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Effect of Wetting and Drying Cycles on Behavior of Concrete Externally Strengthened with CFRP Laminates

Abstract-*This study describes an experimental work that was made to evaluate the effect of wetting and drying cycles on the behavior of concrete specimens externally strengthened with CFRP laminates. The experimental work included testing of twenty-three concrete specimens externally strengthened with CFRP laminates in different positions, with two compressive strength levels. The experimental variables considered in the test program include, compression strength of concrete, number of carbon fiber reinforced polymer (CFRP) strip layers, using CFRP strips throughout the total length of the specimen or within the middle third, and the number of wetting and drying cycles. The testing program included compression strength test, four-point flexural test, direct tension test, single and double face shear tests. The experimental results show that the increasing time of exposure to wetting and drying cycles lead to a significant increase in compressive strength, increasing the cracking loads which reached up to 22%., and decreasing the ultimate load carrying capacity.*

Keywords- *CFRP, Strengthening, Wetting and drying*

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1. Introduction

It is needed to develop economic and efficient methods to upgrade, repair, or strengthen existing concrete structures. The choice of a suitable method of strengthening an existed structure is important, traditional structural rehabilitation methods such as external post tensioning and bonded steel plates often suffer from inherent disadvantages ranging from difficult application procedures to lack of durability, leaving the growing repair and rehabilitation market in need of cost effective and efficient restoration techniques, As a result, new repair alternatives have been researched with a target of extending the life of the concrete structures [1]. Many Departments of Transportation around the world have shown strong interest in the repair, rehabilitation, and reinforcement of bridges using externally bonded fiber reinforced polymers (FRP).

Fiber reinforced plastics (FRP) offer great potential for lightweight cost-effective retrofitting of concrete structures, including bridges [2]. These high performance materials can be bonded to structural elements to increase the strength and stiffness of the structure with savings in application costs and improved durability over conventional methods [3]. The old structure and the new bonded-on material create a new structural element that has a higher strength and stiffness than the original one [4].

When carbon fiber reinforced polymer CFRP laminates, are used for strengthening of an existing concrete structure, the bond between the two interfaces is an important characteristic. Bond is needed for proper transfer of stresses among interfaces and the long-term bond performance under environmental conditions is a major concern.

2. Experimental Work

The main variables included in this study focused on the concrete strength levels (40 and 60 MPa), number of carbon fiber reinforced polymer (CFRP) strip layers (one and two layers), using CFRP strips throughout the total length of the specimen or within the middle third, and the effect of wetting and drying cycles number (40 and 70 cycles) on the behavior of the externally strengthened concrete specimens with CFRP laminates.

I. Specimens Description

Twenty-three concrete specimens with cross sectional dimensions of 100 (mm) width by 100 (mm) height and 400 (mm) length with two different concrete strengths were cast. These concrete specimens were strengthened and bonded with externally CFRP laminates as described below. Nine of them were strengthened or bonded with CFRP laminates without exposure to wetting and drying cycles. While, the other

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fourteen concrete beams were either strengthened or bonded with CFRP laminates and exposed to wetting and drying cycles. A specimen's notation system consisted of five letters was used as explained below.

The first letter indicates whether the specimen is a flexural specimen, tension, or double-faced shear specimen:

Letter (A): indicates that the specimen is a flexural test specimen.

Letter (B): indicates that the test specimen is either a tension or a double-faced shear test specimen.

The second letter (S) indicates that the specimen is a CFRP strengthened concrete specimen, related to this letter, a subscript system consisting of numbers and letters was added to point out the geometry of the strengthening or bonding scheme, which was applied to the specimen.

Numbers one or two: indicate the number of the CFRP laminates that were added to strengthen a concrete specimen.

Letters S and L indicate whether the CFRP laminates are short or long.

Letters C and N indicate whether the CFRP laminates are compound or neighbored.

Letters T and D indicate whether the specimen is tested for tension or double-faced shear test.

Letter M indicates that the laminate is in the middle of the concrete specimen.

The third letter R indicates that the concrete specimen is a reference specimen.

The two letters WD are specified to describe the wetting and drying exposure scenario, which are also subscripted by a number that pointed out the number of cycles that the specimen was exposed to. For example: the specimen **AS1SWD40** is defined as: a flexural test specimen, which is applied with one short CFRP laminate and is exposed to 40 cycles of wetting and drying. Meanwhile, the specimen **BS1MTWD70** is defined as: a tension test specimen, which is exposed to 70 cycles of wetting and drying. A schematic representation of the test specimens is shown in Figure 1. Figure (1-a) represents the group (A) specimens (AS1S, AS2SC, AS2SN, AS1L, AS2LC, AS2LN and AS1M) which are devoted for the flexural test. While Figure (1-b) represents the group (B) specimens (BS1MT and BS2D) which are devoted for the direct tension and double-faced shear test. A steel saw was used to cut concrete specimens of groups (AS1M) and groups (BS1MT and BS2D) into two equal halves. A steel rod was impregnated during the cast phase in the middle of each half of the specimen for group (B) to be used as a shaft gripped by the jaw of the testing machine. Group A consisted of seventeen concrete specimens, while group B consisted of six concrete specimens.

The first subgroup of concrete specimens of group (A) which were denoted as (AS1S) was provided with one layer of CFRP strip having 100 (mm) length, (40) (mm) width, and 1.2 (mm) thickness installed at the middle third of the tension face of the concrete specimens shown in Figure 2.

The second subgroup of concrete specimens of group (A) which were denoted as (AS2SC) was provided with two layers of CFRP strips. Each layer has a 100 (mm) length, 40 (mm) width, and 1.2 (mm) thickness installed one over the other at the middle third of the tension face of the concrete specimens shown in Figure 3.

The third subgroup of concrete specimens of group (A) which were denoted as (AS2SN) was provided with two layers of CFRP strips. Each layer has a 100 (mm) length, 20 (mm) width, and 1.2 (mm) thickness installed one adjacent to the other at the middle third of the tension face of the concrete specimen as shown in Figure 4.

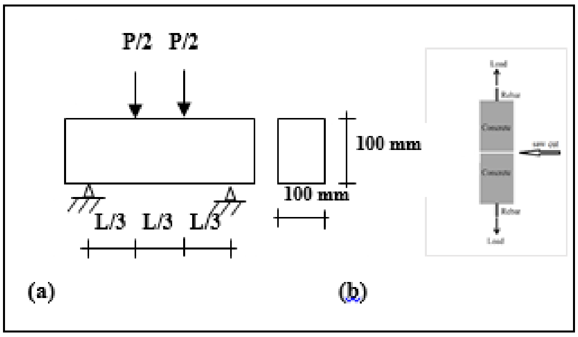

Figure 1: Geometry of laboratory test specimens

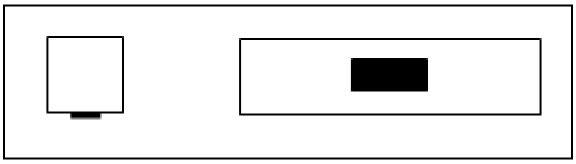

Figure 2: Schematic of specimen AS1S

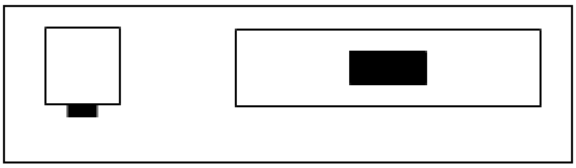

Figure 3: Schematic of specimen AS2SC

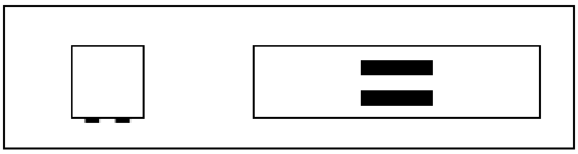

Figure 4: Schematic of specimen AS2SN

The fourth subgroup of concrete specimens of group (A) which were denoted as (AS1L) was provided with one layer of CFRP strip having 280 (mm) length, 40 (mm) width, and 1.2 (mm) thickness installed at the completely clear span of the specimen just before the supports at the tension face of the concrete specimens shown in Figure 5.
The fifth subgroup of concrete specimens of group (A) which were denoted as (AS2LC) was provided with two layers of CFRP strips. Each layer has a 280 (mm) length, 40 (mm) width, and 1.2 (mm) thickness installed one above the other at the whole clear span of the specimen just before the supports at the tension face of the concrete specimen as shown in Figure 6.
The sixth subgroup of concrete specimens of group (A) which were denoted as (AS2LN) was provided with two layers of CFRP strips. Each layer has a 280 (mm) length, 20 (mm) width, and 1.2 (mm) thickness installed one adjacent to the other at the whole clear span of the specimen just before the supports at the tension face of the concrete specimen as shown in Figure 7.
The seventh subgroup of concrete specimens of group (A) which were denoted as (AS1M) was provided with one layer of CFRP strip having dimensions of (100*100) (mm) and 1.2 (mm) thickness bonding the two separated halves of each concrete specimen from the middle, as shown in Figure 8.
The eighth subgroup of concrete specimens of group (B) which were denoted as (BS1MT) was provided with one layer of CFRP strip having dimensions of (100*100) (mm) and 1.2 (mm) thickness bonding the two separated halves of each concrete specimen from the middle, as shown in Figure 9.
The ninth subgroup of concrete specimens of group (B) which were denoted as (BS2D) was provided with two layers of CFRP strips. Each layer has a 100 (mm) length, 40 (mm) width and 1.2 (mm) thickness installed to bond the two separated halves of each half concrete specimen from the opposite sides (top and bottom), as shown in Figure 10.

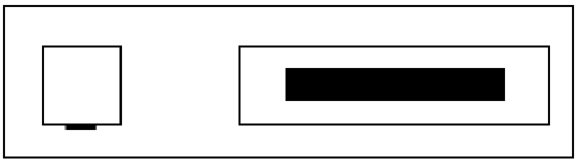

Figure 5: Schematic of specimen AS1L

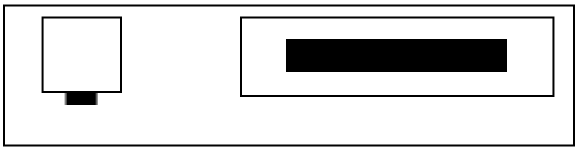

Figure 6: Schematic of specimen AS2LC

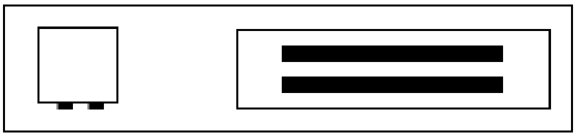

Figure 7: Schematic of specimen AS2LN

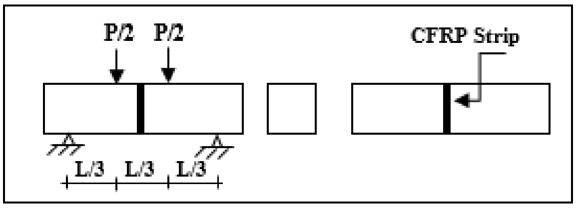

Figure 8: Schematic of specimen AS1M with bonded CFRP strip

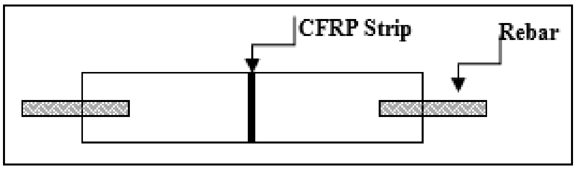

Figure 9: Schematic of specimen BS1MT with bonded CFRP strip

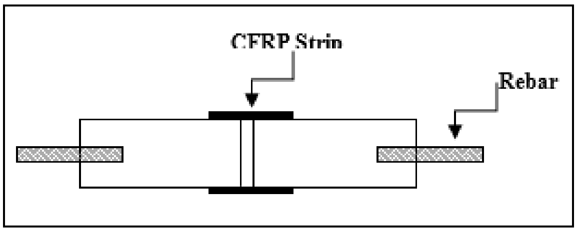

Figure 10: Schematic of specimen BS2D with bonded CFRP strip

II. Materials

1) Cement

Ordinary Portland cement was used throughout this study. It was conforming to the Iraqi standard No. 5/1984 [10]. The cement is made in Iraq and is in the form of 50 kg bags.

2) Fine Aggregate (Sand)

Natural sand from Al-Ukhaider region was used in this study. The fineness modulus, specific gravity (SSD) and sulfate content of this fine aggregate were 2.92, 2.6 and 0.133 percent respectively.

3) Coarse Aggregate (Gravel)

Natural gravel with a maximum size of 12.5 (mm) from Al-Nibaae was used as coarse aggregate. The grading test results were conforming to Iraqi specification (IQS 45/1984) [11] and ASTM C33 [8]. The unit weight, specific gravity (SSD) and sulfate content of this gravel were 1635 kg/m^3, 2.7 and 0.045 percent respectively.

4) Superplasticizer

A high-range water reducing admixture, Sika® ViscoCrete®-PC 20 was used in this study.

5) Mineral Admixtures (Silicafume)

Silicafume, with 10 percent replacement by weight of cement, was used as supplementary cementitious material. It has a specific surface of 20m^2/g.

6) Carbon Fiber Reinforced Polymers (CFRP)

A unidirectional pultruded corrosion resistant laminates manufactured by Sika Company, Switzerland, named Sika CarboDur S512 and Sika CarboDur S1012 were used for externally strengthening.

7) Bonding Materials

Sikadur-30 is a recommended epoxy by the manufacturer to give a proper bond between CFRP laminates and concrete, a two component less viscous epoxy paste manufactured by Sika Company was used throughout this study. The mixing ratio of the epoxy was three parts resin of component A (white paste) to one part hardener, component B (black paste) by weight.

III. Concrete Mix

One of the objectives of this study was to figure out the influence of the concrete strength on the mechanism of failure of CFRP strengthened systems. Two different concrete strengths were conducted throughout this work, a normal strength concrete and a high performance concrete. In order to select the suitable mix proportion to produce concrete strength, three trial mixes for each targeted of concrete strength were carried out in order to obtain cube strength (100*100*100) (mm) of 40 and 65 (MPa) at 28 days respectively.

IV. Curing of Specimens

All specimens were left in the laboratory for 24 hours. After that, they were stripped from the molds and then placed in a water bath filled with clean tap water for four weeks, after that, the specimens were kept inside the laboratory for the preparation of the application of CFRP and for testing.

V. Preparation of Concrete Surface and CFRP Installation

The most crucial part of any strengthening application by the new strengthening techniques is the bond between CFRP laminates and the surface to which the CFRP is bonded [7]. Strong bonding ensures a proper transformation of the force carried by the structural member to the CFRP [6]. Lack of preparation of the concrete surfaces can render the strengthening application completely ineffective. The surface of the specimen should be grinded to remove loose and weak materials; it should be cleaned of any dust, oil, or any other substances that adversely affect the bond. Surface preparation can be accomplished using abrasive or water-blasting techniques. Bug holes and other small surface voids should be completely exposed during surface profiling. All these instructions are very important and must be taken seriously for more advantages of CFRP by ensuring sound and strong substrate to transfer the load, to avoid concentration of stresses. Surfaces were cleaned and checked for any defects in the preparation process as the final step before the application of the CFRP laminates.

After preparing of the surfaces, type A and type B epoxy resin had been mixed to the recommended ratio as directed by the manufacturer.

VI. Environmental Exposure Scenario (Wetting and Drying Cycles)

A series of wetting and drying cycles were applied on some concrete specimens for all of the testing durations. A total of fourteen concrete specimens underwent wetting and drying exposure: specimens remained soaking in a 10-in depth of water for 19 hours, then were removed from the containers and allowed to dry in a 55 °C oven for 5 hours. The total time for one cycle was 24 hours. The wet-dry exposure was continued for 40 cycles for testing stage 1, and 70 cycles for testing stage 2. The cycles were repeated for 40 and 70 days.

VII. Tests of Concrete Specimens

The concrete specimens (AS1S, AS2SC, AS2SN, AS1L, AS2LC, AS2LN and AS1M) were simply supported over an effective simple span of 300 (mm) and were tested under two concentrated line loads applied at third points. The loads were applied to the top face of concrete specimens in successive increments up to failure , thin steel strips were inserted between the top face of concrete and line loads to provide even surface. While, both concrete specimens series (BS1MT) and (BS2D) were tested under direct tension and pure shear by using a Uniaxial Tension Machine.

3. Analysis of Results

I. First group of concrete specimens (AS1S):

(AS1SR40) exhibited a first crack load of 17 (kN) and the specimens failed at an ultimate load of 30.6 (kN), the specimens failed due to high interfacial flexure-shear cracks near the end of the CFRP strips, the cracks initiated from the end of the CFRP strips and propagated towards the middle third of the specimen (the maximum moment region). No de-bonding between CFRP strips and concrete was observed.

(AS1SWD40) exhibited an increase in the first crack load, but a decrease in the ultimate load in comparison with the same group of the control specimens. The First crack occurred at an applied load of 18.8 (kN) and the specimens failed at an ultimate load of 26.3 (kN), with a decrease in strength of about 14 % for the ultimate load with respect to (AS1SR40). The specimens failed due to high interfacial flexure-shear cracks near the end of the CFRP strips, the cracks initiated from the end of the CFRP strips and propagated towards the middle third of the specimen (the max. moment region) with an adhesive failure which induced de-bonding between CFRP strips and concrete. The CFRP surface was covered with a thin layer of concrete. The load-deflection curve for these specimens is shown in Figure 11.

(AS1SWD70) exhibited an increase in the first crack load, but a decrease in the ultimate load in comparison with the same group of the control specimens. The First crack occurred at an applied load of 19.5 (kN) and the specimen failed at an ultimate load of 25.2 (kN), with a decrease in strength of about 18 % for the ultimate load with respect to AS1SR40.

The specimens failed due to high interfacial flexure-shear cracks near the end of the CFRP strips. The cracks initiated from the end of the CFRP strips and propagated towards the middle third of the specimen (the max. moment region) with an adhesive failure which induced de-bonding between CFRP strips and concrete. The CFRP surface was covered with a thin layer of concrete. The load-deflection curve for these specimens is shown in Figure 12.

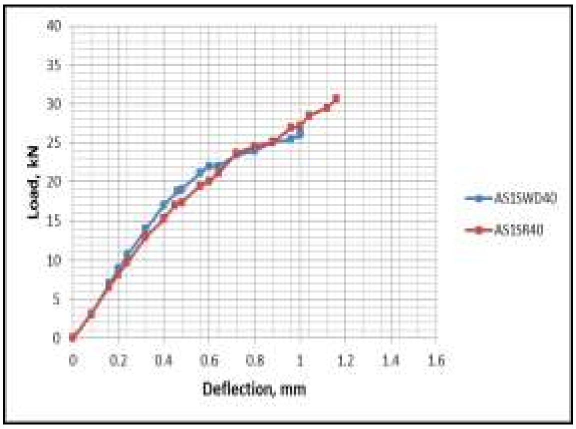

Figure 11: Load-deflection curves of concrete specimen AS1SWD40 and reference concrete specimen AS1SR40

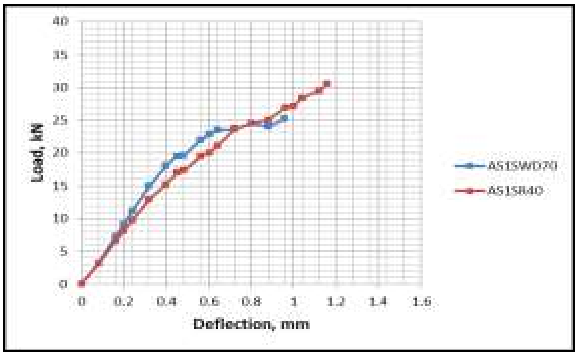

Figure 12: Load-deflection curves of concrete specimen AS1SWD70 and reference concrete specimen AS1SR40

II. Second group of concrete specimens (AS2SC):

(AS2SCR40) exhibited a First crack load of 18.7 (kN) and the specimen failed at an ultimate load of 35.5 (kN), the specimens failed due to high interfacial flexure-shear cracks near the end of the CFRP strips, the cracks initiated from the end of the CFRP strips and propagated towards the middle third of the specimen (the maximum moment region) without any de-bonding between CFRP strips and concrete.

(AS2SCWD40) exhibited an increase in the first crack load, but a decrease in the ultimate load in comparison with the same group of the control specimens. The First crack occurred at an applied load of 21.2 (kN) and the specimen failed at an ultimate load of 31.8 (kN), with a decrease in strength of about 10 % for the ultimate load with respect to (AS2SCR40).

The specimens failed due to high interfacial flexure-shear cracks near the end of the CFRP strips. The cracks initiated from the end of the CFRP strips and propagated towards the middle third of the specimen (the max. moment region), without any de-bonding between CFRP strips and concrete. The load-deflection curve for these specimens is shown in Figure 13.

(AS2SCWD70) exhibited an increase in the first crack load, but a decrease in the ultimate load in comparison with the same group of the control specimens. The First crack occurred at an applied load of 22.8 (kN) and the specimen failed at an ultimate load of 30.8 (kN), with a decrease in strength of about 13 % for the ultimate load with respect to (AS2SCR40).

The specimens failed due to high interfacial flexure-shear cracks near the end of the CFRP strips. The cracks initiated from the end of the CFRP strips and propagated towards the middle third of the specimen (the max. moment region) without any de-bonding between CFRP strips and concrete. The load-deflection curve for these specimens is shown in Figure 14.

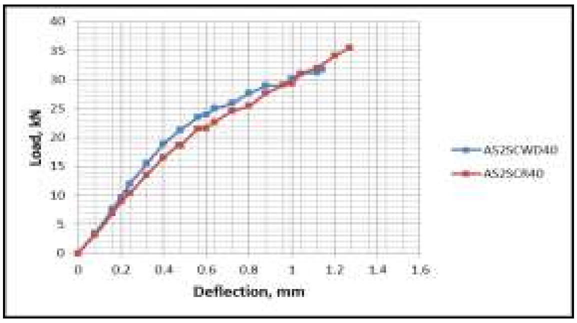

Figure 13: Load-deflection curves of concrete specimen AS2SCWD40 and reference concrete specimen AS2SCR40

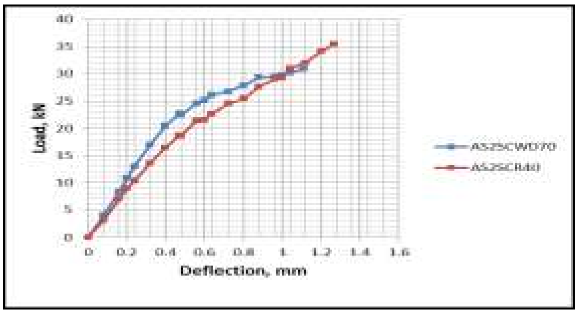

Figure 14: Load-deflection curves of concrete specimen AS2SCWD70 and specimen AS2SCR40

III. Third group of concrete specimens (AS2SN):

(AS2SNR40) exhibited a First crack load of 17.7 (kN) and the specimen failed at an ultimate load of 33.1 (kN), the specimens failed due to high interfacial flexure-shear cracks near the end of the CFRP strips, the cracks initiated from the end of the CFRP strips and propagated towards the middle third of the specimen (the max. moment region) without any de-bonding between CFRP strips and concrete.

(AS2SNWD40) exhibited an increase in the first crack load, but a decrease in the ultimate load in comparison with the same group of the control specimens. The First crack occurred at an applied load of 20.1 (kN) and the specimen failed at an ultimate load of 29.1 (kN), with a decrease in strength of about 12 % for the ultimate load with respect to (AS2SNR40). A substrate failure accompanied by an adhesive failure between CFRP and concrete was also observed where the concrete was crushed and fully adhered to CFRP plates on one side and adhesively failed on the other side. The cracks initiated from the end of the CFRP strips and propagated towards the middle third of the specimen. The load-deflection curve for this specimen is shown in Figure 15.

(AS2SNWD70) exhibited an increase in the first crack load, but a decrease in the ultimate load in comparison with the same group of the control specimens. The First crack occurred at an applied load of 21.5 (kN) and the specimen failed at an ultimate load of 28.1 (kN), with a decrease in strength of about 15 % for the ultimate load with respect to (AS2SNR40).

The specimens failed due to flexural cracks. A substrate failure accompanied by an adhesive failure between CFRP and concrete was also observed where the concrete was crushed and fully adhered to CFRP plates on one side and adhesively failed on the other side of the CFRP strip, which introduced an interfacial de-bonding failure. The cracks initiated from the middle third of the specimen (the max. moment region). The load-deflection curve for these specimens is shown in Figure 16.

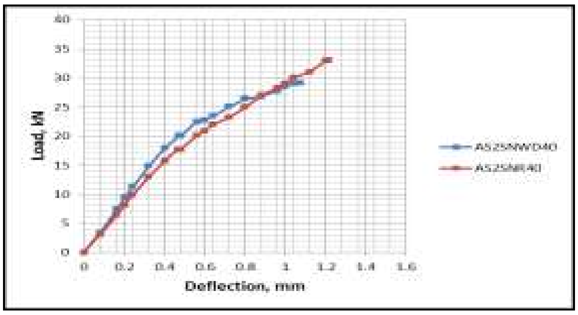

Figure 15: Load-deflection curves of concrete specimen AS2SNWD40 and reference concrete specimen AS2SNR40

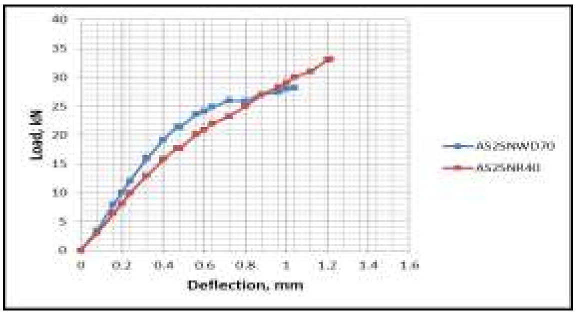

Figure 16: Load-deflection curves of concrete specimen AS2SNWD70 and reference concrete specimen AS2SNR40

IV. Fourth group of concrete specimens (AS1L):

(AS1LR60) exhibited a First crack load of 27.5 (kN) and the specimen failed at an ultimate load of 42.1 (kN), The specimens failed due to high shear stresses near the end of the CFRP strips, the shear cracks initiated from the middle of the concrete specimen due to Mohr's assumption and propagated having an angled path, where there is no intensity of the flexural stresses. No de-bonding between CFRP strips and concrete occurred.

(AS1LWD40) exhibited an increase in the first crack load, but a decrease in the ultimate load in comparison with the same group of the control specimens. The First crack occurred at an applied load of 28.9 (kN) and the specimen failed at an

ultimate load of 39.1 (kN), with a decrease in strength of about 7 % for the ultimate load with respect to (AS1LR60).
The specimens failed due to shear cracks propagated diagonally within the shear span zone towards the compression zone and accompanied by an adhesive failure which induced de-bonding between CFRP strips and concrete. The CFRP surface was covered with a thin layer of concrete. The load-deflection curve for these specimens is shown in Figure 17.

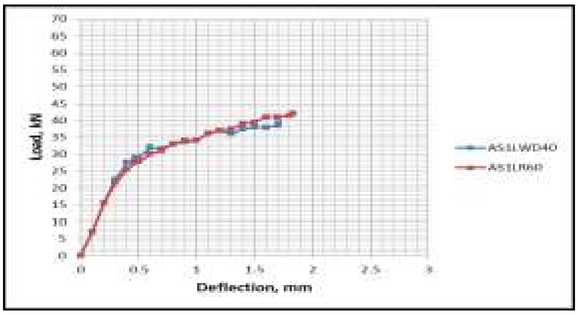

Figure 17: Load-deflection curves of concrete specimen AS1LWD40 and reference concrete specimen AS1LR60

V. Fifth group of concrete specimens (AS2LC):

(AS2LCR60) exhibited a First crack load of 28.4 (kN) and the specimen failed at an ultimate load of 52.1 (kN), the specimens failed due to high shear stresses near the end of the CFRP strips, the shear cracks initiated from the middle of the concrete specimen due to Mohr's assumption and propagated having an angled path, where there is no intensity of the flexural stresses. The CFRP remained intact and fully attached to concrete without any de-bonding between CFRP strips and concrete. (AS2LCWD40) exhibited an increase in the first crack load, but a decrease in the ultimate load in comparison with the same group of the control specimens. The First crack occurred at an applied load of 31.2 (kN) and the specimen failed at an ultimate load of 49.7 (kN), with a decrease in strength of about 5 % for the ultimate load with respect to (AS2LCR60). The specimens failed due to shear cracks without any de-bonding between CFRP strips and concrete. The load-deflection curve for these specimens is shown in Figure 18.

VI. Sixth group of concrete specimens (AS2LN):

(AS2LNR60) exhibited a First crack load of 28.1 (kN) and the specimen failed at an ultimate load of 47.7 (kN), the specimens failed due to high interfacial flexure-shear cracks near one of the ends of one of the CFRP strips, an intermediate flexural crack introduced an interfacial de-bonding failure between the CFRP strip and concrete, a substrate failure was also witnessed where the concrete was crushed and adhered to the CFRP composite. The cracks propagated towards the middle third of the specimen (the max. moment region). (AS2LNWD40) exhibited an increase in the first crack load, but a decrease in the ultimate load in comparison with the same group of the control specimens. The First crack occurred at an applied load of 30.5 (kN) and the specimen failed at an ultimate load of 44.9 (kN), with a decrease in strength of about 6 % for the ultimate load with respect to (AS2LNR60). The specimens failed due to high interfacial flexure-shear cracks. A substrate failure accompanied by an adhesive failure introduced an interfacial de-bonding failure between the CFRP strips and concrete. Concrete was crushed and adhered to one of the CFRP strips. The cracks propagated towards the middle third of the specimen (the max. moment region). The load-deflection curve for these specimens is shown in Figure 19.

VII. Seventh group of concrete specimens (AS1M):

(AS1MR60) specimens failed at an ultimate load of 26.7 (kN), and a modulus of rupture of 8 (MPa) in flexure. The specimens failed due to flexural cracks in the middle, where a single flexural crack was developed from the bottom face towards above. No de-bonding or adhesive failure between concrete and CFRP is witnessed. (AS1MWD40) exhibited an increase in the ultimate load and the modulus of rupture. The specimen failed at an ultimate load of 28.7 (kN), and a modulus of rupture of 8.6 (MPa), with an increase in strength of about 8% for the ultimate load and the same increment for the modulus of rupture. The specimens failed due to flexural cracks in the middle, where a single flexural crack was developed from the bottom face towards above. No de-bonding or adhesive failure between concrete and CFRP is witnessed. The load-deflection curve for these specimens is shown in Figure 20.

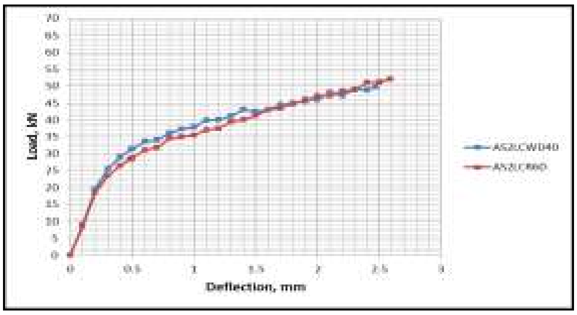

Figure 18: Load-deflection curves of concrete specimen AS2LCWD40 and reference concrete specimen AS2LCR60

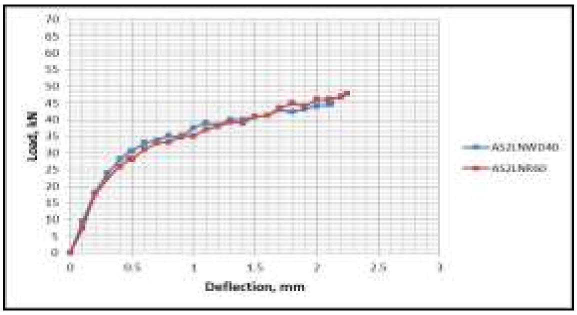

Figure 19: Load-deflection curves of concrete specimen AS2LNWD40 and reference concrete specimen AS2LNR60

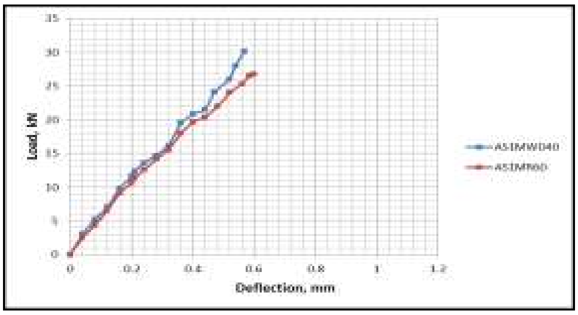

Figure 20: Load-deflection curves of concrete specimen AS1MWD40 and reference concrete specimen AS1MR60

VIII. Eighth group of concrete specimens (BS1MT):

(BS1MTR60) specimens failed at an ultimate load of 38.1 (kN) in tension, the related tension stress was 3.8 (MPa). The specimen failed due to tension failure in concrete because of the tension stresses, no de-bonding or adhesive failure between concrete and CFRP is witnessed.

(BS1MTWD40) exhibited an increase in the tension stress applied on the concrete. The specimen failed at an ultimate load of 41.6 (kN) in tension, the related tension stress was 4.2 (MPa) and the increase in strength was of 9% in comparison with (BS1MTR60). The specimen failed due to failure in concrete because of the tension stresses, no de-bonding or adhesive failure between concrete and CFRP is witnessed. The load-extension curve for these specimens is shown in Figure 21.

(BS1MTWD70) exhibited an increase in the tension stress applied on the concrete. The specimen failed at an ultimate load of 42.8 (kN) in tension, the related tension stress was 4.3 (MPa) and the increase in strength was of 12% in comparison with (BS1MTR60). The specimen failed due to failure in concrete because of the tension stresses, no de-bonding or adhesive failure between concrete and CFRP is witnessed. The load-extension curve for these specimens is shown in Figure 22.

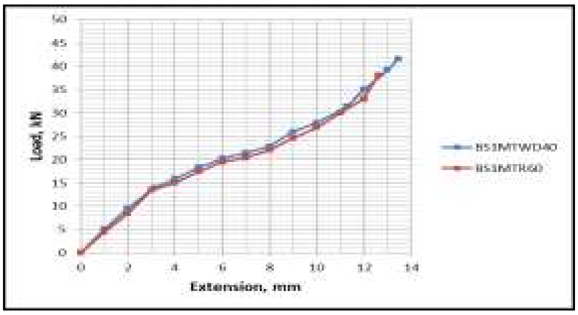

Figure 21: Load-extension curves of concrete specimen BS1MTWD40 and BS1MTR60

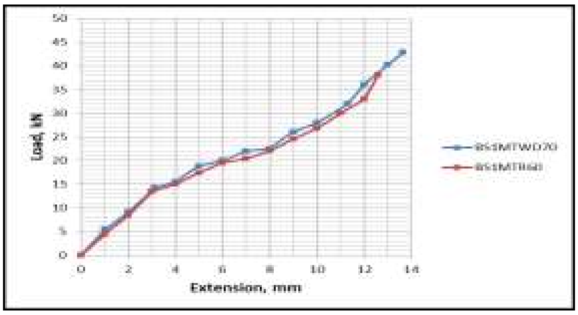

Figure 22: Load-extension curves of concrete specimen BS1MTWD70 and reference concrete specimen AS2SNR40

IX. Ninth group of concrete specimens (BS2D):

(BS2DR60) specimens failed at an ultimate load of 26.5 (kN) in shear, the related shear stress was 3.3 (MPa). The specimens failed due to failure in concrete near the ends of CFRP strips because of the concentration of stresses at the end of the CFRP. No de-bonding or adhesive failure between concrete and CFRP is witnessed.

(BS2DWD40) exhibited a reduction in the shear stress applied on the bond. The specimen failed at an ultimate load of 22.9 (kN) in shear, the related shear stress was 2.9 (MPa) and the reduction in strength was of 14% in comparison (BS2DR60). The specimen failed due to an adhesive failure between CFRP strips and concrete near the ends of CFRP strips because of concentration of stresses at the end of CFRP. The load-extension curve for this specimen is shown in Figure 23.

(BS2DWD70) exhibited a reduction in the shear stress applied on the bond. The specimen failed at an ultimate load of 21.4 (kN) in shear, the related shear stress was 2.7 (MPa), and the reduction in strength was of 19%.

The specimen failed due to an adhesive failure between CFRP strips and concrete near the ends of CFRP strips because of concentration of stresses at the end of CFRP. The load-extension curve for these specimens is shown in Figure 24.

Table 1: Percentage increase/decrease in cracking load, and ultimate load for wetting-drying specimens (AS1S, AS2SC, AS2SN, AS1L, AS2LC, AS2LN, and BS2D)

Specimen	Reference specimens		WD_{40} specimens				WD_{70} specimens			
	P_{cr}, kN	P_u, kN	P_{cr}, kN	% increase	Pu, kN	% decrease	Pcr, kN	% increase	Pu, kN	% decrease
AS_{1S}	17	30.6	18.8	11	26.3	14	19.5	15	25.2	18
AS_{2SC}	18.7	35.5	21.2	13	31.8	10	22.8	22	30.8	13
AS_{2SN}	17.7	33.1	20.1	14	29.1	12	21.5	22	28.1	15
AS_{1L}	27.5	42.1	28.9	5	39.1	7	--	--	--	--
AS_{2LC}	28.4	52.1	31.2	10	49.7	5	--	--	--	--
AS_{2LN}	28.1	47.7	30.5	9	44.9	6	--	--	--	--
BS_{2D}	--	26.5	--	--	22.9	14	--	--	21.4	19

Table 2: Percentage increase in ultimate load for wetting-drying specimens (BS1MT, and AS1M)

Specimen	Reference specimens	WD_{40} specimens		WD_{70} specimens	
	Pu, kN	Pu, kN	% increase	Pu, kN	%increase
BS1MT	38.1	41.6	9	42.8	12
AS1M	26.7	28.7	8	--	--

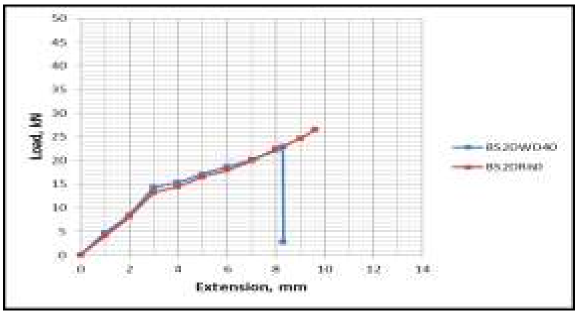

Figure 23: Load-extension curves of concrete specimen BS2DWD40 and reference concrete specimen BS2DR60

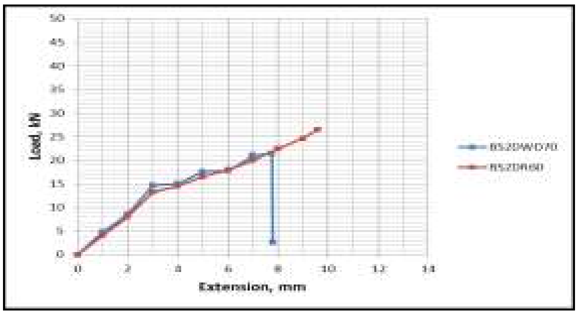

Figure 24: Load-extension curves of concrete specimen BS2DWD70 and reference concrete specimen BS2DR60

4. Discussions

In all cases of strengthening schemes that were conducted throughout this study, the first crack load increased with increasing time of exposure in comparison with the reference specimens that were kept in room conditions, so it could be concluded that exposure to wetting-drying led to an increase in concrete strength, since wetting-drying worked as a further curing for the exposed specimens. The more exposure to wetting-drying resulted in a more increase in first crack load.

The ultimate load decreased also but with the moderate decrement percentage, which could be lead to the conclusion that wetting-drying exposure has a moderate detrimental effect on the bond between CFRP and concrete as it will be seen in the next paragraphs.

In comparison among the strengthening schemes it was observed that a substrate failure happened in the case of AS2SN in comparison with AS1S even with the increase in concrete strength resulted from extra curing.

No de-bonding failure happened in the case of AS2SC, as it was explained in the previous paragraphs.

AS1L specimens exhibited a shear failure. With high concrete compressive strength and extra curing due to wetting-drying, the concrete was

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apparently strong and the mode of failure was shifted from flexure-shear failure into shear failure which gives an indication that the specimens were in a better mode of ductility.

AS2LN specimens also exhibited a substrate failure even with increased concrete strength due to the reasons explained above; this could be due to the concentration of stresses on the interfacial zone between CFRP and concrete.

The increase in concrete strength did not change the failure mode in the case of AS1M, and BS1MT, but increased the ultimate loads they exhibited until failure. In the case of specimen BS2D an adhesive failure occurred but no substrate failure was observed, that was due to concrete increased strength. Tables 1 and 2 illustrate the results gained from wetting-drying failure.

5. Conclusions

Main conclusions have been drawn from experimental work and can be summarized as below:

1) The increasing time of exposure to wetting-drying cycles led to an increase in concrete compressive strength, because wetting-drying cycles worked as a further curing for the exposed specimens.

2) The externally strengthened concrete specimens with bonded CFRP laminates generally showed a significant increase in cracking loads with increasing time of exposure to wetting-drying cycles. This increase reached up to 22 %.

3) The externally strengthened concrete specimens with bonded CFRP laminates generally showed a decrease in ultimate loads which could be lead that wetting-drying exposure has a detrimental effect on the bond between CFRP laminates and concrete.

4) The strengthened specimen with more than one layer of CFRP laminates showed a higher increasing in cracking load with respect to same specimen when strengthened with a single layer of CFRP laminate with the same strengthening area.

5) The strengthened concrete specimens with bonded CFRP laminates generally showed a significant increase in direct tension loads when increasing the time of exposure to wetting and drying cycles. This increase reached up to 12 % for specimen series (BS1MT).

6) The strengthened concrete specimens with bonded CFRP laminates generally showed a decrease in shear loads when increasing the time of exposure to wetting and drying cycles. This decrease reached up to 19 % for specimen series (BS2D).

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