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Flexural Behavior of sustainable High-Performance Hollow Core Slabs Reinforced with Hybrid Fibers Rehabilitated by CFRP Sheets

Zainab M. Hussein[1] , Nagham T. Al-Shafi'i[2]
[1]Department of Highway and Transportation Engineering,
College of Engineering, Mustansiriyah University, Iraq.
E-Mail: zainabali@uomustansiriyah.edu.iq
[2]Department of Civil Engineering, College of Engineering, Mustansiriyah University, Iraq.
E-Mail: dr.nagham_tariq@uomustansiriyah.edu.iq

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Abstract:
This study investigates the behavior of High-Performance Hollow Core Slabs (HCS) reinforced with hybrid fibers containing sustainable lightweight coarse aggregate (LWA) rehabilitated by injection, and carbon fiber polymer (CFRP) sheets together. Five hollow core slab specimens with dimensions of (800×400×100) mm with two types of sustainable LWA; The first conventional HCS specimens (HCSB) contains crushed clay brick as coarse LWA, and the other conventional HCS specimens (HCSA) contains artificial LWA. Three types of fiber used in this study were: Macro-hooked steel fibers (type S1), straight steel fibers (type S), and Micro polypropylene fiber (PP), with different volume fractions. Five tested HCS specimens were repaired by injection and rehabilitated using two layers of CFRP sheets and tested to determine their ultimate load-carrying capacity. A comparison between the behavior of HCS specimens before and after rehabilitation was carried out. The test result showed that the use of CFRP sheets to strengthen the HCS specimens leads to a significant increase in the load capacity for all types of HCS specimens. The percentage recovered of load capacity after rehabilitation was 5.6%, 5.8%, and 6.7% for HCS specimens (HCSB, HCSB1, HCSB3), respectively. The load capacity for HCS specimen containing artificial LWA had been increased by about 7.03% and 8.5% for HCSA and HCSA3 compared to high-performance HCS before rehabilitation. Moreover, The deflection of the rehabilitated HSC specimens was significantly increased in comparison with HSC specimens before rehabilitation.
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Introduction

The utilization of HPLWC members has proven extremely promising in strength, rigidity, durability, and economy. The stronger the concrete, the more brittle it becomes. The lack of elasticity of the HPLWC slab can result in sudden failure without

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warning. Therefore it was found that adding fibers in appropriate quantities and at close distances works to enhance the performance of concrete noticeably as well as improving its dynamic properties. A critical application of a complex retrofitting technique is the use of an FRP jacket or sheets of fiber-reinforced polymer to deliver exterior confinement of reinforced concrete hollow core slabs (HCS) when the current internal transverse reinforcement is insufficient.

The most popular technique applied to the rehabilitation of HPLWC members is by utilizing external CFRP sheets. CFRP can lead significantly enhance the shear and flexural capacity of failed parts and extends their service life. CFRP could be utilized in various forms to strengthen the deteriorated concrete parts as well as the necessary reinforcement of concrete in new construction. The main advantages of using CFRP materials in structural applications are that CFRP can be linked to structural parts in various shapes due to its lightweight and flexibility. Moreover, this material can contribute to required structural properties like high tensile strength, high rigidity to weight ratio, corrosion resistance, and enhanced resistance to fatigue (Nguyen, et al., 2001).

Over the past few years, many techniques have been obtained to repair and strengthen reinforced concrete parts. One of these proven techniques as one of the most efficient methods is the use of CFRP sheets. CFRP can be an excellent replacement to conventional materials for the rehabilitation, strengthening, and repair of existing Reinforced Concrete structures as in modern constructions as an alternative to steel reinforcement (Danraka, et al., 2017; and Dushimimana, et al., 2018).

Reinforced concrete elements may be damaged as a result of overloading inadequate initial capacity. In either case, cracking or other distress is evident, whether this is a repair or activity depends on the source of the damage. Repairing of cracks could be generally achieved by the injection of epoxy to the fiber-reinforced mortar, which is a new technique in the literature (Benyahia et al., 2017). In case the reinforced concrete member is still undamaged, and the structure's live load is to be increased, then the appliance is merely for strengthening functions (Corry, and Dolan 2001).

Most of the literature available was to study the rehabilitation of hollow core slab containing natural coarse aggregate, while there are very few studies dealing with high-performance hollow core slab reinforced by hybrid fibers (single, and triple fibers), including sustainable LWA as crushed clay brick and local artificial aggregate after subject to failure and rehabilitation using reinforced CFRP sheets. There are the significant number of researchers, namely (Mohiuddin ,2006; Hosny, et al., 2006; Elgabbas, et al. 2010 ; Yu, et al. 2012 ; Dhara, et al. 2015 ; Abdulah, Mazen 2015; Sara et al. 2018); used CFRP for the strengthening of the reinforced concrete structure. Generally, studies revealed CFRP to be a useful and significant technology for strengthening and repairing reinforced concrete hollow core slabs (HCS). The main objectives of the present research are:

1- To rehabilitate deteriorated traditional hollow-core slab specimens containing sustainable crushed clay brick (LWA) reinforced with single and triple fibers using CFRP sheets.
2- To rehabilitate deteriorated conventional hollow-core slabs specimens containing artificial LWA reinforced with triple fibers using CFRP sheets.
3- To calculate the ultimate load capacity and draw load-deflection curve for the rehabilitated hollow-core slabs under flexural load.
4- To compare the behavior of conventional hollow-core slabs before rehabilitation with hollow-core slabs specimens after rehabilitations using CFRP sheets.

1. **Experimental Program**

2.1 Materials and Methods

In previous research Hussein, et al. 2018; concrete of (HCS) specimens was constructed using locally produced Portland cement. Chemical and physical properties test results conform to Iraqi specifications No. 5/1984, where natural sand of a maximum size of 4.75 mm that included in Zone 2. The results demonstrated the sand gradation, sulfate content, and physical properties fall within Iraqi specifications No. 45/1984.

Two sorts of LWA were utilized containing artificial LWA and crushed clay bricks as follows:

a) The recovered crushed clay brick was utilized as a durable LWA with a maximum aggregate size of 12.5 mm. Table 1 demonstrates the gradation of crushed clay brick aggregate according to ASTM C330-03 2003; while Table 2 demonstrates the chemical and physical properties of the crushed clay brick aggregate with their relating suitable specifications.

b) The lightweight artificial aggregate used through this study was manufactured by mixing sodium silicate liquid waste from glass plants with bentonite clay (Khalil et al. 2015). The clay / Sodium ratio selected to be 1:1. The gradation of LWA was according to ASTM C 330-03 2003; The general properties of the manufactured LWA are shown in Table 2.

Table 1. Coarse crushed brick (LWA) gradation

Sieve size (mm)	The Selected Cumulative Passing (%)	Cumulative Passing Range (ASTM C330) (%)
12.5	100	100
9.5	85	80-100
4.75	15	5- 40
2.36	0	0- 20
1.18	0	0-10

Table 2. Properties of crushed brick LWA[a] & produced artificial LWA[a]

Properties	Specifications	Test Results	
		crushed brick	artificial LWA
Dry loose unit weight, kg/m^3	ASTM C330	636[b]	538.25 [b]
Dry rodded unit weight, kg/m^3	ASTM 29/C29M/97	729	543.20
Absorption (%)	ASTM C127-01	19.1	12.90

Aggregate crushing value (%)	BS 812-part 110-1990	65.6	51.6
Specific gravity	ASTM C127-01	1.89	1.53
Sulfate content (as SO_3), (%)	BS 3797-part 2-1981	0.89[c]	0.97[c]

a-Physical tests were performed by the National Center of Construction Laboratories, and Researches.

b-In the range of "ASTM C330 ≤ 880 kg/m³".

c- In the field of "BS 3797, part 2 ≤ 1.0%".

There are two sorts of admixtures used in this study; the first one is the High Range Water Reducing Admixture (HRWRA) consisting of enhanced polycarboxylic ether (Sika-Viscocrete-5930) was utilized. It is considered as the third-generation superplasticizer, which meets the conditions of ASTM C494M/04 type F. The second admixture is silica fume produced by the Sika company. The results showed that the used silica fume complied with the physical and chemical specifications in ASTM C1240.

Three sorts of fiber were utilized in this study:

a) Macro-hooked steel fibers type S1 with dimensions of (0.5 mm) diameter and (30 mm) length. The maximum tensile strength and density were 1180 MPa and 7800 kg/m3, respectively.

b) Straight steel fibers (type S) of (0.2 mm) diameter and (13 mm) length. The density for this fiber was 7800 kg/m3, and the maximum tensile strength was 1180 MPa.

c) Micro polypropylene fiber (PP) of (12 mm) length and (18 microns) diameter. The minimum tensile strength was 350 MPa. Distorted joined wire textile net steel sticks with a diameter of (5 mm) were positioned in the tension surface of the slab. The average maximum strength of the textile net was 690 MPa.

2.2 Concrete mixtures

The compressive strength of concrete mixtures should be 20 MPa at 28 days as a minimum requirement for ACI committee 211-2. The mixture proportion used in this study is (1 cement:1.18 sand:0.73 LWA) by weight of the total mixture. The content of cement was 550 kg/m3, and the w/c ratio was 0.44. Numerous trial mixtures were conducted to choose the most appropriate dosages of HRWRA and silica fume to arrange high-performance LWAC.

The selected mixture (control mixture) consists of 2.5 liters HRWRA in 100 kg and 3.0-liter cement in 100 kg.

Silica fume was added by 10% as a partial replacement of cement with 0.26 and 0.25 w/c ratios for crushed brick LWA and artificial LWA, respectively. Two control mixtures (without fiber) were conducted to make two HCS samples. The first mixture (HCSB) consists of crushed clay brick as coarse aggregate, while the second control mixture (HCSA) consists of artificial LWA. Two concrete mixtures consisting of crushed clay brick as coarse aggregate were modified with a single fiber and hybrid triple, whereas one concrete mixture consisting of artificial LWA was modified with triple fiber, which was utilized to conduct three HCS samples as shown in Table 3.

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Table 3. Details of types of volume fractions of fiber used in HCS specimens.

HCS symbol	Volume Fraction of the fiber (%)		
	S1	S	PP
HCSB	0.0	0.0	0.0
HCSB1	0.75	0.0	0.0
HCSB3	0.25	0.25	0.25
HCSA	0.0	0.0	0.0
HCSA3	0.25	0.25	0.25

2.3 Experimental Work

This research involved the manufacturing and testing of five HCS samples with measurements of (800 x 400 x 100) mm. The manufactured specimens are reinforced with a welded wire mesh put on the tensile surface of the slab. HCS is fabricated in accordance with ACI 318 specifications.

A 300-ton competence universal hydraulic machine was utilized to test the HCS slabs. The tested slabs were placed in a curing water bath until the age of 28 days. In order to make it easy to detect crack propagation, the slab of HCS was cleaned and painted in white color prior to being tested. After that, the models will be

placed on the examination device platform of the testing machine with a 600 mm long clear span.

The applied loading was done using two rods of steel ponded with plates in order to prevent stress concentration on the sample, as illustrated in Figure 1, which shows the two-point loading testing machine. A 0.01 mm dial gauge held by steel support was fixed in the mid-span of the slab to measure the deformation. The expected strength of the sample was the determinant for the magnitude of load applied at every single step of loading. The dial gauge recorded the deflection corresponding to each load step.

The appearance of cracks on the surface of each slab was monitored utilizing a magnifying glass to record the initial positions, and the extent of the cracks occurs, and then the cracks were marked in accordance with the magnitude of the load applied. The failure load was recorded as the point when the testing shows a drop in loading with a sharp increase in deformation.

Fig. 1: HCS specimen in the testing machine

2.4 Procedure and Testing

In this research, the HCS specimens tested in previous research (Hussein et al., 2018); were repaired and then sheeted with carbon fiber fabric (rehabilitated HCS) using the following steps:

- The bonding slurry was mixed with the water/powder ratio of (0.17- 0.18), according to the manufacturer instructions. It was applied by brush to the prepared (pre-wetted) concrete slab surface.
- Polymer modified repair mortar was mixed with water /powder ratio of (0.11- 0.13) by weight, according to the manufacturer instructions. The mortar was applied wet on wet to the bonding layer in different layers with a thickness not exceeding 30 mm.
- The repaired parts of the HCS specimens were then cured through covering it with burlap spraying water on it every day, then covering it with polyethylene sheets. The repaired part was cured for 28 days; after that, the specimens were kept in the laboratory for seven days to be dried typically.
- Two-part epoxy impregnation resin was mixed by hand (part A: part B= 4:1 by weight, according to the manufacturer instructions (Manos, et al., 2004); and then apply it to the prepared HCS specimens' surfaces with the aid of a brush.
- The unsound concrete was eliminated, and the surface of the concrete was thoroughly cleaned of dust by a steel brush.
A unidirectional woven CFRP fabric sheet was put around the HCS. HCS is used in parallel with the direction of the tissue until the resin is oppressed between the threads of the fibers and across them and evenly distributed over the entire surface of the tissue.

Accordingly, another layer of CFRP was put on a vertical direction sheet of 400 mm width. The carbon fiber sheet was placed over the sample with the interference of ¼ of the perimeter to limit slipping or loosening the fibers upon testing. The enclosed slabs were allowed at room temperature for seven days prior to testing.

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Table 4. Results of the comparison between conventional and rehabilitated HCS specimens.

Type Symbol	Conventional HCS		Rehabilitation HCS		Rehabilitation Ultimate Loads / Convention Ultimate loads (%)
	Ultimate Loads, Pu (kN)	Deflection at Ultimate Loads Δ_u (mm)	Ultimate Loads, Pu (kN)	Deflection at Ultimate Loads Δ_u (mm)	
HCSB	30.0	4.3	31.8	5.9	5.60
HCSB1	53.5	11.7	56.8	13.7	5.80
HCSB3	59.5	12.5	63.8	14.0	6.70
HCSA	37.0	3.2	39.8	4.2	7.03
HCSA3	68.0	12.3	74.3	14.4	8.50

2.Test and Discussion

3.1 Properties of Bonding of Slurry and Repair Mortar

The specimens for compressive strength testing repaired by bonding slurry and polymer mortar

were cast, cured, and tested according to ASTM C-109 2002. Figure 2 shows the results of the compressive strength for the repaired samples in this study. It is clear that the compressive strength was increased with the sample age.

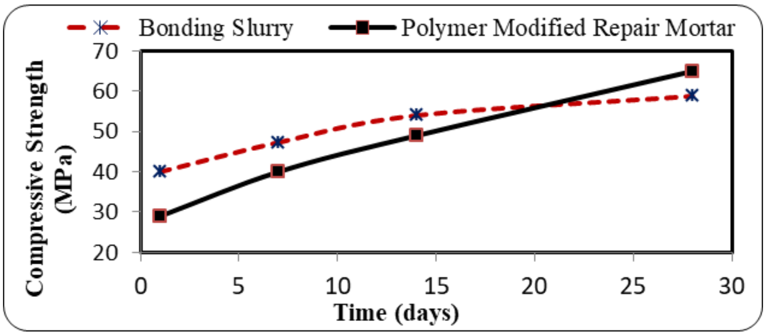

Fig.2: Compressive strength

for bonding slurry used in this research.

3. 2 The Ultimate Loads

The comparison of maximum load-carrying capacity and the resultant deflection between conventional samples modified by artificial LWA and crushed clay brick as coarse aggregate and rehabilitated is as shown in Table 4 and Fig. 3.

Generally, it can be noticed that high-performance HCS after rehabilitation with CFRP sheet shows an enhancement in the maximum load-carrying ability of about 5.6%, 5.8%and 6.7% for HCS specimens (HCSB,

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HCSB1, HCSB3), respectively, compared to conventional high-performance HCS. Moreover, HCS specimens containing artificial LWA showed an increased load-carrying capacity of about 7.03% and 8.5% for HCSA and HCSA3 compared to conventional high-performance HCS.

It was shown that the ultimate loading capacity was increased by 78.6% and 100% for MBS1 and MBH3, relatively, concerning the conventional HCS specimen consisting of crushed clay brick as coarse LWA. Thus, the loading capacity was increased by about 86.7% for HCSA3 compared to conventional HCS specimen (HCSA) containing artificial LWA.

The results also showed that the increase rate in maximum load carrying capacity for rehabilitated fibrous HSCs relative to the conventional HCS specimens was higher than that for non-fibrous concrete slabs. It can be concluded that the rehabilitation of HCS with the CFRP sheet produces greater strength compared to conventional HCS. The increasing loading capacity depends on the sort of failure of the specimen before the rehabilitation, which determines the damage degree of the specimen. This reveals the benefit of CFRP sheets in improving the ultimate strength of HCSs as they delay the appearance of cracks and give adequate adjustment to the posterior expansion of the cracks.

3.3 Mid-Span of Load-Deflection Response

The load-deflection at maximum load significantly increases in comparison with conventional HCS for all rehabilitated specimens, as shown in Table 4 and Figs. 4 and 5.

The load-deflection curve for the rehabilitated slabs is much similar to that of the conventional HCS, but with different limits. Moreover, it can be concluded, the rehabilitation by CFRP sheets has led to a significant improvement in ductility. In Figs. 3 & 4, it is clear from the relation of load-deflection that the slope of the curves decreased after the rehabilitation by CFRP sheets, which means the decreased stiffness of HCS specimens.

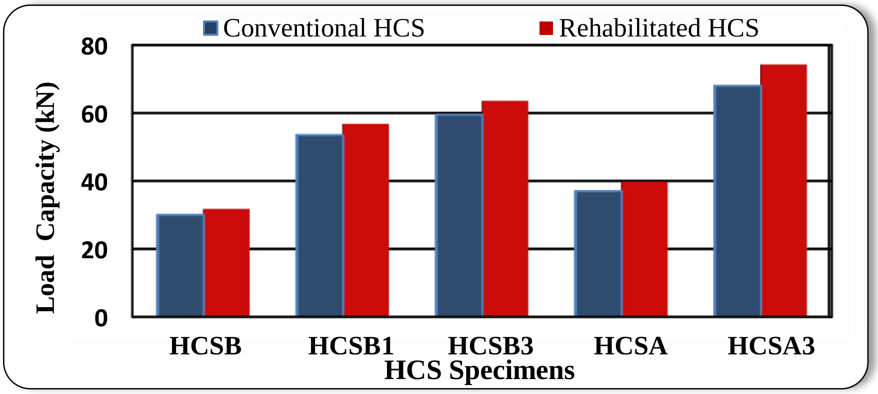

Fig. 3: Load capacity before and after rehabilitation of HCS specimens

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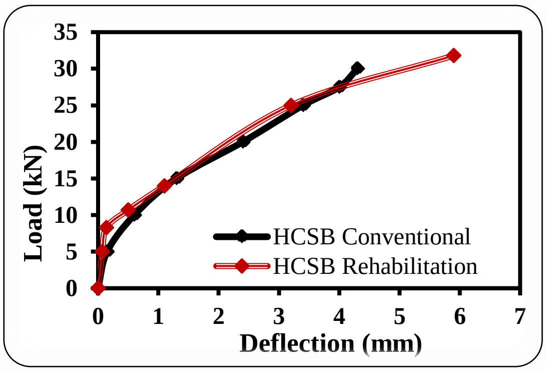


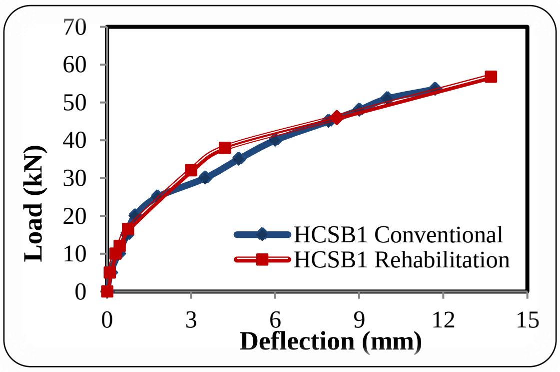
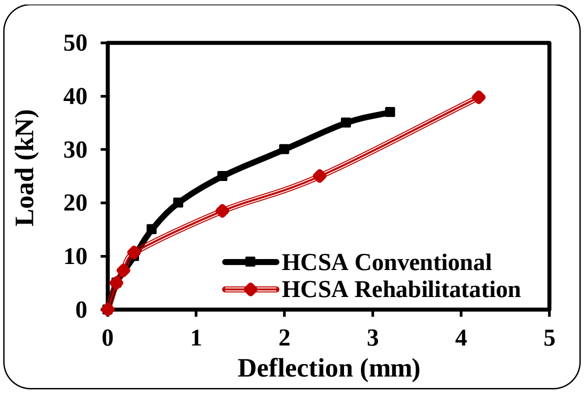


Fig. 4: load – Deflection for HCS specimens before and after rehabilitation using CFRP for containing crushed brick aggregate



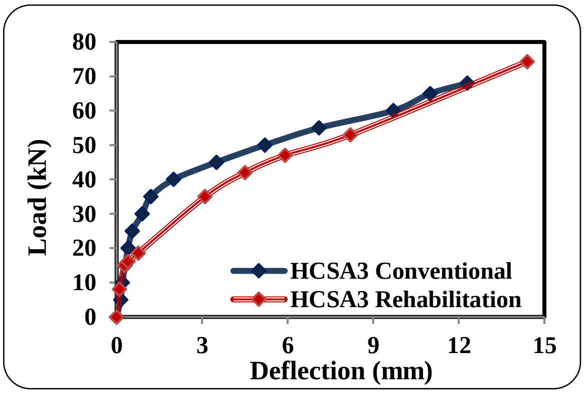


Fig. 5. Load-Deflection for HCS specimens before and after rehabilitation using CFRP.

3.4 Failure Modes

The summary of the mode of failure for the rehabilitated HCS specimens is demonstrated in Fig. 6. Moreover, though the CFRP and reinforced concrete HCS combination is a composite action, most of the load is carried by the CFRP alone.

Clicking sounds were heard during different stages of loading, which could be attributed to the microcracking formation in the concrete that affected the fibers. It was noticed that after the failure of CFRP, the ultimate load of the hollow core slab is reached, and failure occurred as tensile rupture or snatching of a fiber sheet. It was noticed that the breakdown in the CFRP layer was often concentrated in slab specimen end regions (at the edges of HCS). The failure types were the breakdown of concrete along the line connecting the edge of load positions and the load positions beneath the CFRP, which caused to de-bonding the fiber and ruptured it close to the load position.

a- HCS specimen Rupture b- CFRP sheet de-bonding
Fig. 6: The failure modes of the specimens HCS

4. Conclusion

Referring to the experimental outcomes given in this investigation, the following remarks can be concluded:

1.High-performance HCS after rehabilitation with the CFRP sheet caused the increase of maximum load-carrying capacity of about 5.6%, 5.8%, and 6.7% for the modified HCS specimens (HCSB, HCSB1, HCSB), respectively, compared to conventional high-performance HCS. Similarly, HCS specimens containing artificial LWA showed an increase in load cracking capacity about 7.03% and 8.5% for HCSA and HCSA3, respectively, compared to conventional high-performance HCS.

2.The inclusion of fibers (single or triple) to the high-performance HCS resulted in enhanced stiffness and reduced crack width. At failure, the fibrous HCS behaved in a ductile manner as compared with the conventional HCS.

3.The deflection of the rehabilitated HSC specimens is significantly increased as compared to HSC specimens before rehabilitation.

4.The high-performance HCS specimens consisting of crushed clay brick reinforced by single and triple fibers (HCSB1and HCSB3) have shown increased, ultimate load by about 78.6% and 100%, respectively, compared to conventional HCS. Also, HCS specimens containing artificial LWA reinforced by triple fiber (HCSA3) have shown increased, ultimate loading by about 86.7 % compared to conventional HCS.

5.The failure of the rehabilitated HCS occurred as a tensile rupture or snatching of fiber sheet and mostly concentrated in the hollow core slab end region.

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References

1-Abdulah, M. D. (2015). Behavior of Reinforced Lightweight Concrete Two Way Slabs Strengthened With CFRP Sheets. *Engineering and Technology Journal*, *33*(8 Part (A) Engineering), 1813-1829.

March - April 2020
ISSN: 0193-4120 Page No. 10452 - 10463

2-ACI Committee 211. 2004. Standard Practice for Selecting Proportion for Structural

3-Lightweight Concrete. ACI Manual of Concrete Practice, Part 1, pp. 211-218.

4-ASTM C109 / C109M 02- Standard Test Method for Compressive Strength of Hydraulic Cement Mortars. *Annual Book of ASTM Standards*, Vol 04.02, Manual of Cement Testing

5-ASTM C330-03. 2003. Standard Specification for Lightweight Aggregates for Structural Concrete. Annual Book of ASTM Standards, Vol.04-02, Concrete and Aggregates, United States.

6-Benyahia, A., Ghrici, M., Mansour, M. S., & Omran, A. (2017). Elaboration and characterization of fiber-reinforced self-consolidating repair mortar containing natural perlite powder. *Advances in concrete construction*, *5*(1), 001.

7-Corry, R. W., & Dolan, C. W. (2001). Strengthening and repair of a column bracket using a carbon fiber reinforced polymer (CFRP) fabric. *Pci journal*, *46*(1).

8-Danraka, M. N., Mahmod, H. M., Oluwatosin, O. K. J., & Student, P. (2017). Strengthening of Reinforced Concrete Beams using FRP Technique: A Review. *International Journal of Engineering Science*, *7*(6), 13199.

9-Dhara, J. S., Sarma, S. K., & Prakash, S. S. (2015). *Behaviour of Precast Prestressed Hollow Core Slabs with and without FRP 10-Strengthening* (Doctoral dissertation Indian Institute of Technology Hyderabad).

11-Dushimimana, A., Ziada, M., & Tuhta, S. (2018). Effect of Carbon Fiber Reinforced Polymer (CFRP) Composites Applied to Walls and Slabs of Masonry Building. *Development*, *5*(04), 2434-2442.

12-Elgabbas, F., El-Ghandour, A. A., Abdelrahman, A. A., & El-Dieb, A. S. (2010). Different CFRP strengthening techniques for prestressed hollow core concrete slabs: Experimental study and analytical investigation. *Composite Structures*, *92*(2), 401-411.

13-Faraj, S. S., Hamad, N. T., Hammoodi, A. H., & Abduljalel, B. S. (2018). Analysis of reinforced concrete deep beam strengthened by CFRP strips using ANSYS program. *International Journal of Engineering & Technology*, *7*(4), 3372-3378.

14-Hosny, A., Rahman, A. A., Sayed-Ahmed, E. Y., & Alhlaby, N. A. (2006, November). CFRP Strengthening of Prestressed/Precast Hollow Core Slabs to Resist Negative Moments. In *Proceedings, 10th Arab Structural Engineering Conference (10ASEC), Kuwait*.

15-Hussein, Z. M., Khalil, W. I., & Ahmed, H. K. (2018, December). Structural Behavior of Sustainable Hollow Core Slabs Reinforced With Hybrid Fibers. ARPN Journal of Engineering and Applied Sciences, 13(24), 9328-9334.

16-Khalil, W. I., Ahmed, H. K., & Hussein, Z. M. (2015, September). Properties of Artificial and Sustainable Lightweight Aggregate. In *17th International Conference* (Vol. 19, No. 9 Part IV, pp. 14-15).

17-Manos, G. C., Stavroy, D. S., Dimosthenous, M. A., & Kourtides, B. (2004, August). Experimental and analytical investigation of repaired and strengthened reinforced concrete structural elements utilizing CFRP. In *13th World Conference on Earthquake Engineering, Vancouver, Canada* (Vol. 91).

18-Mohiuddin, J. (2006). *Flexural behavior of prestressed precast hollow core slabs strengthened with CFRP sheets* (Doctoral dissertation, King Fahd University of Petroleum and Minerals (Saudi Arabia)).

March - April 2020
ISSN: 0193-4120 Page No. 10452 - 10463

19-Products Catalog, Innovation and Consistency, Product Data Sheet, Edition 6, 2010, Version No. 08. 06, pp.65.

20-Yu, J. T., Liu, Y., Lu, Z. D., & Xiang, K. (2012). Flexural performance of fire damaged and rehabilitated two span reinforced concrete slabs and beams. *Structural Engineering and Mechanics*, *42*(6), 799-813.

21-Yu, J. T., Liu, Y., Lu, Z. D., & Xiang, K. (2012). Flexural performance of fire damaged and rehabilitated two span reinforced concrete slabs and beams. *Structural Engineering and Mechanics*, *42*(6), 799-813.