at the mid-span (Δ_u) divided by the deflection at the first crack load at the mid-span (Δ_{cr}) was used to compute the ductility ratio. Table-8 makes it evident that the inclusion of carbon fibers also caused a rise in the ductility ratio. The ductility proportion increased by 23% and 131.5% for SRPA and SPAF-1.0, respectively, compared with the nonfibrous LWAC hollow core slab (SPAF-0.0). This is to be expected given that the inclusion of fibers lowers the deflection at the first crack loading and raises it at the ultimate load. Table-8 indicates as the ductility proportion also increased with the increase of RE. The ductility proportion increased by 15.8% and 23.2% for SPARE-10 and SPARE-30, respectively, compared with the ductility ratio of the SRPA specimen. This is because the deflection in the ultimate load increases as RE increases, thus raising the ductility ratio.

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Table 8. Experimental First Crack and Ultimate Loads, Deflection at First crack(Δ_{cr}) and Ultimate Load (Δ_u) at mid-span, Ductility Ratio for Test LWC Hollow core slabs.

Groups	Symbol of slabs	First crack load(KN)	Deflection at first crack load Δ_{cr}	Ultimate load Pu (KN)	Deflection at Ultimate load Δ_u	Ductility ratio * (Ψ)
Group1	SRPA	19	3.6	43.72	18.4	5.1
	SPAF-0.0	17.37	4.2	37.45	16.21	4.15
	SPAF-1.0	20.81	2.4	48.77	23.1	9.6
Group2	SPARE-10	18.21	3.72	40.82	22.3	5.9
	SPARE-30	17	3.98	37	25	6.28

*Ductility Ratio (Ψ) = $\frac{\Delta_u}{\Delta_{cr}}$ where Δ_{cr} and Δ_u are the mid-span deflections at first crack load and ultimate load respectively.

3.4. CRACK PATTERNS AND FAILURE MODES

Cracks begin to form in the tension area at the bottom surface of the concrete slabs when the tensile stresses exceed the specified tensile strength of the concrete. The first crack could not be distinguished because it is an interior crack, and after a few seconds, it appears in the middle of the slab and grows gradually across the width on the bottom face of the tensile area of the slab. After that, cracks expand right and left of the first crack with an increase in the applied load until the ultimate crack occurs in the bottom face along the width of specimens. The crack patterns for all slab specimens are illustrated and discussed in two groups. The effect of carbon fibers ratio on crack can be recognized from group one as shown in Figure-10. The tested slabs in this group have failed in flexural failure. The addition of carbon fibers has shown lesser flexural crack width and a low crack growth rate at the failure of LWAC hollow core slabs. The fiber increases the bond strength between fibers and the LWAC matrix and limits cracks' propagation. The slab (SPAF-1.0) with 1% carbon fibers has fewer cracks as compared with cracks of slabs (SPAF-0.0) and (SRPA) with ratios of (0% and 0.5%) respectively. The effect of using the lightweight fine aggregate as a replacement with a percentage of sand (RE) with (Vf =0.5%) on the crack can be recognized from group two, as shown in Figure-11. The tested slabs in this group have failed in flexural failure. The increase of (RE) has increased the cracks number and the width of each crack at the failure of LWAC hollow core slabs. This is because the addition of lightweight fine aggregate decreases strength and toughness, increasing the cracks number and the width of each crack.

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Figure 10. Crack pattern for the HCS specimens of Group one.

Figure 11. Crack pattern for the HCS specimens of Group Two.

4. CONCLUSIONS

1. The addition of carbon fibers to the LWAC hollow core slab significantly improves the load-deflection curve, while the addition of lightweight fine aggregate (fine pumice) as a replacement with a percentage (10% and 30%) of sand in the LWC hollow core slab leads to a negative effect on the load-deflection curve.
2. The ductility ratio increased by 15.8% and 23.2% respectively when using the lightweight fine aggregate (fine pumice) as a replacement with a percentage (10% and 30%) of sand, also the ductility ratio increased by 23% and 131.5% respectively when the volume fraction of fibers in the LWAC hollow core slab increased from 0.0% to 0.5% and 1.0%.

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