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Static and Dynamic Behavior of High-strength Lightweight Reinforced Concrete One-way Ribbed Slabs

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ABSTRACT

Nowadays, reducing the self-weight of structures and vibration problems is the primary goal for design requirements in most civil constructions. Two-point loading and harmonic loading tests were conducted to examine the strength and serviceability of high-strength reinforced concrete one-way ribbed slabs. Six slabs were cast and tested. The behavior of cracking, deflection, and vibration was investigated. The experimental results showed that using high strength-lightweight concrete (HSLWC) instead of high strength-normal weight concrete (HSNWC) in constructed one-way ribbed slab led to a decrease in the density by 19.31%, the strength by 17.70%, and ultimate deflection by 17.33%. Although the addition of steel fibers to HSLWC led to an increase in the density of concrete its addition enhances the load-deflection relationship and ultimate load for slab specimen which reduced the reduction in strength by 14.49%. Furthermore, ductility index, stiffness, and toughness index for ribbed slab specimens with steel fibers showed better behavior than those without steel fibers. The HSNWC gave a negative impact on the vibration of the one-way ribbed slab at both operation frequencies (25 and 50) Hz, while using HSLWC with and without steel fibers, led to reducing the vibration effect by (30.11and 30.68) % and (15.26 and 20.25) % at 25Hz and 50Hz, respectively.

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NOMENCLATURE

e	Eccentric distance (m)	**Greek Symbols**	
fc`	Cylinder compressive strength (MPa)	μ_d	Displacement ductility index
f_{cu}	Cubic compressive strength (MPa)	ω_o	Operating frequency (rad/sec)
f_r	Flexural strength (MPa)	**Subscripts**	
f_t	Splitting tensile strength (MPa)	ACI	American concrete institute
m	Eccentric rotating mass (kg)	ASTM	American society for testing and materials
P_{cr}	Cracking (kN)	HSLWC	High strength-lightweight concrete
P_d	Dynamic load (N)	HSNWC	High strength – normal weight concrete
P_s	Service load (kN)	LVDT	Linear variable differential transducer
P_u	Ultimate load (kN)	LWA	Lightweight aggregate
t	Dynamic time (sec)	LWC	Lightweight concrete
V_f	Volume fraction of fiber	NSLWC	Normal strength lightweight concrete
w_c	Unit weight of concrete (kg/m^3)	SE	Structural efficiency
		SLWC	Structural lightweight concrete

1. INTRODUCTION

The serviceability behavior of slabs is crucial because it deals with concepts such as cracking, excessive deflection, and vibration. Even if the structure may remain stable, poor performance under service load will affect the comfort of those who use it. Slabs are slender elements with a much smaller dimension in the direction

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of the action than spans. Because of this, they are susceptible to deflection. The requirement for reduced deflection governs the design criteria in a large number of cases [1].

Structural construction in the world forwards towards using sustainability structure throughout decrease in weight of building which is leading to decrease in usage of the concrete material. The introduction of high strength-normal weight concrete (HSNWC) may result in the reduction of the slab thickness. This means you'll be more sensitive to deflection [1]. Also, other approaches to reduce the weight of slabs by using lightweight concrete (LWC). One of the most common methods of producing LWC is to use lightweight aggregate (LWA). During the last few decades, a variety of lightweight aggregates, such as (Leca, pumice, perlite, scoria, etc.) [2].

Solid slabs consider as one of the most structural elements in multi-story buildings consuming concrete, so many researchers investigated the possibility of using different types of concrete and slabs to overcome this problem [3-7].

The application of ribbed slabs contributes to the reduction of the floor weight; this is achieved by removing the part of concrete volume underneath the neutral axis of the normal solid slab [8]. The addition of steel fiber to reinforced concrete structures appears to be a good combination for strength. It has good ductile behavior and energy absorption that can help brittle concrete. The steel fiber incorporation in ribbed slabs may aid in the reduction of reinforcement in structures while also improving slab flexural strength [9].

Ahmad et al. [10] studied the performance of reinforced normal strength normal weight concrete ribbed slab with fiber inclusion with different top slab thickness. The results indicated that the addition of steel fibers helped in reducing the sudden brittle failure, thus proving its ability to increase energy absorption capacity and improve cracking behavior.

The behavior of reinforced ribbed slabs of normal strength lightweight concrete (NSLWC) was investigated by authors [11]. The ratio of rib depth to overall beam depth was the variable in this study. The findings revealed that increasing the rib depth to overall beam depth in ratio improved structural behavior by increasing ultimate load carrying capacity and lowering deflection.

The vibration of floor systems in buildings can be caused by a variety of sources, including the sources that occur inside of a building such as (walking, aerobics, elevator, conveyance systems, HVAC equipment, and rotating mechanical equipment on an elevated floor or roof), also, the external sources outside or attached to a building such as nearby roadways, construction activities, and industrial activities.

Vibration is an important factor to consider when designing a building. Vibrations can be simply annoying or cause significant problems, especially when occupants' daily activities, sensitive equipment performance, or important functions are routinely disrupted [12].

The main aim of this study is to investigate structural and serviceability behavior for (high strength-lightweight, high strength-normal weight, and fiber high strength-lightweight) reinforced concrete one-way ribbed slabs under static load and dynamic load (harmonic load) to choose the best slab which gives an improvement in the structural efficiency and lead to mitigate and control the dynamic effect of vibrating sources like generators.

2. EXPERIMENTAL PROGRAM

The experimental program includes studying the effect of replacing normal weight aggregate (gravel) with lightweight aggregate (pumice stone) with and without steel fiber (volume fraction (V_f =0.25%) on the strength and serviceability behavior of HSNWC reinforced one-way ribbed slabs under static and dynamic (harmonic) loading. As shown in Table 1.

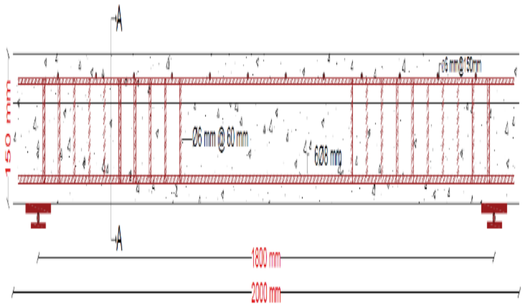
The experimental program consisted of casting and testing six reinforced concrete one-way ribbed slabs with dimensions 2000 mm length, 900 mm width, and 150 mm depth. The slabs were designed by the ultimate method to fail by flexure under the applied static load according to ACI 318-19 [13]. The main reinforcement in each rib was 2 Ø 8mm. Square mesh sheet reinforcement of (Ø6@150) mm was used in the slab flange to achieve the requirements of shrinkage and temperature reinforcement. To ensure that the shear failure occurring is prevented, (20Ø6) mm diameter stirrups were provided in each rib. The reinforcement and geometry details of the one-way slab sections are shown in Figure 1.

2. 1. Materials

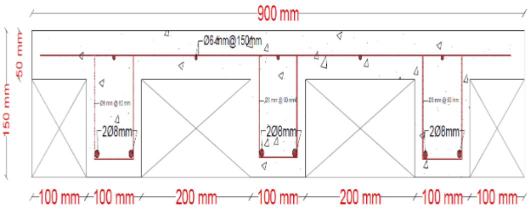
Table 2 shows the materials that were used to casting the specimens with their properties. In this study, The HSLWC mix proportion was obtained by conducting several trial mixes by ACI 363.2R [14] to select a suitable mix that meets the workability, strength,

TABLE 1. Designation and study variables of the specimens

S/N	Slab symbol	Variables to study the effect of			
1	S1	Loading type	Static loading	Concrete type	HSNWC
2	S2				HSLWC
3	S3				F0.25 HSLWC
4	HS1		Dynamic loading		HSNWC
5	HS2				HSLWC
6	HS3				F0.25 HSLWC



(a) Longitudinal section of the one–way ribbed slab



(b) Details of section A-A

Figure 1. Steel reinforcement details of all tested one–way ribbed slabs

TABLE 2. The materials of the one-way ribbed slabs with their properties

Materials	Properties
Cement	Iraqi manufactured Portland limestone cement (KARASTA) was used in this study. These properties are confirmed with EN 197-1[15].
Fine aggregate	Al-Ukhidher natural fine aggregate was used in this study. The grading of this sand within zone 2 and conformed to the IQS limits No.45/1984 [16].
Coarse aggregate	10 mm maximum size natural normal weight aggregate (gravel) from Al-Nebai quarry, with a dry density of 1573 kg/m^{3}which conforms to Iraqi specification No.45, 1984 [16]. 9.5mm maximum size natural lightweight aggregate (Pumice Stone) with dry density 708 kg/m^3, which conforms to ASTM C330 [17].
Silica fume	Micro Silica Fume, commercially known as MegaAdd MS(D), was used in this study. It is complying with ASTM C 1240-20 [18].
Superplasticizer	SikaViscoCrete® 5930-L was used in this study. It meets the requirement for a superplasticizer according to ASTM C494/C494 – 19[19].
Water	Ordinary tap water was used for mixing, pouring, and curing all concrete mixes in this study.
Sugar molasses	byproduct liquid material was supplied from a sugar factory in Babylon city of Iraq.
Steel fiber	Macro hooked ends steel fiber with a length of 35 mm, and an aspect ratio of 70 was used in this study.
Steel reinforcement	Deformed steel bars of diameters (6 mm and 8 mm) and square mesh sheet of 6 mm were used in this study and yield stress of (495,509, and 495) MPa, respectively. It meets the requirement of ASTM A 615/615M-20 [20].

and density requirements of most codes of structural lightweight concrete (SLWC).

The other mixes have the same mix proportion detail of HSLWC except to replace pumice stone with gravel at the same volumetric ratio, for (HSNWC) mix and add steel fibers for (F0.25HSLWC) mix, Due to the high specific gravity of steel fibers (0.25%) of the volumetric ratio was used in this study, as shown in Table 3.

2. 2. Testing Setup

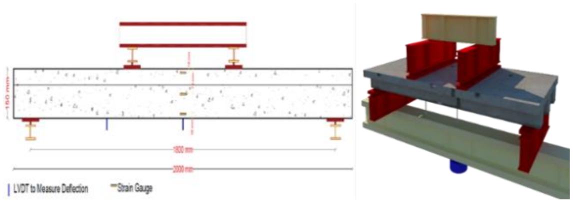
In the static testing, a hydraulic testing machine was used to test the ribbed slab specimens at the laboratory of civil Engineering/ Babylon University. The ribbed slabs were tested as a simply supported slab with a 1700mm clear span under two-point loads. Steel plates were placed under the two-point loads and on the supports to prevent stress concentration and local crushing of concrete. The static load was applied monolithically with a loading rate of 0.05kN/sec until the failure.

The vertical deflection was measured using one LVDT (KTR-100mm) type with a maximum capacity of 100mm with an accuracy of 0.01, that was placed at the bottom face of the mid-span of the slab, and the data was collected by using a data logger, which was connected to the computer, as shown in Figure 2.

On the other hand, the dynamic testing was conducted by using an electric motor (ZW-5) with a capacity of 1100 Watt, which can run up to the maximum speed

TABLE 3. Concrete mixes

Material	Concrete mixes quantity (kg/m^3)		
	HSNWC	HSLWC	F0.25HSLWC
Cement	525	525	525
Silica fume	75	75	75
Sand	590	590	590
Gravel	1100	----	----
Pumice stone	----	495	495
Water	142	142	142
Superplasticizer	7.85	7.85	7.85
Sugar molasses	1.05	1.05	1.05
Steel fiber	----	----	19.5



(a) 2D static model (b) 3D static model

Figure 2. Test details of the one–way ribbed slabs tested under static load

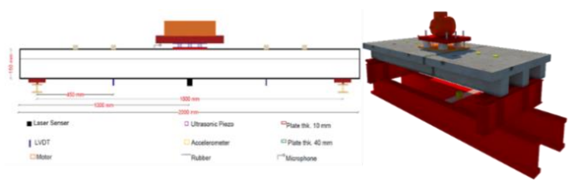
50Hz; the rotary speed of the motor was controlled through using a control speed unit (AC Driver), the weight of the motor and its unbalance mass was about of (22 and 2.1) kg, respectively. The dynamic load applied to the slabs was sinusoidal load (harmonic load) induced by an unbalanced rotating motor mass. The value of this load depends on the characteristics of an unbalance mass and operating frequency of the motor, as shown in Equation (1).

The vibration amplitude was measured by using laser sensor type (LK-081). The data was collected by using data acquisition for sound and vibration type NI PXIe - 1062QP [21]. Over the steel plate, the motor was suitably positioned with the help of bolts, then was mounted at the top surface of the slab, as shown in Figure 3. In this study, the results of applying two frequencies (maximum and a half) motor capacity (i.e., 25Hz and 50Hz) were chosen to be discussed. At each of these frequencies, the amplitude of displacement was found to stabilize approximately after 20 sec.; once it was stabilized, the readings were taken.

3. RESULTS AND DISCUSSION

3. 1. Mechanical Properties Results of Concrete Mixes

From Table 4, It can be seen that using HSLWC mix without steel fiber instead of HSNWC decreased the compressive strength of cube (150) mm and cylinder (150×300) mm specimens by 23.61% and 27.24%, respectively. The tensile strength also decreased by 34.04% and 37.5 % for f_t and f_r, respectively. On the other hand, the density was improved by 19.31%. Moreover, the addition of 0.25 % as volume fraction in the HSLWC mix led to enhancement in its compressive and tensile strength properties only. The enhancement was (3.9, 4.7, 0.7, 0.6) MPa for f_{cu}, f_c\`, f_t, and f_r, respectively, while the density increased by19 kg/m^3.



(a) 2D dynamic model (b) 3D dynamic model

Figure 3. Test details of the one–way ribbed slabs tested under harmonic load

TABLE 4. Mechanical properties of concrete mixes

Conc. Mix	f_{cu} (MPa)	f_c\` (MPa)	f_t (MPa)	f_r (MPa)	w_c (kg/m^3)
HSNWC	68.2	58.0	4.7	5.6	2408
HSLWC	52.1	42.2	3.1	3.5	1943
F0.25HSLWC	56.0	46.9	3.8	4.1	1962

3. 2. Slab Specimens under Static Loading

3. 2. 1. Cracking Behavior

The cracking behavior results of ribbed slabs, which are shown in Table 5, revealed that:

- Using HSLWC in slab S2 instead of HSNWC reduced the cracking and ultimate loads by 44.4 % and 17.70 %, respectively.
- Using steel fiber in HSLWC slab S3 instead of HSNWC led to reducing the cracking and ultimate loads by 33.24 % and 3.21%, respectively.
- The addition of steel fiber in slab S3 increased first crack and ultimate strength capacity by 20.06 % and 17.60 %, respectively, concerning a slab without fibers.
- The initial crack had a width not exceeding 0.02mm, while the maximum crack width at service load was 0.11mm,0.22 mm, and 0.2 mm for S1, S2, and S3, respectively. These values meet the limitation requirement of ACI 318-19 [13], which is 0.4 mm.

Figure 4 shows the cracking patterns for specimens tested under static load.

3. 2. 2. Deflection Behavior

From the load-deflection curve for all specimens tested under static load, as shown in Figure 5, it was found the following characteristics:

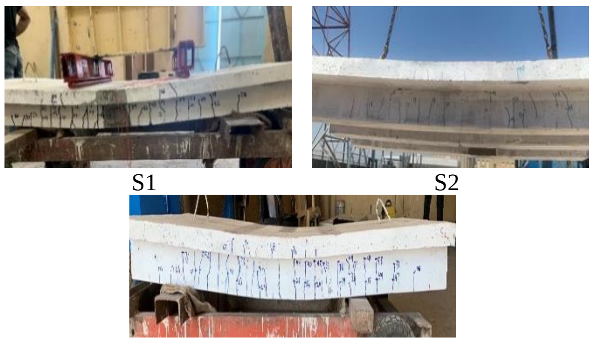
- **Deflection at Service Stage**

The deflection at the service load stage was 6.02 mm, 7.20 mm, and 7.84 for slabs S1, S2, and S3, respectively. These values are compared with limitations of ACI 318-

TABLE 5. Results of cracking behavior under static load

S/N	Slab Symbol	P_{cr} (kN)	% Diff. in P_{cr}	P_s (kN)	W_{cr}* (mm)	P_u (kN)	% Diff. in P_u
1	S1	22.50	---	60.93	0.11	93.74	---
2	S2	12.51	-44.4	50.15	0.22	77.15	-17.7
3	S3	15.02	-33.24	58.97	0.20	90.73	-3.21

*Crack width at service load (P_s =0.65 P_u) [22]



S1 S2

S3

Figure 4. Cracking patterns for specimens tested under static load

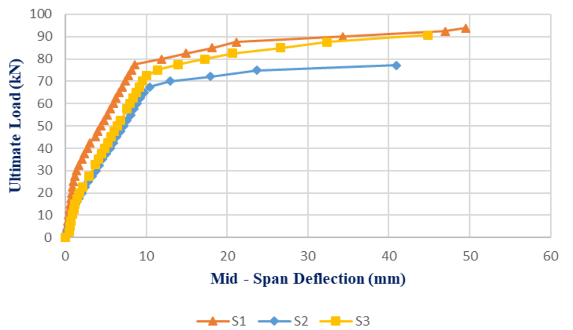


Figure 5. Load–deflection curves for specimens tested under static load

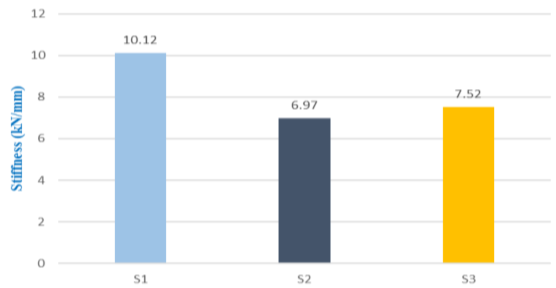


Figure 7. Stiffness for specimens tested under static load

19 for immediate deflection for roofs due to maximum live load (effective span /180 = 10 mm) [13]. It was found that using three types of concrete (HSNWC, HSLWC, F0.25HSLWC) in ribbed slabs meets the ACI serviceability requirement.

- **Ductility Index**

The term ductility is defined as "the ability of the material/ member to sustain deformation beyond the elastic limit while maintaining a reasonable load carrying capacity until total failure" [23]. In the present study, the displacement ductility index (μd) is calculated according to the deflection at ultimate load divided by the deflection at the yield load. The yield load is indicated by a change in curve slope between the first crack appearing and the curve achieving its peak value [24].

It can be seen in Figure 6 that using HSLWC in slab S2 instead of HSNWC led to a decrease in the μ_d by 28.52%, while the addition of steel fiber in slab S3 led to reducing the μ_d only 23.77%.

- **Stiffness**

From the load-deflection curves, the value of stiffness of the tested slabs was obtained. The stiffness at the service load level [22] is indicated by the slope of the line at about 65% of the ultimate load. The value of slabs stiffness is shown in Figure 7. From the load-deflection curves in Figure 5, it can be seen that the slope becomes steeper when using HSNWC slab S1 more than using HSLWC slab S2 and F0.25HSLWC slab S3. The stiffness of slabs S2 and S3 reduced by about 31.13 % and 25.69%, respectively, compared to slab S1. This indicates that the stiffness depends on the strength, types of aggregate, and strength of concrete. The addition of steel fiber in S3 recovered about 5.44% of stiffness reduction due to replacing gravel with a pumice stone.

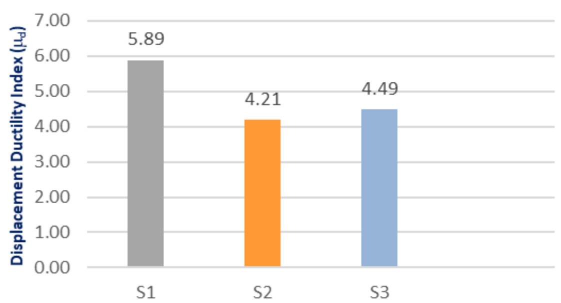


Figure 6. Ductility index for specimens tested under static load

- **Toughness Index**

Toughness index values were calculated by using the ASTM C1018 method [25]. The areas under the load-deflection curve up to the deflection of the first crack and at selected multiples deflection (3, 5.5, and 10.5) of the first crack of reinforced concrete ribbed slab specimens were calculated by Microsoft Excel software computer program. The values of toughness index and residual strength factors for all tested slab specimens under static load have been presented in Table 6.

From Table 6 can be seen that toughness index I5, I10, and I20 improved in slabs S2 and S3 by (5.11 % and 34.53 %), (16.47 % and 55.83%), and (42.48 % and 79.43 %) over slab S1, respectively. The residual strength factors R5,10 and R10,20 also improved in slabs S2 and S3 by (24.03 % and 70.07%), and (57.45% and 93.03%), respectively.

From the results above, it was found that the addition of steel fiber plays a significant role in enhancement the toughness index and residual strength of the HSLWC slab due to its ability to absorb energy.

3. 2. 3. Structural Efficiency

The ratio of strength to density is used to define structural efficiency (SE) [26]. In this study, the SE is calculated by dividing the ultimate

TABLE 6. Toughness index and residual strength factor

Slab Symbol	S1	S2	S3
Toughness Index			
I_5	6.66	7.00	8.96
I_{10}	16.64	19.38	25.93
I_{20}	45.55	64.90	81.73
Residual Strength factor*			
$R_{5,10}$	199.60	247.56	339.46
$R_{10,20}$	289.10	455.18	558.05

*$R_{5,10} = 20\,(I_{10} - I_5)$, $R_{10,20} = 10\,(I_{20} - I_{10})$

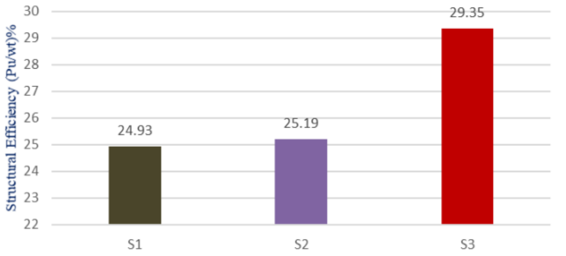


Figure 8. Structural efficiency for specimens tested under static load

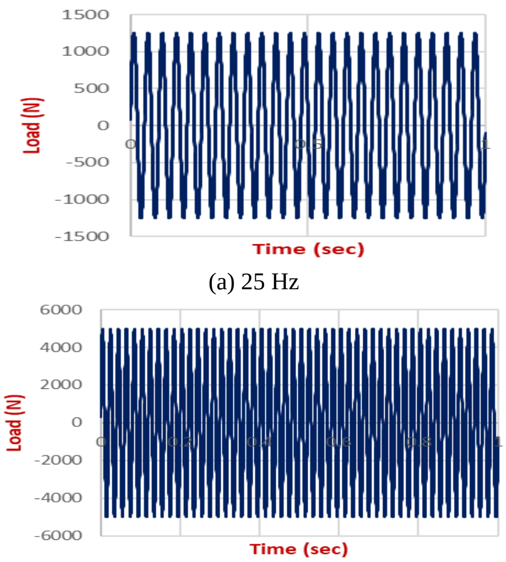
strength of the slab by its weight. SE in slabs S2 and S3 increased by1.04% and 17.73%, respectively, as depicted schematically in Figure 8. This behavior was due to decreasing the weight of slab S2 and increasing the strength of slab S3, respectively.

3. 3. Slab Specimens under Harmonic Loading

3. 3. 1. Cracking Behavior Here, the vibration serviceability of slab specimens was assessed by finding the response of specimens under the effect of harmonic loading induced by an electric motor. The applied harmonic load on slabs (HS1, HS2, and HS3) induced by applied 25 Hz and 50 Hz can be calculated mathematically by using the formula below [27]. Figure 9 shows the details of considered cases of harmonic load.

$$P_d = 2 * m * e * \omega_o^2 * \sin \omega_o * t \qquad (1)$$

where: P_d is the induced harmonic dynamic load (N), m is the eccentric rotating mass (kg), e is the eccentric distance (m), and ωo is the operating frequency (rad/sec).



(a) 25 Hz

(b) 50 Hz

Figure 9. Load–time history for specimens tested under harmonic load

After applied 50 Hz, the hairline cracks have appeared in the slab HS2 while not noticed any hairline cracks in slabs HS1and HS3. As shown in Figure 10. From this outcome can be concluded the addition of steel fiber in the slab HS3 improves the cracking behavior of slab HS2.

3. 3. 2. Vibration Behavior The peak amplitude of vibration for time one – the second was drawn as displacement- time history for slabs tested under harmonic load for 25 Hz and 50 Hz, respectively. As shown in Figure 11.

The displacement amplitude outcomes in Figure 12 implied that the vibration of slabs has induced by the harmonic load is affected by characteristics of a slab (stiffness, natural frequency, and damping) and applied of an operating frequency. It was found that in both

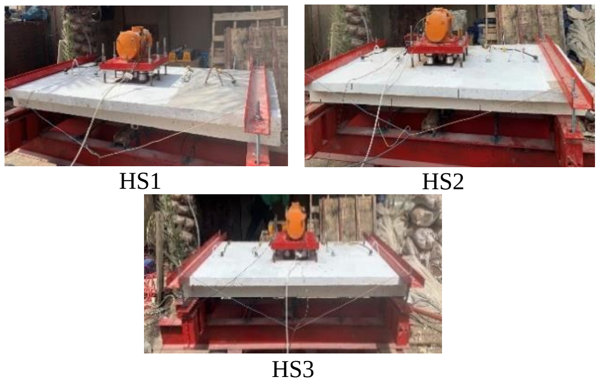
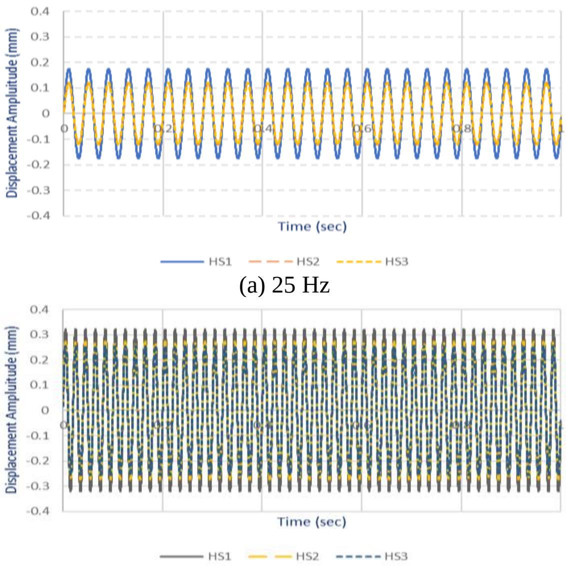


Figure 10. Cracking patterns for specimens tested under harmonic load



(a) 25 Hz

(b) 50 Hz

Figure 11. Displacement – time history for all specimens tested under harmonic load

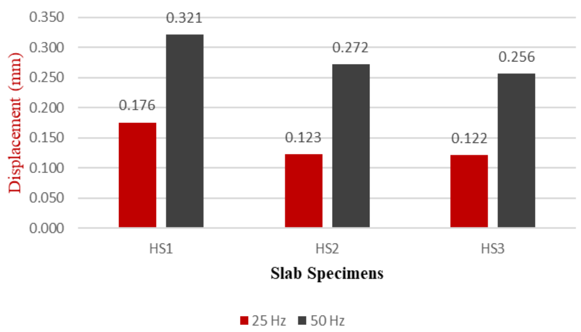


Figure 12. Displacement amplitude for specimens tested under harmonic load

operation frequencies (25 and 50) Hz, the HSNWC in slab HS1 gave the highest displacement value followed by HSLWC in slab HS2 and F0.25HSLWC in slab HS3. This behavior may belong to the nature of HSNWC which was a denser composition and a larger bonding strength between the aggregate and mortar, which results in a reduction of energy dissipation and damping ratio of the slab.

The displacement in slabs HS2and HS3 decreased by (30.11 and 30.68) % for 25 Hz and (15.26 and 20.25) % for 50 Hz in comparison to slab HS1, respectively.

4. CONCLUSION

The behavior of one-way ribbed slabs that were produced from three types of concrete (HSNWC, HSLWC, and F0.25HSLWC) under the effect of static and dynamic loads was tested. Based on the experimental test results, the following main conclusions can be drawn.

- Using HSLWC mix without steel fiber instead of HSNWC mix led to a decrease in the density of concrete by 19.31%, while the inclusion of steel fiber in HSLWC mix with V_f = 0.25% led to the increasing density of concrete from (1943 to 1962) kg/m^3, but remain with limitation of lightweight concrete.
- The mechanical properties of the HSLWC mix (f_{cu}, f'_c, f_t, and f_r) improved by using steel fiber (0.25%) by (7.49,11.37, 22.58, and 17.14) %, respectively.
- Using HSLWC in slab S2 instead of HSNWC led to a decrease in the first crack and ultimate load capacity by 44.4%and 17.70%, respectively.
- The addition of steel fiber in the HSLWC slab led to a recovery of 11.16 % and 14.49 % of lack in a first crack and ultimate load capacity, respectively.
- Using three different types of concrete (HSNWC, HSLWC, F0.25HSLWC) in construction one–way ribbed slab gave crack width and deflection that meet with ACI–code serviceability requirement.
- the addition of steel fiber in the ribbed slab led to overcoming almost 4.75% of ductility reduction.
- The toughness indices I5 and I10 for all ribbed slab specimens are higher than the standard values 5,10, and 20, respectively. The values of the toughness index indicated that all the behavioral pattern of the slabs approaches perfectly – plastic condition.
- The highest improvement in structural efficiency was in the F0.25HSLWC ribbed slab.
- Using HSLWC in ribbed slab instead of HSNWC under dynamic load effect led to a significant reduction in the amplitude displacement by 30.11% and 15.26% at 25 Hz and 50Hz, respectively.
- The addition of steel fibers in the ribbed slab led to reducing the negative effect of vibration by 0.81% and 5.88% at 25 Hz and 50Hz, respectively.

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Persian Abstract

چکیده

امروزه کاهش وزن سازه‌ها و مشکلات ارتعاشی هدف اولیه برای الزامات طراحی در اکثر سازه‌های عمرانی است. آزمایش‌های بارگذاری دو نقطه‌ای و بارگذاری هارمونیک برای بررسی استحکام و قابلیت سرویس‌دهی دال های آجدار یک طرفه بتن مسلح با مقاومت بالا انجام شد. شش نمونه اسلب ریخته‌گری و آزمایش شدند. رفتار ترک خوردگی، انحراف و ارتعاش مورد بررسی قرار گرفت. نتایج تجربی نشان داد که استفاده از بتن سبک با مقاومت بالا (HSLWC) به جای بتن با وزن معمولی با مقاومت بالا (HSNWC) در دال آجدار یک طرفه ساخته شده منجر به کاهش دانسیته تا ۱۹/۳۱ درصد، مقاومت به میزان ۱۷/۷۰ درصد و ۱۷/۳۳ درصد انحراف نهایی شد. اگرچه افزودن الیاف فولادی به HSLWC منجر به افزایش چگالی بتن شد، اما افزودن آن رابطه بار-انحراف و بار نهایی را برای نمونه دال افزایش می‌دهد که کاهش مقاومت را تا ١٤/٤٩ درصد کاهش داد. علاوه بر این، شاخص شکل‌پذیری، سفتی و چقرمگی برای نمونه‌های دال آجدار با الیاف فولادی رفتار بهتری نسبت به نمونه‌های بدون الیاف فولادی نشان دادند. HSNWC تأثیر منفی بر ارتعاش دال آجدار یک طرفه در هر دو فرکانس عملیاتی (۲۵ و ۵۰) هرتز گذاشت، در حالی که استفاده از HSLWC با و بدون الیاف فولادی، منجر به کاهش اثر ارتعاش به میزان (۳۰/۱۱ و ٣٠/٦٨) درصد و (١٥/٢٦ و ۲۰/۲۵) درصد به ترتیب در ۲۵ هرتز و ۵۰ هرتز شد.