Load-Deflection Relationship of White Hollow Core reinforced Concrete Panels under Static Load

Rafal Mahdi Saleh
Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
rafal@uomustansiriyah.edu.iq (corresponding author)

Husain Khalaf Jarallah
Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
Khalfdce@uomustansiriyah.edu.iq

Mohammed Mosleh Salman
Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
Mmsalman56@uomustansiriyah.edu.iq

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ABSTRACT

The main objective of this research is to examine the load-deflection behavior of White Concrete-Hollow Core Slab (WC-HCS) panels, which were made using white cement, crushed Limestone (LS) as sand, and coarse LS aggregate. The panels were subjected to symmetrical two-point static loads and the results were compared with Normal Concrete-Hollow Core Slab (NC-HCS) panels, which were made utilizing cement, sand, and gravel. The flexural response of steel-reinforced Hollow Core Slab (HCS) was also evaluated. The experimental study involved casting 12 HCS specimens. Each slab had dimensions of 1000 mm length and 450 mm width, with varying thicknesses of 80 mm, 100 mm, and 120 mm. All slabs featured a constant hollow diameter of 32 mm. The slabs were divided into four groups based on three variables: slab thickness, steel reinforcement ratio, and concrete type, namely White Concrete (WC) or Normal Concrete (NC). Concrete mechanical properties, including compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity, were studied. Non-destructive testing was performed using Ultrasonic Pulse Velocity (UPV) to assess the concrete quality. The results showed that, for the slabs with varying thickness but the same reinforcement ratio, the deflection decreased by 16.8%, 63.77%, 63.44%, 3.18%, and 57.7%. For NC-HCS slabs, deflection reductions of 23.4% and 47.9% were observed. When varying the reinforcement ratio while maintaining the same slab thickness, the deflection in WC-HCS slabs decreased by 53.5% at 80 mm thickness and by 4.6% at 100 mm thickness, whereas it increased by 18.8% at the same thickness. At 120 mm thickness, the deflection increased by 17.3% and then decreased by 38.3%. The study also explored the effect of concrete type. For slabs with 80 mm thickness, the deflection increased by 48% in WC-HCS compared to NC-HCS. At 100 mm thickness, the deflection decreased by 29.7%, while at 120 mm, it increased by 5.8%.

Keywords-white concrete; hollow core slab; deflection; white concrete panel; load-deflection relationship

I. INTRODUCTION

WC is synonymous with light, clear colors and beautifully consistent surfaces whether utilized in large, small buildings, or in facilities of any size. Constructions automatically look more elegant and slimmer when created using WC. In addition, its light-reflecting property is beneficial as a practical function in the manufacture of curbs, road markings, tunnel ramps, paving stones, in-situ constructions, mortar, and paints [1]. It has been demonstrated that WC can have a good-to-high performance [2]. In place of the more common gray aggregates, like gravel and sand, WC mixes whiter materials, like crushed marble, quartz, or LS. In contrast to the usual gray tone of concrete, a combination of white aggregates gives the impression of being white or light gray in hue [3]. Hollows or openings are used in concrete members, especially in Reinforced Concrete (RC) slabs for construction and service purposes or to reduce the weight of the slab. Different types of hollows can be used, such as longitudinal, transversal, and vertical, and many benefits can be obtained when the longitudinal hollow technique is deployed. These involve:

- Using a hollowed slab significantly reduces the slab's weight, which forms a large portion of a building's dead load. By decreasing the self-weight of the slab, the total building weight is also reduced. This reduction leads to an economic design of structural members, particularly the foundations, and creates a more structurally efficient section.
- Longitudinal hollows are used as ducts to meet the mechanical or electrical requirements.
- Hollows make the slabs more adequate for isolation and fire.
- Precast HCS are popular in the construction industry due to their numerous benefits, such as saving materials and energy, reducing construction costs and time, and providing lightweight roofing [4].

Using hollows in slab construction offers a practical alternative to lightweight materials for producing lightweight concrete slabs. This approach addresses the significant impact lightweight materials have on the slab behavior, which often includes a considerable reduction in slab capacity [5]. Additionally, the production of lightweight concrete is associated with practical challenges that make it less favorable. Previous experimental studies have explored the structural behavior of reinforced HCS made with recycled lightweight materials. In [6], six HCS specimens were cast, each measuring 1200 mm in length, 450 mm in width, and with varying thicknesses at 200 mm, 250 mm, and 325 mm. To mitigate shear failure, which is common in thicker HCS, shear reinforcement was employed. The findings revealed that the addition of shear reinforcement enhanced the shear strength by up to 50% and increased the maximum deflection by the same margin. Furthermore, the inclusion of shear reinforcement shifted the failure mode from shear to flexural, demonstrating its effectiveness in improving the slab performance.

II. RESEARCH SIGNIFICANCE

The primary significance of this research lies in the development of an HCS system using WC made entirely from locally available natural materials. This includes LS as coarse aggregate, crushed LS as white sand, and white cement. The study aims to produce bright WC using these local resources while investigating its behavior under static loading conditions.

III. EXPERIMENTAL PROGRAM

The experimental work included casting 12 HCS with dimensions of 1000 mm length × 450 mm width, with different slab thicknesses of 80 mm, 100 mm, and 120 mm designed to display flexural failure. The slabs were divided into four groups based on the type of the variables adopted. The parameters considered in this study, which were:

- Effect of thickness.
- Effect of reinforcement ratio.
- Effect of concrete type.

The cast samples are described in Table I along with the reinforcement details and the parameters of this study. All the specimens were subjected to a static two-point load. Figures 1 and 2 show the setup of the HCS specimens.

TABLE I. DETAILS OF SPECIMENS AND TYPE OF FAILURE

Group	**Slab designation**		**Slab thickness**	**Flexural steel reinforcement ratio(ρ) in longitudinal direction**	**Failure type**
Group (A)	A-White-T1	S1	80 mm	ρmin.=0.0018 3Φ6	Flexural
		S2	100 mm		Flexural
		S3	120 mm		Flexural
Group (B)	B-White -T2	S4	80 mm	2ρmin.=0.0036 7Φ6	Flexural and shear
		S5	100 mm		Flexural
		S6	120 mm		Flexural
Group (C)	C-Normal -T2	S7	80 mm	2ρmin.=0.0036 7Φ6	Flexural
		S8	100 mm		Flexural
		S9	120 mm		Flexural
Group (D)	D-White-T3	S10	80 mm	3ρmin.=0.0054 9Φ6	Flexural and shear
		S11	100 mm		Shear
		S12	120 mm		Shear

Fig. 1. Setup of HCS specimen.

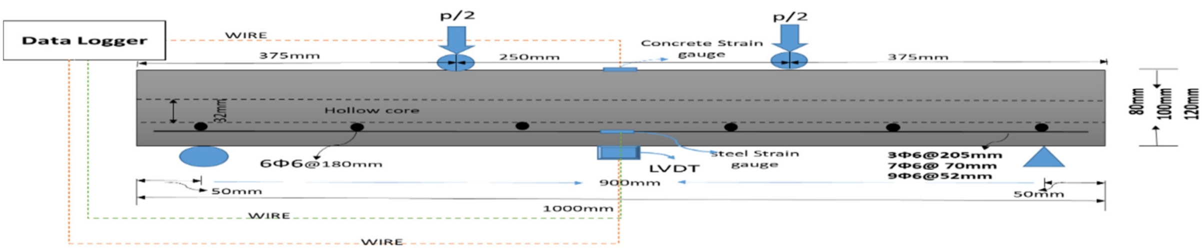


Fig. 2. Details of the slab test.

A. *Materials and Mix Properties*

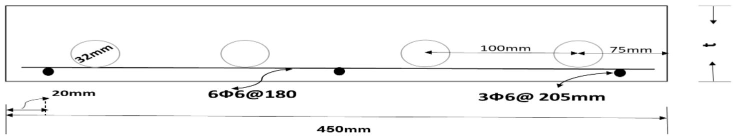
This research utilized Ordinary Portland Cement (OPC) and White Portland Cement (WPC). White sand was created using a fine aggregate with a maximum size of 4.75 mm and crushed LS. Local coarse aggregate and LS aggregate were also included as components in the WC mix. The mix proportions, outlined in Table II, were adopted from [7]. For reinforcement, deformed steel bars with a 6 mm diameter were used, complying with [8]. These bars served as both the main longitudinal reinforcement and secondary transverse reinforcement, as depicted in Figure 3. The steel test was performed to calculate the yield load. This was achieved by dividing the steel's yield strength by its modulus of elasticity and comparing the results with strain data. The experimental setup used a Linear Variable Displacement Transducer (LVDT) to measure the deflection and yield load at the midpoint of the slab.

TABLE II. MIX PROPORTION BY WEIGHT (1:1.78:2,42) FOR NC AND WC

Cement	**Sand**	**Coarse aggregate**	**Water cement ratio w/c**
425 kg/m^3	760 kg/m^3	1030 kg/m^3	0.5

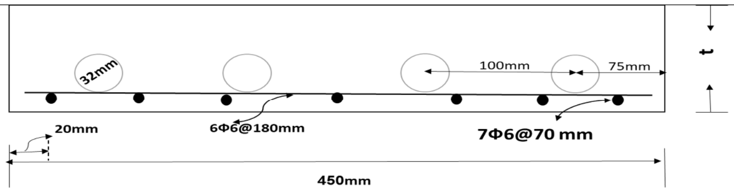
Slab — **Steel reinforcement in the main direction**

A-White-T1 -80 -S1
A-White-T1 -100 –S2
A-White-T1 -120 –S3



B-White-T2 -80 –S4
B-White-T2 -100 –S5
B-White-T2 -120- S6

C-Normal-T2 -80 –S7
C-Normal-T2 -100-S8
C-Normal-T2 -120-S9



D-White-T3 -80 –S10
D-White-T3 -100-S11
D-White-T3 -120-S12

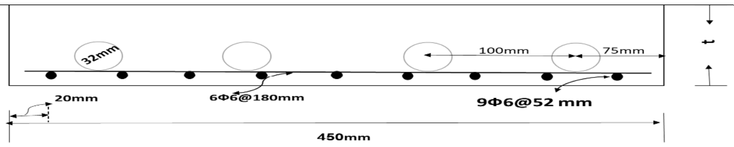


Fig. 3. HCS with steel reinforcement details in the main direction t = 80 mm, 100 mm, 120 mm.

B. Mechanical Properties

The compressive strength test was conducted in accordance with [9]. The test utilized 100 mm × 100 mm × 100 mm cubes made from WC and NC, after 28 days of curing. An electrical testing machine with a capacity of 1000 kN, as shown in Figure 1, was used for the procedure. The results were based on the average of three specimens for each mix. Table III presents the compressive strength results, demonstrating that the WC cubes achieved higher compressive strength compared to the NC cubes. Both types exceeded the target compressive strength of 25 MPa. The cube compressive strength fcu was converted to an equivalent cylinder strength f'c using the equation f'c = 0.85 fcu, as noted in [10] and depicted in Figure 4.

Fig. 4. Compressive strength test.

Figure 5 presents the compressive strength results. Concrete is known for its high compressive strength but low tensile strength. Without reinforcement, it tends to crack and fail under relatively small loads, often exhibiting abrupt and brittle failure [11]. The experimentally determined mechanical properties of both concrete types are summarized in Table IV and displayed in Figure 6.

TABLE III. COMPRESSIVE STRENGTH RESULTS

Mix sample	Average compressive strength fcu (MPa) for each mix	f'c (MPa) = 0.85×f_{cu} [9]
NC	29.2	25
WC	35.03	29.77

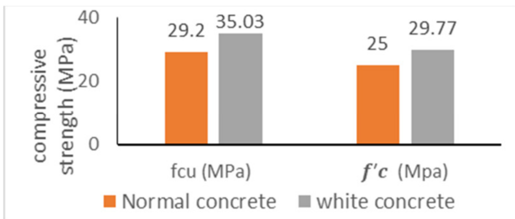


Fig. 5. Compressive strength results.

TABLE IV. EXPERIMENTAL RESULTS OF CONCRETE MECHANICAL PROPERTIES

Specimen designation	fct (MPa) [12]	fr (MPa) prisms [13]	Ec (MPa) [14]
NC	3.64	5.1	27300
WC	3.57	4.74	26133

C. Ultrasonic Pulse Velocity Non-Distractive Test

The bond strength of the concrete matrix was evaluated using the non-destructive UPV method. This test assessed factors influencing the bond between the steel and concrete, including concrete quality, concrete cover, corrosion presence, and curing time. The standard test method measures UPV of compressional waves propagating through the concrete. This evaluation was used to determine the structural quality of concrete. This method, independent of the dimension of the body, provided reflected waves from boundaries, which do not complicate the arrival time of the directly transmitted pulse.

To conduct the UPV test, an appropriate coupling agent, such as grease, should be applied to the transducer diaphragms, the test surface, or both. This ensures no air is trapped between the transducer diaphragms and the concrete surface. The transducers are then pressed firmly against the concrete surface to establish good contact, and the transit time is measured [15]. The relationship between the compressive strength and pulse velocity depends on factors such as the modulus of elasticity of the aggregate, aggregate content in the mix, mix proportions, concrete moisture condition, and water-cement (w/c) ratio [16]. Table V presents the UPV results after 28 days of curing and the corresponding compressive strengths. The average UPV values ranged between 4.5 m/s and 4.8 m/s, indicating excellent concrete quality [17].

TABLE V. RESULTS OF UPV

Cement Type	**Sample**	**V=L/T (m/sec)**
WC	Cubes 10 cm × 10 cm ×10 cm, L=100 mm	4.861
NC	Cubes 10 cm × 10 cm ×10 cm, L=100 mm	4.8

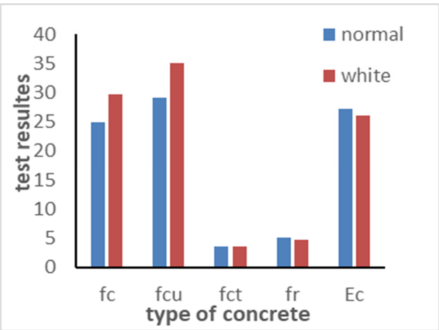


Fig. 6. Test results.

IV. RESULTS

The deflection of HCS specimens was measured at a single point at the mid-span of the tension surface. This measurement was taken using a LVDT placed 450 mm from the center of the support, as displayed in Figures 2 and 7. The LVDT readings were recorded in a data logger for every 0.01 kN load increment. Once the slabs reached their ultimate load, the mid-span deflection rapidly increased. The load-deflection response can be described in three stages:

1. Elastic Behavior: During the initial stage, the deflection increased linearly with the applied load. This linear relationship continued up to the first crack, resulting in a curve with a constant slope.
2. Crack Development: In the second stage, vertical flexural cracks formed in the tensile region of the slab, near the maximum bending moment. As the load increased, these cracks spread, reducing the section's stiffness. The load-deflection relationship became nonlinear, as the deflection rate increased continuously with the applied load.
3. Ultimate Strength: In the final stage, the slab reached its flexural capacity. The deflection continued to increase with minimal load increments. The load-deflection curve became nearly horizontal until failure occurred.

In this study, load-deflection curves for all tested HCS slabs were plotted in groups, with each group varying one parameter while keeping others constant. These relationships were analyzed to compare the deflection characteristics at the ultimate load and ductility ratio. The ductility ratio was calculated as the ratio of the deflection at the ultimate load (Δu) to the deflection at the yield load (Δy). The experimental load and corresponding deflections for the first crack (Δcr), yield load, and ultimate load stages are summarized in Table VI.

TABLE VI. EXPERIMENTAL RESULTS FOR TESTED HCS

Group	**Slab**	**First crack stage**		**Ultimate load stage**		**Yield load stage**	
		load P_{cr} (kN)	Deflection Δcr (mm)	load Pu (kN)	Deflection Δu (mm)	Load Py (kN)	Deflection Δy (mm)
Group A	W-T1-S1-80	3.7	2.9	8.33	16.73	5.86	6.31
	W-T1-S2-100	16.91	0.89	25.93	8.19	25.75	6.34
	W-T1-S3-120	19.1	0.66	34.2	6.81	Not ductile	
Group B	W-T2-S4-80	5.68	0.23	41.50	21.61	35.12	7.12
	W-T2-S5-100	12.33	0.35	52.99	7.82	51.1	5.47
	W-T2-S6-120	28.32	0.64	72.51	7.99	70.15	5.57
Group C	N-T2-S7-80	10.03	0.66	49.58	14.53	44.8	6.63
	N-T2-S8-100	17.88	0.70	62.02	11.11	59.8	6.41
	N-T2-S9-120	25.63	0.83	77.23	7.55	Not ductile	
Group D	W-T3-S10-80	6.57	0.40	47.92	10.04	44.6	6.53
	W-T3-S11-100	19.55	1.16	71.43	9.72	Not ductile	
	W-T3-S12-120	26.33	1.37	68.66	4.24	Not ductile	

Fig. 7. Testing instrument.

V. DISCUSSION

A. Effect of Slab Thickness

The slab groups were studied with regard to thickness variation for stable reinforcement ratio. The increase or decrease in deflection refers to a change in the amount of bending or deformation of a structural element under the application of external force or load.

- For group A, by varying the thickness and for stable reinforcement ratio of 0.0018, at the same load level, the deflection decreased when using LS as coarse aggregate, crushed LS as sand, and WC, as shown in Figure 8. This is because the WC demonstrated a stiffer behavior than normal, thus strengthening the concrete. Hence, at the same load level the deflection of HCS (S2-100) and (S3-120) were decreased compared to (S1-80). Regarding the load-deflection response of HCS-A, at ultimate load, a decrease in deflection (Δu) was observed due to the increase in thickness. The HCS thickness resulted in a decrease in the deflection value by 16.8 % for S3-120 compared to the deflection value of the HCS2-100 specimen.

- For group WC-B, by varying the thickness and for stable reinforcement ratio of 0.0036 (2ρmin), at the same load level the deflection decreased as exhibited in Figure 8. This is because the increase in reinforcement ratio reduced the width of the flexural cracks, and thus decreased the HCS deflection. At the same load level, a steady decrease in deflection was evidenced with rising thickness values. At ultimate load, the deflection (Δu) decreased with the thickness increase, by 63.77 % and 63.44 %, respectively, compared to the deflection (Δu) of the S4-80 specimen. This can be attributed to the considerable increase in the tensile strain of the reinforcing bars, which causes a deflection increase at ultimate load, which is inversely proportional to the height of the slab. That is, when the thickness is high the deformation becomes less. This behavior emerges from the increased flexure rigidity of HCS.

- For group NC-C, with a stabilized reinforcement ratio of 0.0036 (2ρmin), the load-mid-span deflection relationship was used as a reference, as portrayed in Figure 8. In the initial stages of loading, the deflection increased with increased slab thickness. This behavior can be attributed to the enhanced stiffness of WC-HCS and the superior mechanical properties of WC. At ultimate load, the deflection decreased as the slab thickness increased. It, specifically, decreased by 23.4% in the S8-100 slab and by 47.9% in the S9-120 slab compared to the S7-80 slab. This reduction is due to the ability of the slab to arrest crack propagation and control the growth of the flexural cracks. As a result, the slabs can sustain greater loads and deflections before failure, demonstrating improved structural performance with increased thickness.

- For group WC-D, which features a reinforcement ratio of 0.0056 (3ρmin), the deflection decreased as the slab thickness increased, as illustrated in Figure 8. This reduction in deflection is attributed to the higher steel ratio, which slows the propagation of macro cracks by enhancing the bridge effect for larger cracks. Consequently, at ultimate load, the deflection (Δu) significantly decreased with an increased slab thickness. In specific, the deflection decreased by 3.18% for the S11-100 slab and by 57.7% for the S12-120 slab compared to the S10-80 slab. This behavior can be explained by the improved bond strength between the steel reinforcement and the WC matrix. The stronger bond helps stabilize the cracks at their peak, even under higher deflection levels. Additionally, this enhanced interaction significantly improves the post-cracking tensile strength of the concrete, contributing to a better overall slab performance.

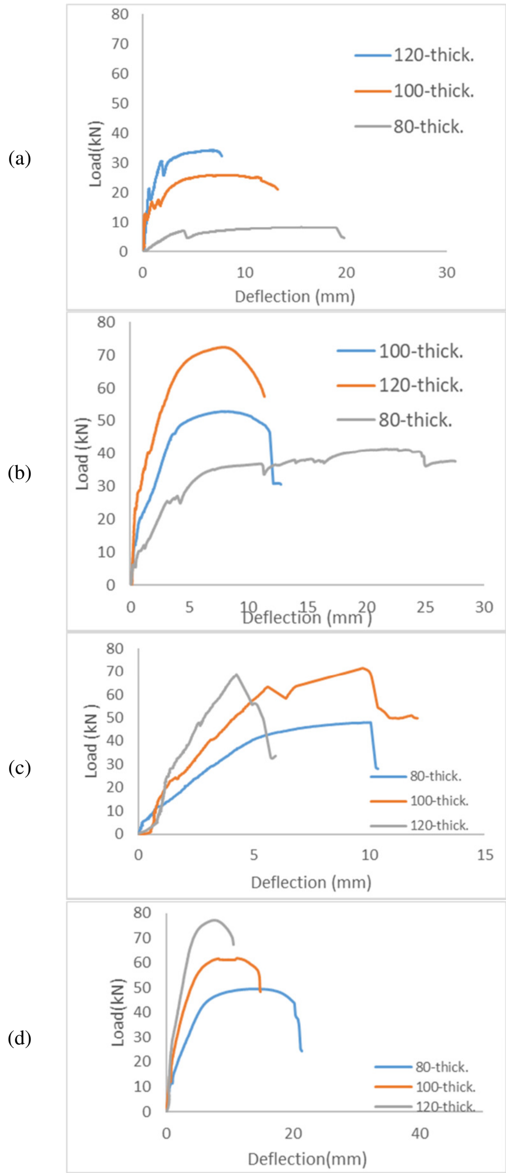


Fig. 8. Effect of thickness on HCS: (a) WC-HCS-A with ρmin, WC-HCS-B with 2ρmin, WC-HCS-D with 2ρmin, (d) NC-HCS-C with 2ρmin.

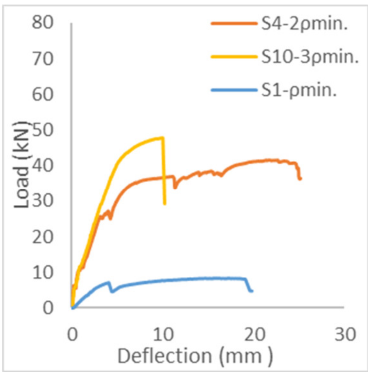
B. Effect of Reinforcement Ratio on White Slabs

This group focuses on the variations in the steel reinforcement ratio (ρ) while keeping the slab thickness (t) constant:

- At the same load level, the deflection of the WC-HCS slabs with a thickness of 80 mm decreased as the steel ρ increased, as depicted in Figure 6. This occurred because the *ρ* increase reduced the width of the flexural cracks, having led to a lower deflection in WC-HCS. Comparing the load- deflection responses of HCS1 ($\rho = 0.0018$), HCS4 ($\rho = 0.0036$), and HCS10 ($\rho = 0.0054$), the following trend emerges: the deflection initially increased with a rising (*ρ*) and then decreased. Specifically, at ultimate load, the deflection increased as the *ρ* rose from HCS1 to HCS4, but decreased when it reached 3ρmin in HCS10. At ultimate load, the deflection for HCS10 was reduced by 53.5% compared to HCS4. This behavior can be explained by the initial increase in the tensile strain of the reinforcing bars as the *ρ* rose, which led to greater deflection. However, at higher *ρ* values, the flexural rigidity of the slab improved, resulting in a reduction in deflection at ultimate load.
- As can be seen in Figure 9, the deflection of WC-HCS slabs with a thickness of 100 mm for HCS2-100 ($\rho = 0.0018$), HCS5-100 ($\rho = 0.0036$), and HCS11-100 ($\rho = 0.0054$) exhibited a consistent decrease at ultimate load as the *ρ* initially increased. However, at higher values, the deflection began to increase. Specifically, the deflection decreased by 4.6% from HCS2 to HCS5-100 but then increased by 18.8% in HCS11-100 compared to HCS2.
- Figure 9 demonstrates the deflection of the WC-HCS slabs with a thickness of 120 mm for HCS3 ($\rho = 0.0018$), HCS6 ($\rho = 0.0036$), and HCS12 ($\rho = 0.0054$). It is observed that at ultimate load, the deflection initially increased with rising *ρ* values but decreased at higher values. In specific, it increased by 17.3% from HCS3 to HCS6 but then decreased by 38.3% in HCS12 compared to HCS3.

These results illustrate that, for both 100 mm and 120 mm thick slabs, the relationship between the deflection and *ρ* is non-linear, with deflection decreasing at lower *ρ* values but increasing or stabilizing at higher values due to the interaction between the steel reinforcement and the concrete matrix.

(a)



(b)

(c)

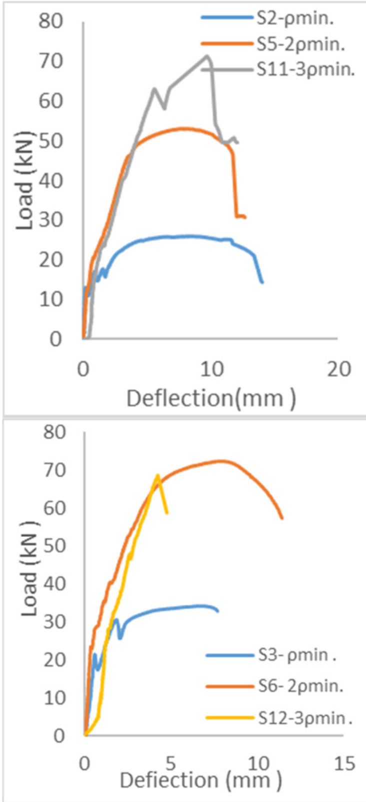


Fig. 9. The effect of reinforcement ratio on the tested WC- HCS: (a) WC-HCS -80 mm, (b) WC- HCS -100 mm, (c) WC- HCS-120 mm.

C. Effect of Concrete Type

A comparison between the NC-HCS and WC-HCS with the reinforcement ratio 2ρmin is provided, as demonstrated in Figure 10.

- HCS-80 mm: The effect of the concrete type was evaluated while maintaining constant thickness (80 mm) and *ρ*. Although the overall curve behavior for NC-HCS and WC-HCS was similar, differences in ductility were observed. At the ultimate load, the deflection in WC-HCS-4 was 48% higher than that of NC-HCS-7, indicating greater ductile behavior in WC slabs.
- HCS–100 mm: For the slabs with 100 mm thickness and the same *ρ*, the deflection at ultimate load was noticeably lower in WC-HCS compared to NC-HCS. Specifically, the deflection decreased from 11.11 mm in NC-HCS-8 to 7.8 mm in WC-HCS-5, reflecting a 29.7% reduction. This highlights the stiffer behavior of WC at this thickness.
- HCS–120 mm: When the thickness increased to 120 mm, the deflection at ultimate load showed a slight increase in WC-HCS compared to NC-HCS. The deflection rose from 7.55 mm in NC-HCS-9 to 7.99 mm in WC-HCS-6, representing a 5.8% increase. This suggests that, at this thickness, the WC slabs exhibit a slightly greater flexibility under load.

These results display how the type of concrete influences the load-deflection behavior across varying slab thicknesses.

(a)

(b)

(c)

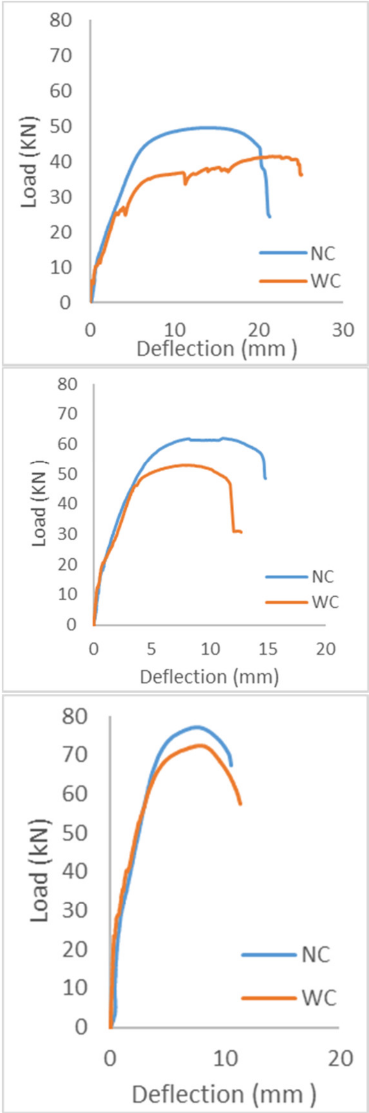


Fig. 10. Effect of concrete type: (a) HCS-80 mm, (b) HCS-100 mm, (c) HCS-120 mm.

VI. CONCLUSIONS

- Mechanical properties for White Concrete (WC) compared to Normal Concrete (NC) as a reference mix:

1. The cubic and cylindrical compressive strength increased by 19.9%.
2. The tensile strength decreased by 3%.
3. The flexural tensile strength (modulus of rupture) decreased by 7%.
4. The modulus of elasticity decreased by 4.27%.

- The UPV results for both mixes indicate excellent performance for each type of concrete.
- Varying the thickness and using the same reinforcement ratio for each group, the deflection of WC-HCS at ultimate load decreased by 16.8% with ρmin, by 63.77% and 63.44% with 2ρmin, and by 3.18% and 57.7% with 3ρmin.
- Varying the thickness and using 2ρmin, the deflection of WC-HCS at ultimate load decreased by 63.77% and 63.44%, compared to that of NC-HCS, which decreased by 23.4%, and 47.9%.
- Varying the reinforcement ratio, but using the same thickness value, the deflection of HCS-WC at ultimate load decreased by 53.5% at 80 mm thickness, by 4.6% at 100mm, and then increased by 18.8%. At the highest thickness of 120 mm the deflection increased by 17.3% and then decreased by 38.3%.
- Varying the type of concrete and using 2ρmin and the same thickness, the deflection of WC-HCS at ultimate load increased by 48% at 80 mm thickness, decreased by about 29.7% at 100 mm, and increased by about 5.8% at 120 mm.

VII. RECOMMENDATIONS

Using WC can simplify construction work, as it has similar properties to NC. HCS-B can produce slabs that demonstrate improved load-bearing capacity at different stages, with reduced deflection.

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