



Research Paper / Makale

Mechanical Properties of Confined Damaged Concrete Strengthened with Fibre Reinforced Polymer Wraps

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Abstract: This study aims to investigate behaviour and failure modes of damaged concrete strengthened using fibre reinforced polymer (FRP) with three different thickness (50 mm, two-50 mm, and 150 mm strips) and different configurations of CFRP wraps. The mechanical performance of damaged concretes was evaluated utilizing carbon fibre reinforced polymer (CFRP) composites under compression tests. The strengthened confined damaged concrete specimen was compared with unconfined damaged concrete in terms of compressive strength, failure modes, and cracks patterns. A total of 8 different damaged and undamaged specimens were tested, with one of these specimens acting as a control damage specimens and the remaining specimens wrapped with different cross-section configurations of CFRP by different wrapping schemes. The results revealed that the partially-wrapped damaged specimens exhibited a higher compressive strength as compared to the corresponding control damaged specimens. The strengthened confined concrete specimen displayed more ductile behaviour, which depends on the failure mode. As a result of using the two-50 mm thickness of CFRP strips, a significant increase in the ultimate load was observed due to the high strength of the composites.

Keywords: FRP, confined, failure, strength, composites.

Fiber Takviyeli Polimer Sargılar ile Güçlendirilmiş Hasarlı Betonların Mekanik Özellikleri

Öz: Çalışmada, üç farklı kalınlıkta (50, 2 adet 50 mm ve 150 mm şeritler) ve CFRP sargılı fiber takviyeli polimer (FRP) kullanılarak güçlendirilmiş hasarlı betonların davranışını ve kırılma davranışlarını incelemeyi amaçlamaktadır. Hasar görmüş betonun mekanik performansı, tek eksenli yük testleri altında CFRP kompozitler kullanılarak değerlendirilmiştir. Güçlendirilmiş, sargılı hasarlı beton numunelerinin, basınç dayanımı, göçme modları ve çatlak modelleri açısından, hasarlı kontrol beton numune ile karşılaştırılmıştır. Toplam 8 farklı hasarlı ve hasar görmemiş örnekler test edilmiştir; bu örneklerden biri kontrol hasarlı numune olarak diğer örnekler ise CFRP'nin farklı kesit ve kalınlıkta konfigürasyonları uygulanmıştır. Sonuçlar, sargılı hasarlı numunelerin karşılık gelen kontrol hasarlı numuneler ile karşılaştırıldığında daha yüksek dayanımı sergilediğini belirlenmiştir. Güçlendirilmiş beton numune, kırılma moduna bağlı olarak daha sünek davranış sergilemiştir. 2 adet 50 mm kalınlıkta CFRP kullanılarak güçlendirilen numunede, bu kompozitlerin daha yüksek mukavemet göstermesi nedeniyle nihai yükte önemli bir artış gözlenmiştir.

Anahtar Kelimeler: FRP, sargılı, kırılma, dayanım, kompozitler.

1. Introduction

Steel or reinforced concrete jacketing methods are generally used in the rehabilitation and strengthening of existing structures [1]. However, fiber-reinforced polymers (FRPs) have gained popularity recently as a relatively new reinforcement method [2, 3]. Structural elements reinforced with composite materials have low weight [4], high tensile strength [5, 6], enhanced corrosion

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resistance [7, 8], and longer life span [9]. Under the effect of lateral loads, many damages were observed in reinforced concrete (RC) structural elements especially during earthquakes [10]. For this reason, it is very important to repair and strengthen building elements with these materials that are under earthquake effects [11].

Damage to these structural elements in concrete surfaces damaged by earthquakes is very dangerous for a building [12]. High-tensile-strength FRP composite materials are used in the reinforcement of these load-bearing elements and provide structural integrity by facilitating energy distribution and making large displacements [13]. High-performance FRP composite materials are applied externally to strengthen or repair structural members to improve load resistance and service life, as well as to recover existing structural elements [14]. Many researchers have noted that strengthening RC elements using FRP increases the load capacity [15], ductility [16], and energy dissipation capacity [17].

Camata et al. [18] stated that FRPs improve the deformation level that RC element sections can reach without a loss of strength. They also increased their energy absorption capacity with their ductile behaviour. Amran et al. [19] reported that the composites are widely used in building load-bearing systems since they are easily applied in different areas and different techniques and do not cause corrosion. Ahmet et al. [20] noted that wrapping concrete structures using FRP composites provides significant lateral limitation of axial force and ductility.

An appropriate strengthening method should be selected to ensure building safety in both damaged and normal strength concretes. These composites generally increase the cost of application throughout the entire surface of the building elements. In this study, the effect of the FRP wraps and number of confining FRPs on the mechanical properties of damaged concrete specimens were experimentally investigated in compression tests. Damaged concrete specimens were compared with undamaged specimens in terms of load capacity, failure modes, and crack patterns. The mechanical and physical characteristics of the specimens with FRP composite were determined in detail in laboratory tests.

2. Materials and Methods

2.1. Test Specimens

A total of eight different cubic specimens 150 mm x 150 mm x 150 mm size were investigated in damaged and un-damaged concrete specimens. Portland cement was used in these investigations (type CEM I 42.5R according to standard TS-EN 197-1 [21] in Table 1).

Table 1. Physical and chemical analysis of cement

Analysis results	CEM-I 42,5 R	TS-EN 197-1
SiO ₂ (%)	18,40	-
Al ₂ O ₃ (%)	4,60	-
Fe ₂ O ₃	3,50	-
CaO	62,60	-
MgO	2,10	-
SO ₃ (%)	3,25	≤ 4,0
MgO (%)	2,10	-
Cl (%)	0,030	≤ 0,10
Loss on Ignition (%)	3,15	≤ 5,0
Specific gravity (gr/cm ³)	3,15	-
Insoluble residue (%)	0,50	≤ 5,0
Specific surface (cm ² /g)	3600	-
Setting time (minutes)	145	≥ 60
Volume constancy (mm)	0,5	≤ 10,0

The Portland cement used was supplied by Çimentoş Cementir Holding. Physical and chemical test results such as setting time and chemical composition of the cement produced are shown in detail in Table 1.

The mixed design of these concretes is given in Table 2. The mix proportion by volume used in this paper was 1:0.40:2.25:3 cement: water: fine aggregate: coarse aggregate. Firstly, 150 mm cubic concrete samples produced in these mixing ratios were exposed to damage under the uniaxial compression test. Three samples were produced from each sample and their compressive strength was determined by taking the average of these samples. The concrete cubic specimens were loaded at a constant rate of 13.5 kN/s. Later, these damaged samples were strengthened with FRP composites and tested again under the same loading speed.

Table 2. The mix design of concretes

Mix proportion	
Cement [kg/m ³]	525
Water [kg/m ³]	210
Sand [kg/m ³]	1182
Aggregate [kg/m ³]	1575
Water/cement ratio	0,40

2.2. Strengthening Materials

2.2.1. Adhesive

Teknobond 300 TIX adhesive was used as a bonding composite material between the concrete surface and the fiber polymer composite of the samples. The adhesive components were produced with a ratio of about 3:1 to obtain a uniform grey color by the manufacturer. It is mixed in these proportions with an electric mixer (maximum 400 rpm) for 2-3 minutes until a homogeneous color is obtained. The prepared 300 TIX mixture is applied to the concrete surface with a roller. The tensile, flexural, bond and compressive strength of the epoxy adhesive provided by the manufacturer are 30 MPa, 40 MPa, 4 MPa, and 80MPa, respectively (see Table 3).

Table 3. Properties of epoxy adhesive

Epoxy Type	Teknobond 300 TIX
Mechanical properties	
Tensile strength (MPa)	30
Flexural strength (MPa)	40
Bond strength (MPa)	4
Compressive strength (MPa)	80

2.2.2. FRP Types

CFRP was chosen due to its high strength and rigidity. The fibre composite displays unique performance with excellent resistance and bonding properties. Pultruded CFRP laminate with a thickness of 0.70 mm, a width of 500 mm, and 2500 mm in length was used for repairing and retrofitting the damaged concrete specimens. The average tensile strength, Young's modulus, and elongation of the CFRP given by the manufacturer are 4137 MPa, 242 GPa, and 1.5%, respectively (Table 4).

Table 4. Mechanical properties of FRP

FRP type	CFRP
Thickness (mm)	0.70
Specific gravity strength (g/m^2)	600
Tensile strength (MPa)	4137
Young's Modulus (GPa)	242
Elongation (%)	1.50

As shown in Figure 1, the FRP wrapping procedure was applied to the surface of damaged concrete specimens. The lengths of each FRP sheet were 70 cm and 140 cm for one and two layers of FRP wrapping, respectively. FRP sheets were wrapped with three different thicknesses (50 mm, two-50 mm, and 150 mm) between each surface layer. After the wrapping process, the damaged concrete specimens were kept in the laboratory for seven days.

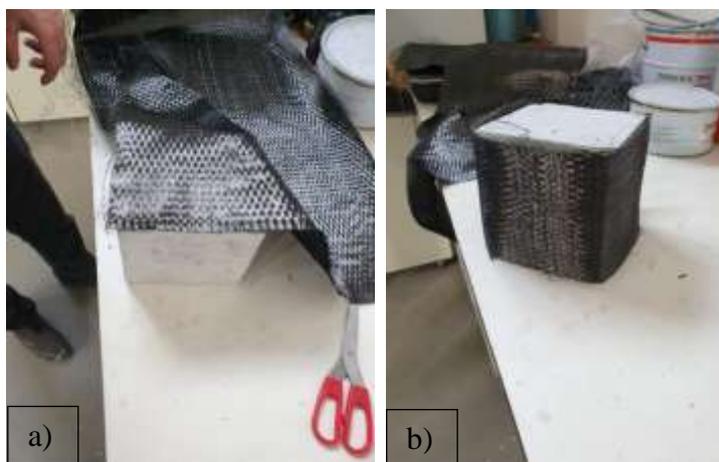


Figure 1. Textile used in this study: (a) CFRP textile; (b) FRP wrapping

2.3. Repair and strengthening of concrete specimen

A total of 8 different damaged and undamaged specimens were tested, with one of these specimens acting as control damage specimens and the remaining specimens wrapped with different cross-sections configuration of CFRP by different wrapping schemes.

**Figure 2.** Configuration steps of preparation surface and surface treatment method

Out of eight specimens, seven were wrapped with CFRP one damaged specimen, and one undamaged specimen with the Teknobond 300 TIX adhesive epoxy. In this study, the effect of the FRP wraps (different thickness 50 mm, two-50 mm, and 150 mm) and a number of confining FRP (one and two layers) on the mechanical properties of the damaged concrete specimens were investigated in compression test experimentally. The specimens under vertical load were strengthened. Firstly, the grinder machine was used to clean the external surfaces of the damaged specimens. In the gluing operation, the air compressor was also used to remove any loose particles on the surface. The application of the first part of the rehabilitation process to repair the cracks is demonstrated in Figure 2 step by step. The detailed strengthening of the damaged and un-damaged concrete specimens is demonstrated in Figure 3.

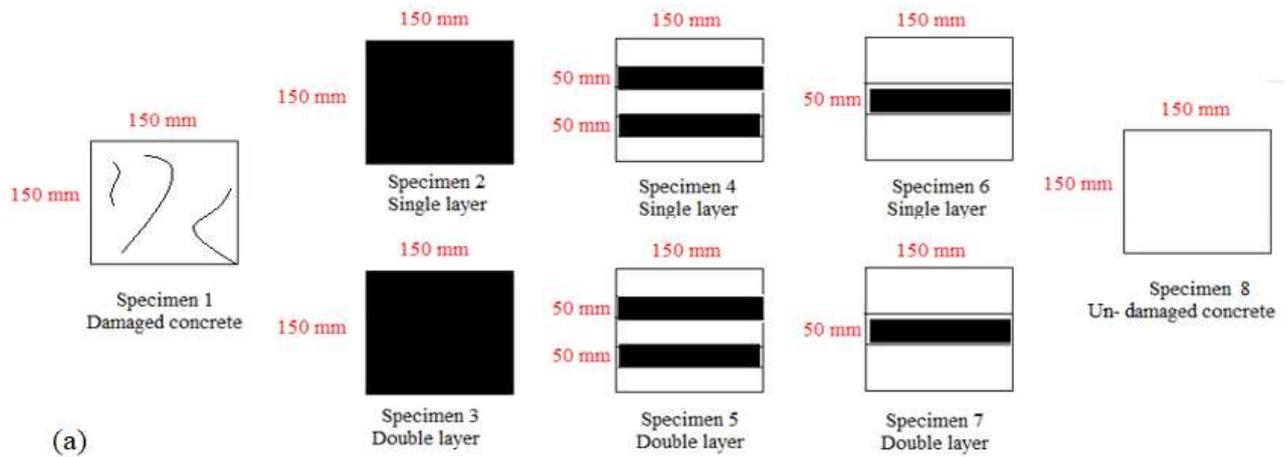


Figure 3. Details of unconfined and confined concrete specimens

2.4. Test Setup and Testing Procedures

The damaged and undamaged concrete specimens were subjected to uniaxial compression tests, and the ultimate load capacity was investigated. The compressive strength of the cube specimens (150*150*150 mm) was tested in accordance with ASTM C 39 [22]. The average test results of three samples were determined. The compression strength of the sample was determined by dividing the ultimate load capacity by the cross-sectional area:

$$\sigma = \frac{P_k}{A} \tag{1}$$

where σ is the compressive strength (MPa), P_k is the ultimate load (N), and A is the area (mm^2)

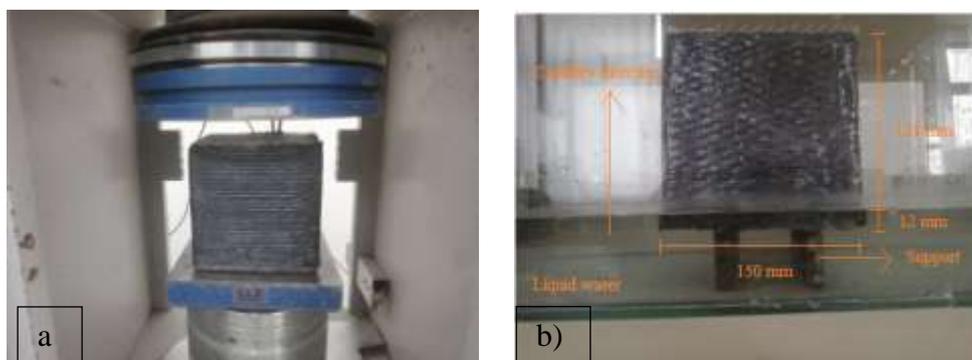


Figure 4. Concrete specimens: (a) uniaxial compression test; (b) Capillary water absorption

In practical engineering situations, the capillary water absorption coefficient A_{cap} is often used as the main parameter for evaluating the liquid water transfer capacity in building materials according to ASTM C1585, [23] which can be calculated with equation (2). The water absorption test apparatus is shown in Figure 4b.

$$A_{cap} = \frac{m_{wc} - m_{dr}}{a\sqrt{t}} \quad (2)$$

where A_{cap} is the water absorption coefficient ($\text{kg}/\text{m}^2\text{min}^{0.5}$), m_{wc} is the wet mass (kg), m_{dr} is the dry mass (kg), A is the surface area (m^2) and t is time (min)

3. Results and Discussion

3.1. Capillary Water Absorption Coefficient

Experimental investigations were carried out on damaged concrete specimens retrofitted by applying FRP strips to the surfaces of the specimens. The strengthened concrete specimens (S2-S7) and undamaged specimens (S8) were compared with a control damaged specimen (S1) in terms of the capillary water absorption coefficient. The experimental results of the confined and unconfined concrete specimens were investigated. The average mass change per contact area in the capillary water absorption (A_{cap}) over time is shown in Figure 5.

A_{cap} curves of the specimens were obtained as a function of the root of time. The highest A_{cap} value was obtained from the unconfined damaged concrete specimen (S1). Zeyad et al. [24] and Niu et al. [25] stated that the absorption rate of water is increased due to the capillary absorption of a porous damaged concrete specimen. The damaged concrete specimen disintegrated when it was permeated by water. The lowest A_{cap} value was obtained from the undamaged concrete specimen (S8). Feng and Janssen [26]; Zhang et al. [27] stated that as the capillary water absorption of the concrete specimen decreases, the strength is improved.

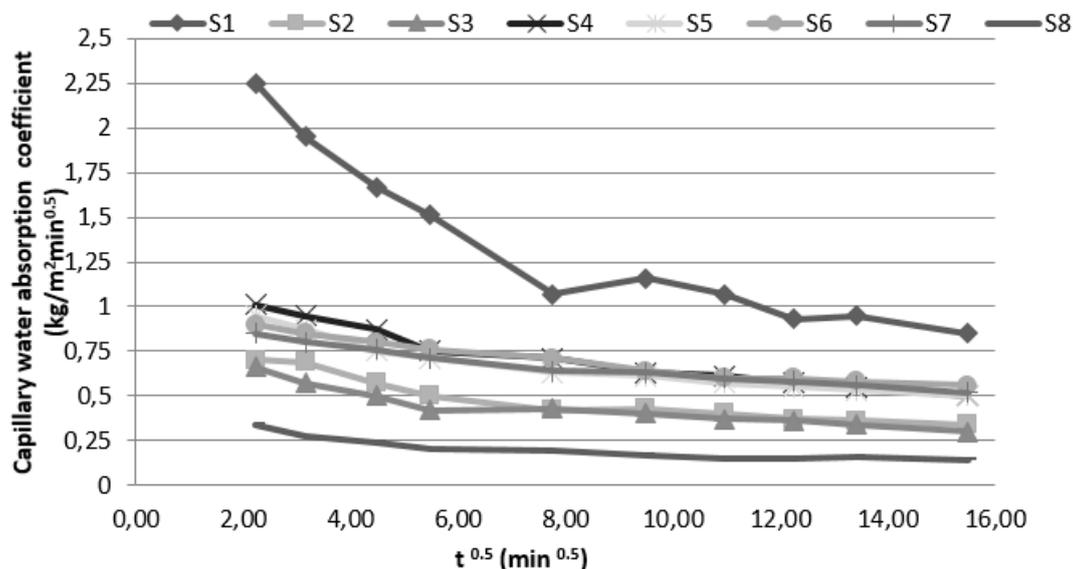


Figure 5. The capillary water absorption coefficient of concrete specimens: S1-S8

The effect of confinement type on capillary water absorption was compared on the damaged and undamaged specimens. In the capillary water absorption coefficients of fully, FRP wrapped concrete samples (S2 and S3), very close results were obtained in single- and double-layer applications. In these samples, no significant change was observed in the capillary water absorption

coefficient values with the increase of the coefficient. The highest A_{cap} value was obtained from the most damaged concrete specimen (S1). Fully wrapped concrete samples were also obtained less capillary water absorption coefficients than CFRP strips confined concrete specimens. Furthermore, the capillary water absorption of CFRP wrapped concrete samples with different layers (single or double) and strip type (one or two strips) were close relationships.

3.2. Uniaxial Compression Tests

The confined concrete specimens (S2-S7) and unconfined specimen (S8) were compared with the control damaged specimen (S1) in terms of the ultimate strength, crack patterns and failure modes. The effects of three different thicknesses (50 mm, two-50 mm, and 150 mm) and FRP wraps of strengthened concrete specimens are presented in Figure 6. The control damaged specimen S1 failed at a load of 693.0 kN from crushing of the concrete surface after the ultimate load capacity. The comparison of the ultimate strength between S3 and S5 using CFRP composite-strengthened samples displayed higher improvements of 70.5% and 72.4% compared to the control sample (S1), respectively.

Saberi et al. [28] stated that FRP improved both the peak strength and ultimate displacement of concrete. Li [29] reported that FRP-jacketed cylinder specimens demonstrated high compressive strength and ductility due to the higher interfacial bonding strength. Similarly, Wu et al. [30] stated that strengthening a concrete specimen region by wrapping with FRP resulted in high strength and energy absorption capacity of the structural elements. Chen et al. [31] and Lee et al. [32] noted that the application of FRP in RC members decreased the load capacity in the longitudinal reinforcements and improved the fatigue life of RC elements.

The experimental results of compressive strength of confined and unconfined specimens are shown in detail in Table 5. The results demonstrated that damaged concrete specimens confined with CFRP displayed a higher increase in uniaxial compressive strength than the control specimen. The strengthening of the damaged concrete specimen specimens (S6, S8) using CFRP composite increased the ultimate strength by up to 48.4% and 35.7% compared to the control damaged specimen, respectively. Al-Tersawy [33] noted that using CFRP as a strengthening wrap improved the shear strength of reinforced concrete specimens remarkably. In addition, many researchers reported that FRP composites improved the performance thanks to high energy absorption and load-carrying capacity [34-37].

Table 5. Test data for compressive strength

Specimens of tests	Compressive strength of specimens (MPa)	
	Unconfined specimen	Confined damaged specimen
Specimen 1	30.8	-
Specimen 2	-	47.1
Specimen 3	-	52.5
Specimen 4	-	50.7
Specimen 5	-	53.1
Specimen 6	-	45.7
Specimen 7	-	51.1
Specimen 8	41.8	-

The effect of confinement type on the strength was compared on the damaged and undamaged specimens. The compressive strength of the fully FRP wrapped damaged concrete specimens (150 mm thick wrapping) increased as the layer number improved. The highest strength value was obtained from a two-50 mm FRP wrapped damaged concrete specimen (S5). Fully wrapped concrete samples were also obtained higher strength than CFRP strips confined concrete specimens using the one-50 mm CFRP wrapped specimen (S6 and S7). The compressive strength values of damaged concrete samples reinforced with all CFRP wraps (single or double layers and one or two strips) were determined to be higher than the undamaged concrete specimen. It can be seen from Figure 6, that sample 5 is higher, which is covered as 2 strips, than S3 which is fully covered. The reason for this has been observed that the resistance increases with the increase in the coefficient of CFRP windings made in critical regions. In addition, it is thought that the reinforcements made in these areas will provide economical use by reducing the use of FRP composite materials in sample sections.

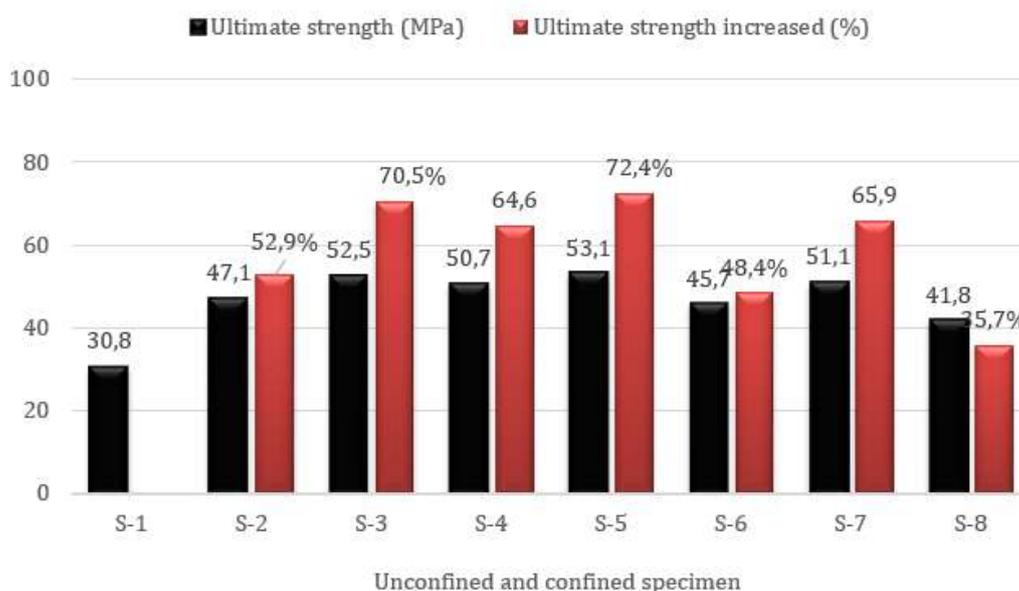


Figure 6. Ultimate strength and increase in ultimate strength compared to control specimen

3.3. Typical Failure Observations and Crack Patterns

The failure modes and crack patterns of the test specimens are shown in Figure 7. All CFRP-wrapped specimens were succeeded by the FRP wrap due to the high tensile strength. The initial failure of the S2 and S3 specimens after rehabilitation showed fine and low cracks. The cracking of the S6 specimen started in a similar way, but wide cracks occurred.

In the S6 specimen, the cracks started in a similar way and developed towards the left corner. However, failures of the unconfined damaged specimens (S1) were also higher than that of the other specimens wrapped with CFRP composite. Despite that reference specimen indicating similar behaviour, the S7 specimen developed thin cracks with minor widths compared to that of the S1 damaged concrete specimen. This supports results from many experts who stated that specimens strengthened using FRP composite exhibited higher energy absorption and ductility than their counterparts [38-43].

Strengthening of the S4 specimen with CFRP strips controlled the crack width in comparison with the control specimen. As a result of using two-50-mm thick CFRP, a significant increase in the ultimate load was observed due to the high strength of the composites. The test results indicated that the technique using CFRP wraps resulted in high strength [44] and excellent ductility [45, 46 and

47]. For the concrete specimens strengthened with the CFRP, the appearance and width of shear cracks were reduced.

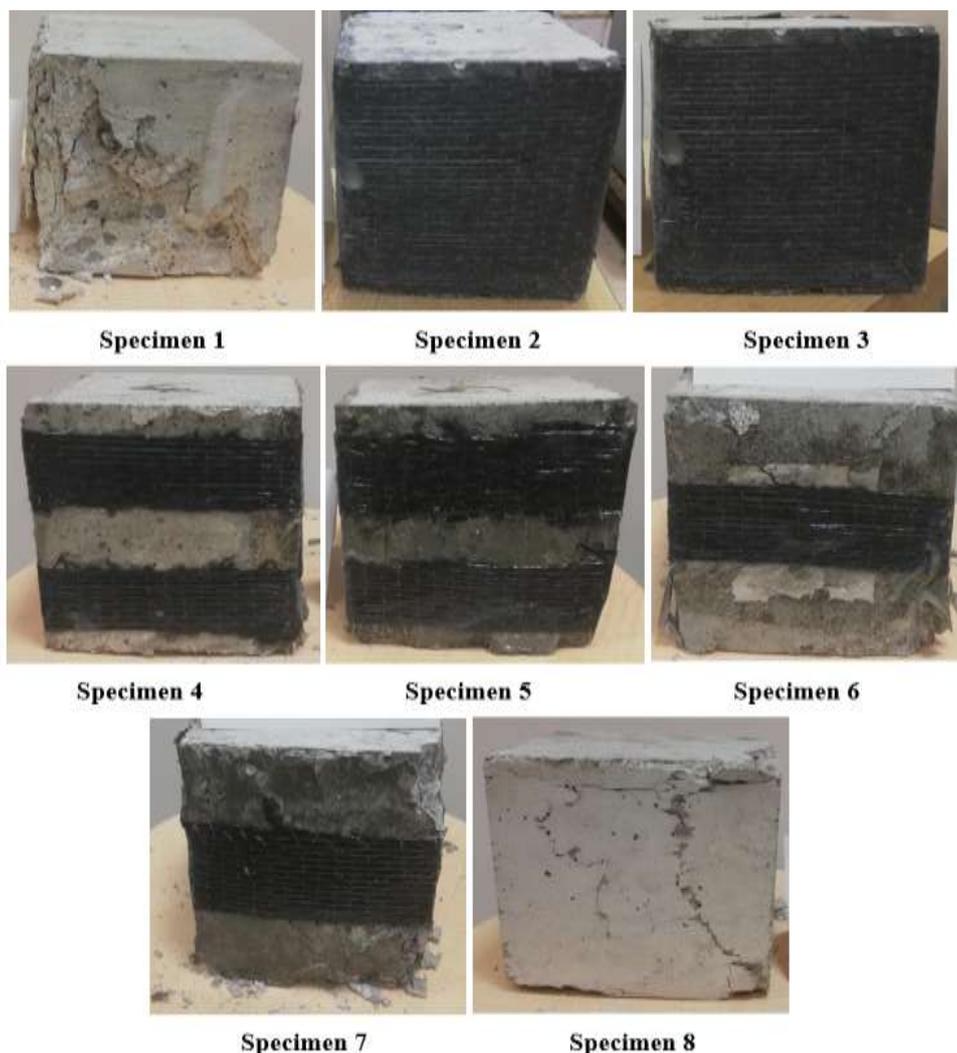


Figure 7. Crack pattern upon the failure of unconfined and confined concrete

4. Conclusions

In the study, the compressive behaviour and crack pattern of damaged concrete strengthened using FRP and different configurations of CFRP wraps were evaluated. According to the experiments, the following conclusions were obtained:

- Fully wrapped concrete samples were also obtained less capillary water absorption coefficients than CFRP strips confined concrete specimens.
- The capillary water absorption of CFRP wrapped concrete samples with different layers (single or double) and strip type (one or two strips) were close relationships.
- The compressive strength values of damaged concrete samples reinforced with all CFRP wraps (single or double layers and one or two strips) were determined to be higher than the undamaged concrete specimen.
- The highest strength value was obtained from two-50 mm FRP wrapped damaged concrete specimen (S5).
- The comparison of the ultimate strength between S3 and S5 using CFRP composite-strengthened samples displayed higher improvements of 70.5% and 72.4% compared to the control sample (S1), respectively.

- The failures of the unconfined damaged specimens (S1) were also higher than that of the other specimens wrapped with fibre composite.
- Strengthening of the specimen with two-50 mm CFRP strips controlled the crack width in comparison with the control specimen.

Authors' Contributions

MMM wrote up the article. The author read and approved the final manuscript.

Competing Interests

The author(s) declare that they have no competing interests.

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