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Effect of CFRP Wraps on the Compressive Strength of Normal and Structural Lightweight Concrete

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Abstract

Concrete is one of the most prominent building materials in the construction industry. Further, lightweight concrete has recently emerged, contributing to the sustainable values of modern construction. Many researchers have worked on enhancing the concrete's compressive strength by applying externally bonding fiber-reinforced polymer (FRP) composites via epoxy adhesives. Such FRP materials are very promising due to their lightweight and high tensile strength along with high corrosion, impact, and fatigue resistance. This paper aims to investigate the use of carbon fiber reinforced polymer (CFRP) wraps in enhancing concrete's compressive properties. The study is conducted on strengthened and control normal weight (NWC) and structural lightweight concrete (LWC) cylinders (150 mm x 300 mm). Experimental results show that CFRP wrapping increase the compressive strength and stiffness of both types of concrete. The compressive strength of structural LWC increased by 67.9% and 118.1%, compared to an increase of 46.1% and 105.0% for LWC, using one and two layers of CFRP, respectively. Further, the ductility is significantly enhanced with CFRP wrapping, suggesting increased resilience and ability to absorb energy during deformation. In terms of behavior at failure, LWC exhibited a more favourable response than NWC at failure. Results indicate that LWC has a satisfactory performance in withstanding compressive loads. This underscores the potential for lightweight concrete to serve as a viable structural material and highlights the role of CFRP reinforcement in further elevating its structural capabilities.

Keywords: Strengthening, CFRP, retrofitting, LWC, FRP wrap

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1. Introduction

Buildings serve as a center for residential, commercial, industrial, and other purposes for people. Although structures are designed to operate for several decades, there is always a risk of experiencing catastrophes, such as seismic and fire events. According to Brushlinsky et al. (2022), the number of recorded fire events ranged from 2.5 to 4.5 million from 1993 to 2020. Indeed, in 2020, 4.0 million fires were recorded in 48 countries (Brushlinsky et al. (2022)). Lightweight concrete, with its unique composition and properties, offers several significant benefits for fire resistance in structural applications. Its advantages in mitigating the effects of fire make it an attractive choice for various construction projects, especially those where fire safety is a paramount concern. The integration of lightweight structural concrete into retrofitting strategies offers a compelling solution. It addresses the imperative of ensuring structural safety and aligns with the broader objectives of sustainable and energy-efficient construction practices.

Research has shown that fiber-reinforced polymers (FRP) can be applied to enhance the performance of concrete through strengthening of structural members (Abdalla et al. (2020); Abdalla et al. (2022); Abokwiek et al. (2021); El-Hacha et al. (2010); Hawileh et al. (2022); Hawileh et al. (2014); Mhanna, et al. (2019); Sancak et al. (2008)). FRP is considered an exceptional material for strengthening of concrete due to its light weight, high tensile strength, and high resistance to corrosion, impact, and fatigue (Guler and Ashour (2016)). Studies have shown that FRP can improve the strength, shear resistance, and ductility of concrete (Naser et al. (2019)). This integration can be done in numerous ways, whether incorporating fibers within the mix, using FRP rebars, or applying external reinforcement. External reinforcement can be accomplished in the form of jacketing, wraps, or strips (Bakis et al. (2022)). For retrofitting and strengthening of existing structures, application of FRP wraps could be considered the most feasible and economical method. Contrary to wrap application, jacketing increases columns' cross-sectional area, thus, increasing the dead load of structural systems (Chinthapalli et al. (2020); Zhou and Wang (2019)). Among the types of FRP materials that can be utilized as wraps, carbon fiber-reinforced polymers (CFRP) have shown promising results in increasing concrete's compressive capacity (Bisby et al. (2011); Lenwari et al. (2016)).

Reviewing the existing literature, Seffo and Hamcho (2012) examined the use of CFRP on normal weight concrete (NWC) cylinders with an average compressive strength of 37.15 MPa. Results show that CFRP wrap increases concrete's axial and lateral strength, ductility, and stiffness. Further, increasing the number of CFRP layers resulted in a higher compressive strength capacity, ductility, and stiffness. All wrapped specimens failed by rupture of the CFRP at the center of the cylinder or throughout the entire height. Research results also demonstrate that fibers' orientation affects the increase in axial capacity and ductility of the cylindrical specimens. Larger ultimate strains are recorded when fibers are oriented horizontally or perpendicular to load application. Two-way (horizontal and vertical) fiber orientation yielded higher compressive strength values. However, four-way (horizontal, vertical, and diagonals) fiber orientation resulted in the least axial capacity values.

Exploring the application of CFRP wraps on lightweight concrete (LWC) cylinders, Zhou et al. (2016) studied the application of CFRP wraps on LWC with varying types of lightweight (LW) aggregates. Results reported that the compressive strength of CFRP-wrapped LWC increases considerably when more layers are applied. Further, findings displayed significant improvement in ductility and concrete's strength. Overall, results show largest ductility enhancement for concrete with low grade LWA and highest strength improvement for concrete containing high grade LWA. Liu et al. (2020) examined stress-strain diagrams of CFRP-wrapped LWC standard cylinders with an average density of 1850 kg/m^3 and 50 MPa. The variables in the experiment include mix proportions with different amounts of lightweight aggregate and integrated fibers (carbon and polypropylene). Three different wrapping schemes were investigated: full wrapping, three spaced rings, and six spaced rings. The observed failure modes of all specimens were CFRP rupture contained in the middle of the cylinder. The different wrapping scheme and fiber proportions did not incur significant influence on the failure mode. Further, NWC demonstrated relatively higher disintegration when compared to LWC. In all mix proportions, full wrapping scheme yielded the highest compressive strength values.

This study aims to investigate the mechanical properties of LWC and NWC wrapped with CFRP laminates. The experiment was conducted on 9 LWC and 9 NWC specimens. Each type of concrete was divided into sets of three specimens: (1) unwrapped, (2) one-layer-CFRP-wrapped, and (3) two-layers-CFRP-wrapped concrete. The properties were examined through compressive strength test. The results were interpreted to determine the compressive strength and plot the stress-strain diagrams forming a basis for comparison of the tested specimens.

2. Experimental Program

2.1. Material properties

2.1.1 Concrete mix properties

The details of the mix proportions of the specimens were provided by Emirates Beton. The average density of NWC and LWC are 2500 kg/m^3 and 1900 kg/m^3, respectively. The mixed proportions of the NWC and LWC specimens are provided in Table 1 and 2 for a design strength of 30 MPa, respectively. The weights listed in the table represent the saturated surface dry weights of aggregates. The strengthened cylinders were wrapped with MapeWrap-C UNI-AX, a high strength, carbon fiber, monodirectional fabric wrap with a weight of 300 g/m^2 at a thickness of 0.164 mm. It has a density of 1800 kg/m^3. The reported tensile strength of this CFRP wrap reaches 4900 N/mm^2 with an elastic modulus of 252 GPa. The elongation at breakage is 2%. The accompanying epoxy resin for the CFRP wrap is MapeWrap 31 medium viscosity dry system epoxy. The tensile strength, elastic modulus, and elongation at breakage for the epoxy resin are 28 MPa, 1 GPa, and 3.4%, respectively.

Table 1. Mixed Proportions of NWC Cylinders.

Component	Amount
Ordinary Portland Cement	170 kg
Water	143 kg
Ground Granulated Blast-Furnace Slag (GGBS)	170 kg
20 mm Crushed Aggregate	600 kg
10 mm Crushed Aggregate	380 kg
Dune Sand	366 kg
0-5 mm Washed Sand	624 kg
Masterpolyheed 3533	4 kg

Table 2. Mixed Proportions of LWC Cylinders.

Component	Amount
Ordinary Portland Cement	425 kg
Microsilica	32 kg
Water	174 kg
Perlite Aggregate	56 kg
0-5 mm Crushed Sand	850 kg
Dune Sand	400 kg
AEA admixture	0.1 L

2.2. Test matrix and specimen preparation

The experimental program consists of 18 specimens, of which 6 are unwrapped normal weight concrete (NWC) and structural lightweight (LWC) concrete cylinders. The remaining specimens are CFRP-wrapped normal and structural lightweight concrete cylinders. The dimensions of the standard concrete cylinders are 15 cm in diameter and 30 cm in height following ASTM C31 code (ASTM International (2019)). All specimens were cured for 28 days in room temperature water.

The specimen preparation primarily involves wrapping concrete cylinders with CFRP wraps following ACI 440.2R-17 (American Concrete Institute (2017)). Before the application of an epoxy layer on the CFRP specimens, a grinder was used on the specimens to harden the surface. Subsequently, the specimens were wrapped with CFRP laminates with an overlap of 20 cm following the guidelines of the manufacturer. Before the application of the second layer, a layer of sand was applied to roughen the surface to enhance the adhesiveness of the second layer of CFRP wrap onto the first layer. After applying the epoxy adhesive, the specimens were left to cure for 7 days before testing.

Three samples were tested for each group. The specimens are denoted by the first letter to determine if they are unwrapped or wrapped, where the letter U resembles unwrapped and the letter W denotes wrapped specimens. The second letter will determine if it is structural lightweight or normal weight concrete (L = lightweight concrete, N = normal weight concrete). The number of layers is designated by a number preceding the group name.

2.3. Test setup

All specimens were tested under the Universal Testing Machine (UTM) in accordance with ASTM C39 (ASTM

International (2016)). Capping was applied on all specimens to ensure a uniform load on the specimens following ASTM C617 (ASTM International (2015)). The loading rate applied was 0.2 MPa/s, and the settings of the machine were set to be load-controlled. Strain gauges are attached to some specimens for obtaining data related to the stress-strain curves. The strain gauges were placed on unwrapped and CFRP-wrapped specimens. For unwrapped specimens, 60 mm strain gauges were used, and 10 mm strain gauges were used for CFRP-wrapped specimens. Two strain gauges were placed on one specimen in each specimen group. The gauges were placed vertically and horizontally at the center of the cylindrical specimen to measure the axial and hoop strain, respectively.

3. Experimental Results and Discussion

The parameters investigated in this study are failure modes, compressive strength, and elastic modulus of the specimens. Axial and hoop stress-strain diagrams were also developed to further understand the behaviour of CFRP-wrapped NWC and LWC. The experimental results are tabulated in Tables 3 and 4 for NWC and LWC, respectively. The standard deviations of the test specimens are within the acceptable range given that each group contains 3 samples.

3.1. Failure mode

Unwrapped NWC specimens reported a cone and split failure pattern, as shown in Fig. 1(a). Unwrapped LWC showed columnar failure, as illustrated in Fig. 1(b). Similar to the results Liu et al. (2020), the failure mode of all CFRP-wrapped test specimens demonstrated rupture of CFRP, as illustrated in Fig. 2. This mode of failure indicates the effectiveness of the CFRP wrapping. The rupture of the CFRP occurred at the middle of the cylinder. In minor cases, CFRP detachment occurred at either end of the specimen. Further, in alignment with Liu et al. (2020) findings, it was noticed that NWC specimens experienced relatively more severe disintegration than LWC specimens.

(a) (b)

Fig. 1. Failure pattern of (a) U-N and (b) U-L

(a) (b) (c) (d)

Fig. 2. Failure pattern of (a)1W-N, (b) 1W-L, (c) 2W-N, and (d) 2W-N

3.2. Compressive Strength

For NWC specimens, the control specimen group had an average strength of 49.7 MPa. One layer and two layers of CFRP wrapping increased the compressive strength to 72.6 MPa and 101.9 MPa, respectively. Thus, the of increase ratio ($P_{wrapped}/P_{unwrapped}$) were 1.5 and 2.1. The control LWC specimen had a compressive strength of 24.3 MPa. LWC with one layer of wrap had a compressive strength of 40.8 MPa. LWC with two layers of CFRP wrap had a compressive strength of 53.0 MPa. Both specimens showed a great percentage in the increase of the compressive strength with a ratio increase of 1.7 and 2.2 corresponding to one and two layers of CFRP wrapping, respectively. The test results of NWC and LWC specimens are tabulated in Tables 3 and 4, respectively.

Results show that applying CFRP laminates on concrete cylinder increase its axial capacity due to the confinement effect. LWC reported a larger degree of compressive strength increase than NWC specimens. This result can be attributed to the different types of aggregates in LWC and NWC specimens. The mix properties of LWC specimens included perlite aggregates compared against the conventional crushed sand used in NWC specimens. Perlite is a relatively finer aggregate that reduces the strength and density of the concrete. This result can also be justified by the fact that the compressive strength of the control LWC specimen is less than that of the NWC specimen. This outcome supports the results found by Zhou et al. (2019) that CFRP results in larger compressive strength increase when applied to a sample of originally lower compressive strength. Further, adding more layers of CFRP resulted in larger increase in compressive capacity, as supported by Zhou et al. (2019) and Seffo and Hamcho (2012).

Table 3. Results of NWC Specimens

Specimen Group	Sample	Failure Load (kN)	Ultimate Stress (MPa)	σ (MPa)	Average Ultimate Stress (MPa)	fc/f'c	Ultimate Axial Strain (μstrain)	Ultimate Hoop Strain (μstrain)	Modulus of Elasticity (GPA)
U-N	1	900.4	50.950	1.6	49.7	1.0	1641	210	49.9
	2	887.4	50.218						
	3	845.5	47.846						
1W-N	1	1205.4	68.209	4.1	72.6	1.5	2159	8444	176.9
	2	1350.9	76.446						
	3	1292.6	73.147						
2W-N	1	1799.0	101.804	2.4	101.9	2.1	4038	12128	195.6
	2	1760.4	99.606						
	3	1844.6	104.385						

Table 4. Results of LWC Specimens

Specimen Group	Sample	Failure Load (kN)	Ultimate Stress (MPa)	σ (MPa)	Average Ultimate Stress (MPa)	fc/f'c	Ultimate Axial Strain (μstrain)	Ultimate Hoop Strain (μstrain)	Modulus of Elasticity (GPA)
U-L	1	452.3	25.6	1.1	24.3	1.0	1625	773	21.7
	2	415.1	23.5						
	3	419.7	23.8						
1W-L	1	680.9	38.5	2.1	40.8	1.7	9513	8890	26.6
	2	732.4	41.4						

	3	751.3	42.5						
	1	945.9	53.5						
2W-L	2	1014.3	57.4	4.7	53.0	2.2	9851	8597	28.3
	3	849.1	48.1						

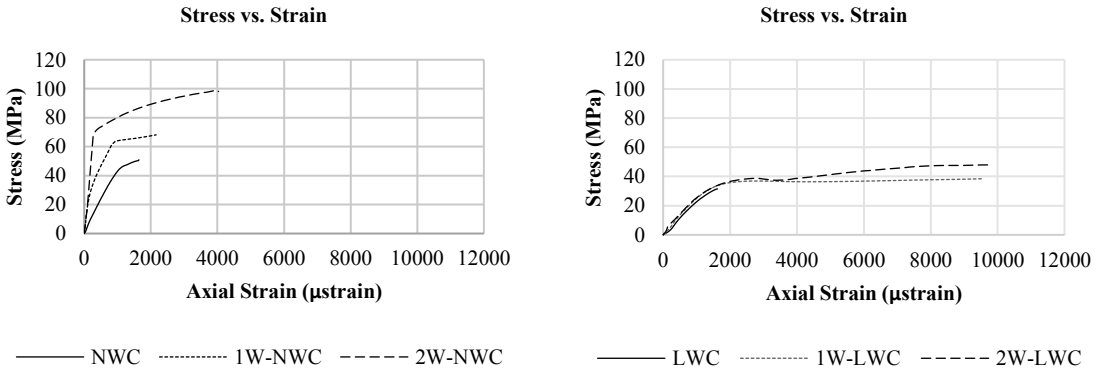
3.3 Axial stress-strain results

The stress-strain diagrams of unwrapped, one-layer wrapped, and two layer-wrapped NWC and LWC specimens are shown in Fig. 3(a) and 3(b). In both types of concrete, the use of CFRP wrapping increased the ductility of the specimen. More Specifically, for NWC specimens, the ultimate strain with one and two layers of CFRP wrapping was 2159 µstrain and 4038 µstrain, reporting an increase ratio of 1.3 and 2.5, respectively. For LWC specimens, the ultimate strain with one and two layers of CFRP wrapping was 9513 µstrain and 9851 µstrain resulting in an increase ratio of 5.9 and 6.1.

The modulus of elasticity of NWC specimens increases with the CFRP wrapping. As the number of layers of CFRP increases, the modulus of elasticity increases, as shown by the slope of the elastic portion on the axial stress-strain diagrams. Applying one layer of wrapping, the elastic modulus increases by 3.5 times for NWC and 1.2 times for LWC. Using two layers of CFRP, the elastic modulus increases by 3.9 times and 1.3 times for NWC and LWC, respectively.

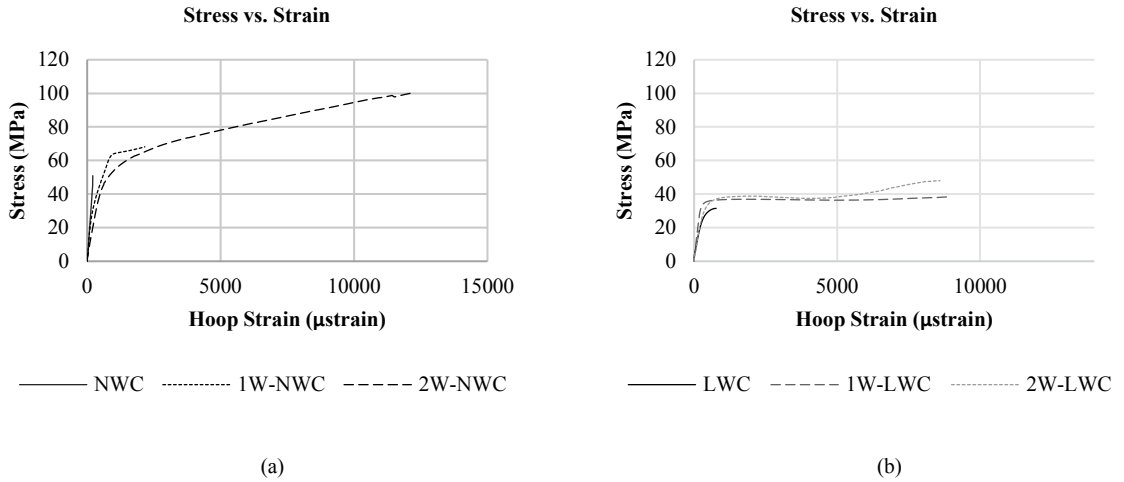
3.4 Hoop stress-strain results

The hoop stress-strain diagrams of the control, one-layer, and two-layers of CFRP-wrapped NWC and LWC samples are developed in Fig. 4(a) and 4(b). The hoop strain appears to increase significantly with the use of CFRP wrapping. For NWC specimens, the ultimate hoop strain with one and two layers of CFRP wrapping increased by 38.4 and 40.2 to 8062 µstrain and 8444 µstrain, respectively. For LWC specimens, the ultimate strain with one and two layers of CFRP wrapping was 8890 µstrain and 8597 µstrain resulting in an increase ratio of 11.5 and 11.1 times. For NWC specimens, the increase in the number of layers resulted in a larger increase of ultimate hoop strain. For NWC specimens, the hoop stress-strain diagrams show that the cracks along the circumference start at an early compressive strength (around 60 MPa) and increases until the ultimate strength is reached. For LWC, the hoop stress-strain diagram shows that cracks start to appear as ultimate strength is reached. Subsequently, cracks along the circumference of hoop strain gauge increases at the ultimate stress. Although the use of CFRP increases the ultimate hoop strain, the results show that the change in the number of CFRP layers does not influence the degree of hoop strain increase for LWC specimens.



(a) (b)

Fig. 3 Axial stress-strain diagrams for (a) NWC and (b) LWC



(a) (b)

Fig. 4 Hoop stress-strain diagrams for (a) NWC and (b) LWC

4. Conclusion

This study investigated the performance of NWC and structural LWC concrete cylinder wrapped with variable layers of CFRP laminates. The main conclusions are:

- CFRP wrapping enhance the compressive capacity of concrete. For NWC specimens, the strength increased by 1.5 and 2.1 using one and two layers, respectively. For LWC specimens, the strength increased by 1.7 and 2.2 using one and two CFRP layers, respectively.
- All strengthened specimens failed by CFRP rupture, indicating the effectiveness of the wrap. NWC experienced more severe fracture than LWC.
- The application of CFRP laminates results in significant increase in ductility.
- The stiffness of both types of concrete also increases with the application of CFRP laminates. A larger magnitude of increase is observed when applying more layers of CFRP.
- Hoop stress-strain diagrams show that cracks along the hoop form earlier for NWC specimens than LWC. For LWC, cracks along the hoop start to form once the ultimate stress is achieved. However, for NWC, cracks start early and start to propagate along with increase in stress until the compressive capacity of the CFRP-wrapped specimen is reached.

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