Experimental Investigation on CFRP-Confined Low Strength Concrete after High-Temperatures Exposure

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Abstract. The current research studies the effect of high temperatures on the behavior of low-strength concrete after wrapping it with one layer of polymer carbon fiber (CFRP) for strengthening. Eighty-four specimens were examined, 42 wrapped with fiber CFRP sheets and 42 un-wrapped, where the study was conducted on cylindrical specimens (150 x 300 mm) that were exposed to different temperatures ranging from (100 to 600°C) for 1 and 2 hours as a period of exposure to heat. The behavior of low strength concrete represented by compressive strength, ultrasonic pulse velocity, dynamic modulus of elasticity, and weight loss are the focus of the practical part of the study. The results revealed, the compressive strength of the wrapped specimens increased by (35%) and (49%) when exposed to temperature (200ºC) and for a period of one and two hours, respectively, compared to the unwrapped specimens and at the same degree. Also, the external strengthening with CFRP sheets acted as a protective layer for the concrete, which led to an improvement in the behavior of the low strength concrete.

Keywords. Low strength concrete, CFRP sheets, Strengthening, High temperature, Residual concrete strength.

1. Introduction
During the life of many concrete structures, they are got exposed to high temperatures. This exposure may be due to the nature of the structure's use, for example, if the facility is a chemical plant, a nuclear reactor, a furnace, and a chimney. Alternatively, it may be that the cause of the high temperature is the exposure of the buildings and facilities to fire accidents caused by natural causes, or the burning be human-made, and the temperature may reach to approximate (1000°C) within a short time [1]. The concrete is a construction material resistant to fire, incombustible, resistant to heat transfer, has a relatively weak thermal conductivity, can be considered a protective barrier from the fire [2,3,4]. Its exposure to high temperatures changes its engineering properties due to physical and chemical changes that occur to concrete during its exposure to heat, as the high temperature affects the compressive strength, elastic modulus, and other properties. All of these have an adverse effect on the properties of concrete and steel reinforcement [5]. Consequently, it affects the structure's overall strength, durability, and life [6]. Concrete is classified into structural concrete (for structural design) and non-structural concrete (weak) for various purposes. The American Concrete Institute at (ACI 318-10) and (ACI 318R-14) have defined in their codes that the structural concrete is concrete that has not less than strength compressibility (17 MPa) [7,8]. Fibers (FRP)
have a very high tensile strength. That is, a slice of carbon fiber, whose thickness does not exceed a few millimeters, can replace steel reinforcement with a large diameter in increasing tensile strength, so carbon fiber (CFRP) is usually used in reinforcement, maintaining the shape of the installations and restoring high compressive strength. This technology has proven to be effective in economic and engineering terms. There are several types of polymer fibers, such as carbon fiber (CFRP), glass fiber (GFRP), and aramid fiber (AFRP)[9]; as these fibers are characterized by multiple characteristics that make them the most appropriate and reliable choice in solving many engineering problems. These materials possess high strength relative to their weight, easy to carry or lift, and simple to handle due to their lightweight, chemically stable, do not affect the dimensions of concrete members, When covered with finish layers, it does not leave a visible trace of the reinforcement operations. It is sometimes the only way in some cases where there is not enough space to use huge steel sections to support, and it has a low thermal expansion coefficient [10,11].

AL-Salloum et al. 2011 studied the behavior of concrete wrapped with FRP after exposure to high temperatures. Two types of FRP were used for external wrapping (CFRP) and (GFRP). The compressive strength of the concrete was 40MPa. Fourteen (14) cylindrical specimens without external wrapping, 14 specimens wrapped with a single layer of CFRP, and 14 specimens wrapped with a single layer of GFRP were equipped. The samples were then exposed to different temperatures (100 and 200 ⁰C) for one, two, and three hours. The researchers found that the loss of compressive strength at the temperature of 200 ⁰C was more pronounced, especially for the cylinders wrapped with CFRP. They also found that it is not advisable to exceed the temperature (200 ⁰C) when wrapping the specimens with CFRP due to the apparent deterioration in the concrete's compressive strength [12]. Yaman S.S. Al-Kamaki and Riadh AL-Mahaidi (2013) study the possibility of restoring the compressive strength of concrete specimens pre-exposed to heating at a temperature of 500ºC for one hour by externally strengthening them with (one, two, three layers) of (CFRP) and with use of primary and secondary reinforcement. One of the most important conclusions reached by the study was that the CFRP is beneficial in strengthening concrete cylinders that have been damaged by high temperatures. A confined concrete cylinder's capacity increases in proportion to the increase in the number of CFRP layers. The compressive strength of the concrete that has been heated can also be restored to its original level or higher than the un-wrapped and non-exposed specimens [13]. In 2013 Xu et al. used confined and unconfined cylinders (RC) wrapped with (1, 2, and 3) carbon fiber layers with a geopolymer adhesive. They exposed the specimens to high temperatures up to 300ºC, then applied axial pressure, notice an increase in compressive strength 106.4%. There is no evident deterioration In the properties of the concrete after heating [14]. Gamal et al. (2015) studied the effect of high temperatures on the compressive strength of standard cylinders strengthened by wrapping them externally with carbon and glass fiber reinforced polymer. The samples were exposed to 100, 200, and 300 ⁰C for 1, 2, and 3 hours. The researchers found that the wrapped specimens had a lower loss in compressive strength due to the temperature than the unwrapped specimens. They also concluded that the CFRP wrapped specimens have higher efficiency than the GFRP wrapped specimens [15]. Hia et al. (2016) studied the properties of the standard concrete reinforced with carbon fiber (CFRP) under the influence of high temperatures (100, 200, and 300 ºC) by using three layers of wrapping for two hours of heating. The researcher concluded that the carbon fiber has excellent resistance to high temperatures and that the inorganic geopolymer adhesive has good resistance to high temperatures that Less than 300 ºC [16].

2. Research significance
This research's importance is that the light will be shed on strengthening low strength concrete by wrapping it externally with carbon fiber reinforced polymer (CFRP) and then exposing it to elevated temperatures for 1 and 2 hours. Then, study the behavior of low strength concrete that was exposed to different levels of temperatures. The low strength concrete specimens were prepared and wrapped externally with CFRP sheets. It was then exposed to elevated temperatures ranging from (100 to 600 ºC)
for variable periods of one and two hours. After the heating period ends, the compressive strength, weight loss in the specimens, and ultrasonic pulse velocity are recorded.

3. Experimental program

3.1. Materials

3.1.1. Cement. Ordinary Portland cement was used, which is following the Iraqi Standard. Tables (1), (2) illustrate the physical and chemical properties of the cement, respectively.[17]

| Chemical Composition | Value % | Limits % |
|----------------------|---------|----------|
| SiO$_2$              | 20.35   | ----     |
| Al$_2$O$_3$          | 4.81    | ----     |
| Fe$_2$O$_3$          | 3.51    | ----     |
| CaO                  | 61.52   | ----     |
| MgO                  | 2.27    | 5        |
| SO$_3$               | 1.59    | 2.5      |
| Free Lime            | 0.56    | ----     |
| Loss on Ignition     | 1.94    | 4        |
| Insoluble Residue    | 0.44    | 1.5      |
| Total                | 96.99   | ----     |

Table 2. Physical properties for the OPC.

| Property                  | Test result (min) | Standard IQS |
|---------------------------|-------------------|--------------|
| Initial setting time      | 105               | ≥45 (min.)   |
| Final setting time        | 180               | ≤600 (min.)  |
| Compressive strength (MPa)|                   |              |
| at 3 days                 | 20.4              | ≥15.0 (MPa)  |
| at 7 days                 | 30                | ≥23.0 (MPa)  |

3.1.2. Fine Aggregate. Local river sand was used; the specific weight of fine aggregate was (2.67)[18], after conducting the sieve analysis. Table (3) shows the results of the analysis of the used fine aggregates [19].

| Sieve Size | %Specification Limits | %Passing of used sample |
|------------|-----------------------|-------------------------|
| 100        | 100                   | 100                     |
| 5.0        | 90-100                | 98                      |
| 2.36       | 60-95                 | 73                      |
| 1.18       | 30-70                 | 48                      |
| 600μm      | 15-34                 | 30                      |
| 300μm      | 5-20                  | 16                      |
| 150μm      | 0-10                  | 5                       |
3.1.3. Coarse aggregate. Local river gravel was used and free of clay materials. MAS 20 mm, specific gravity of coarse aggregate (2.7)[20]. Table (4) shows the results of the analysis of the used coarse aggregates [19].

| Sieve Size (mm) | %Specification Limits | %Passing of used sample |
|----------------|-----------------------|-------------------------|
| 37.5           | 100                   | 100                     |
| 20             | 95-100                | 100                     |
| 10             | 30-60                 | 41                      |
| 5              | 0-10                  | 5                       |

3.1.4. Carbon fiber Reinforced polymer. Carbon fiber polymer (CFRP) sheets were used in the external strengthening of specimens; it is of medium strength (SikaWrap-300 C) type [21].

3.1.5. Epoxy adhesive. The process of external strengthening with carbon fiber reinforced polymer sheets is only done with the presence of epoxy adhesive. For this reason, Sikadur-330 was adopted as an adhesive material in the process of wrapping. The resin ratios: the hardened material was 1: 4 by weight because it gives a very high adhesive strength after mixing [22, 23, 24].

3.2. Concrete mixture
Table (5) shows the quantities of materials used in concrete mixes used in the current research and designed according to the British D.O.E [5] method. The specimens used in all the study investigations are the standard cylindrical specimens (150×300mm).

| Mix                | Cement Kg/m³ | Fine Agg. Kg/m³ | Coarse Agg. Kg/m³ | Water Kg/m³ | Comp. strength MPa |
|--------------------|--------------|-----------------|-------------------|-------------|--------------------|
| Low Strength       | 235          | 690             | 1380              | 150         | 18.1               |

After casting the specimens and completing the curing period, the specimens were divided into two groups. The first group, which is the unwrapped specimens and considered as control specimens, the second group are the specimens that have been wrapped with a single layer of CFRP sheets. As seen in Figure (1), the specimens were exposed to high temperatures by placing them in an electric furnace for variable periods of one hour and two hours.

Figure 1. Specimens wrapped with CFRP Sheets.
3.3. The mechanism of heating concrete specimens
The specimens were heated to variable temperatures (100, 200, 300, 400, 500, 600º C) by the electric furnace shown in Figure (2). As it contains a large room for heating, and the maximum temperature of the oven was 600 ºC, the following steps summarize the method of heating and cooling adopted in the current research:
- Initially, the required heating temperature was fixed, and waiting until the furnace reaches the desired temperature.
- The concrete specimens (wrapped or un-wrapped) were placed inside the furnace, and then the furnace was closed tightly and left for 1 or 2 hours.
- At the end of the heating exposing period, the furnace is turned off, and then the gate is opened, and the specimens are left inside the furnace to cool down to the laboratory temperature for (24) hours.

![Electric furnace](image)

**Figure 2. Electric furnace.**

4. Result and discussion

4.1. Compressive strength
After heating the specimens to different temperatures for different periods, a compressive strength test was performed for the specimens [25]. There is a step before testing the specimens, which is to perform the specimens’ capping process [26] to ensure that the surface is flat, as shown in Figure (3). Figure (4) shown ALFA compressive test device.

![Capping process](image)

**Figure 3. Capping process.**
Figure 4. ALFA compressive test device.

Table (6) shows the results of the compressive strength test for the un-wrapped specimens (control specimens) and wrapped specimens with CFRP sheets that were exposed to high temperatures (100, 200, 300, 400, 500, 600 °C).

Table 6. Compressive strength for specimens.

| Temp. °C | Un-Wrapped* | Wrapped With CFRP* |
|---------|-------------|-------------------|
|         | 1hr 2hr     | 1hr 2hr           |
| 23      | 18.1 18.1   | 29 29             |
| 100     | 22.7 19.2   | 29.6 29           |
| 200     | 20.0 17.10  | 31.0 33.5         |
| 300     | 16.9 15.60  | 28.6 28.1         |
| 400     | 15.4 14.1   | 26.6 26.5         |
| 500     | 15.0 12.4   | 22.1 20.8         |
| 600     | 14.4 11.3   | 18.3 12.2         |

*The results are an average of three specimens.

First of all, when comparing the compressive strength of the specimens wrapped with carbon fiber sheets with the control specimens at laboratory temperature (23°C), it is noticed that there was a clear contribution of the externally strengthening of carbon fiber sheets to enhance the compressive strength. It is noticed that the rate of increase reached (60.2%), and the reason for this is the external confinement provided by the externally strengthening by CFRP sheets, which restricts the lateral expansion of concrete, which in turn improves the behavior of concrete [27, 28, 29].
As for the effect of heating on the behavior of the concrete wrapped with CFRP sheets, it is noticed that the effect of the temperature did not appear beyond (100ºC) as this degree did not affect the compressive strength upon exposure for one or two hours. In contrast, it can be seen that the effect of this degree was evident on the unwrapped specimens (control specimens) through the increase in compression strength, which reached (25.4%) and (6.1%) upon exposure for one and two hours respectively, as shown in the Figure (5). The reason for this is attributed to the occurrence of a new hydration process of cement at these temperatures, which did not occur at lower temperatures [30, 31, 32].

It can also be seen that the specimens wrapped with CFRP sheets show an increase in their compressive strength at a temperature of (200ºC), where the increase in compressive strength at this temperature upon exposure for one and two hours reached (35%) and (49%) respectively compared to the control specimens. However, when compared to the wrapped specimens that were tested at the laboratory temperature, it is noticed that the amount of increase is (6.5%) and (13.4%) upon exposure for one and two hours, respectively. This can be explained by the difference between the thermal expansion of the CFRP sheets and the concrete material and the epoxy's good heat resistance. As the coefficient of thermal expansion of both the CFRP sheets and concrete is equal to (0 ºC-1) and (0.008T + 6) × 10-6 ºC -1) respectively, this leads to the fact that the CFRP sheets make a prestress for the surface of concrete, and this prestress works to restrict the expansion of the concrete laterally and thus will provide an enhancement for the compressive strength of the wrapped concrete specimens at high temperatures. Also, the epoxy material's good resistance provides a good bond between the sheets and the concrete, which results in the sheets continuing to provide confinement to the concrete core [16].

By observing the results in Figure (5), it is noticed that there is a decrease in the compressive strength of concrete after a temperature of (200ºC) for the control specimens and after a temperature of (300ºC) for the specimens wrapped CFRP sheets. As the percentage decrease for the wrapped specimens reached (6.6%) and (13.8%) after exposure for one and two hours when compared to the control specimens, and the percentage decrease in compressive strength of the CFRP sheet wrapped specimens reached (1.4%) and (3.1%) after exposure for one and two hours respectively when compared to the control specimens. This decrease in exposure to high temperatures is due to many chemical and physical processes that occur within concrete exposed to high temperature, caused by the variation in the coefficient of thermal expansion of coarse and fine aggregates and the coefficient of thermal expansion of cement. This leads to the formation of stress at the contact surface between the cement and aggregates, which is a critical area, as these stresses break the bonds between cement and aggregates, which weakens the compressive strength. Besides, the increase in internal vapor pressure resulting from the loss of moisture due to exposure to high temperatures coincides with the chemical changes of the cement paste. Among the most important of these changes is the conversion of calcium hydroxide to calcium oxide at temperatures between 400-450ºC, which causes the cement paste to shrink, so that high tensile stresses form, generating compressive stresses in the aggregate, which leads to poor bonding [9,33,34].

On the other hand, when cooling concrete is exposed to high temperatures to reach the laboratory temperature, this has decreased the concrete strength. This is because the cooling speed inside the heated specimens differs from the speed of cooling the external surface of the specimens. This variation leads to an increase in Cracks generated from the previously mentioned reasons [34]. The reason for the low compressive strength of specimens wrapped with CFRP sheets after exposure to high temperatures can also be attributed to the loss of epoxy to its role as a binder material after exposure to elevated temperatures, which leads to the loss of the CFRP sheets to their function of providing confinement to concrete and enhancing the compressive strength [35].
Figure 5. Compressive Strength for wrapped with CFRP sheets and Un-wrapped Specimens.

4.1.1. Mode of failure. Figure (6) displays the un-wrapped concrete specimens' failure patterns after exposure to elevated temperatures, where the failure was in a uniaxial cone shape. Among the things that were noticed on these specimens is the change of the color of the outer surface to a light brown color after exposure to a temperature of (400,500,600 °C).

Figure 6. Failure of Un-wrapped concrete specimens.

As for the failure of the wrapped specimens that are not subject to heating, it was caused by rupture of the CFRP sheets in the middle third as shown in Figure (7). While the failure took many forms for these specimens after exposure to high temperatures(100,200,300,400°C), including uniaxial cones, Annular rupture in the CFRP sheets in the last third of the specimen, CFRP sheets are torn in the upper third and annular, but the most frequent failure was the rupture of the CFRP sheets in the middle third of the specimen, At temperatures (500&600°C), the concrete failed in a uniaxial conical shape, and there was no rupture of the fiber due to its loss of bonding with the concrete due to the complete combustion of epoxy and loss of its properties. The CFRP sheets also change their color clearly after exposure of the samples to temperatures up to (300,400,500,600°C). It is worth noting that the tearing of the CFRP sheets was preceded by a warning, which was hearing sounds caused by the sheets separating from the concrete surface due to cracks occurring in the wrapped concrete and that these sounds are made in the last stages of testing and before the final failure occurs.
Figure 7. Failure of concrete specimens wrapped with CFRP sheets.

4.2. Ultrasonic and dynamic modulus of elasticity

Ultrasonic velocity and dynamic modulus of elasticity were calculated for low strength wrapped and un-wrapped concrete specimens by using Equations (1, 2) as follows:

\[ v = \frac{L}{T} \]  

(1)

\[ E_d = \frac{\rho v^2 (1-\mu)(1-2\mu)}{(1-\mu)} \]  

(2)
Where; \( \text{Ed} \): dynamic modulus of elasticity (GPa), \( V \): the UPV (km/s), \( \rho \): concrete density (kg/m\(^3\)), and \( \mu \): Poisson’s ratio (0.2) [36]. Table (7) shows the classification of concrete according to the pulse velocity. Table (8) shows the calculated pulse velocity and the dynamic modulus of elasticity for wrapped and un-wrapped concrete specimens exposed to high temperatures.

### Table 7. Classification of concrete according to the pulse velocity [37].

| Concrete quality | Pulse velocity (km/sec) |
|------------------|--------------------------|
| Excellent        | ≥ 4.5                    |
| Good             | 3.5 - 4.5                |
| Doubtful         | 3.0 - 3.5                |
| Poor             | 2.0 - 3.0                |
| Very poor        | ≤ 2.0                    |

### Table 8. Pulse velocity and the dynamic modulus of elasticity.

| Temp. ºC | Un-Wrapped | Wrapped With CFRP |
|----------|------------|-------------------|
|          | 1hr        | 2hr               | 1hr                | 2hr                |
|          | V (km/Sec) | Ed (GPa)          | V (km/Sec) | Ed (GPa) | V (km/Sec) | Ed (GPa) |
| 23       | 3.25       | 23.19             | 3.25       | 23.19    | 3.25       | 23.19    |
| 100      | 3.25       | 23.19             | 3.12       | 21.37    | 3.25       | 23.19    | 3.17     | 22.06   |
| 200      | 3.04       | 20.29             | 3.04       | 20.29    | 3.14       | 21.65    | 3.11     | 21.23   |
| 300      | 2.91       | 18.59             | 2.72       | 16.24    | 2.99       | 19.63    | 2.8      | 17.21   |
| 400      | 2.6        | 14.84             | 2.25       | 11.11    | 2.65       | 15.42    | 2.415    | 12.80   |
| 500      | 2          | 8.78              | 1.72       | 6.49     | 2.15       | 10.15    | 1.78     | 6.95    |
| 600      | 1.75       | 6.7               | 1.24       | 3.37     | 1.8        | 7.11     | 1.36     | 4.06    |

As for the un-wrapped specimens that were not exposed to heat, the value of the ultrasonic velocity was 3.25 km/sec, which is why this type of concrete can be classified as Doubtful. The same applies to specimens wrapped with CFRP sheets at the same temperature. It is also noticed that the pulse velocity of the ultrasonic waves and the dynamic modulus of elasticity decrease with the increase in temperature and for both heating periods, except at 100 ºC for a heating period of 1 hour, no significant effect on the pulse velocity of the specimens was recorded. Among the matters that can be observed, the values of ultrasonic velocity and dynamic modulus of elasticity are higher for specimens wrapped with CFRP sheets than un-wrapped specimens for both heating periods. Figures (8) and (9) illustrate the effect of temperature on the pulse velocity in the wrapped and un-wrapped specimens’ low strength concrete. Regarding the pulse velocity, by observing the results, the inverse relationship is the higher the temperature, the lower the pulse velocity.

![Figure 8. Pulse velocity for two heat periods.](image-url)
4.3. Weight loss

After exposing the un-wrapped and wrapped specimens to several temperature levels for a period of one and two hours, a weight loss was observed for the specimens and at all temperature levels, as shown in Table (9). Except for the temperature of 100 ºC, where no weight loss was recorded, and for the two heating periods. The weight loss occurred due to the evaporation of excess water, which is trapped inside the voids when the samples are exposed to high temperature [38,39].

Table 9. The percentage of weight loss.

| Type of wrapped | CFRP | UN-Wrapped |
|----------------|------|------------|
| Temp.ºC | 1hr | 2hr | 1hr | 2hr |
| 100 | 0 | 0 | 0 | 0 |
| 200 | 0.086 | 0.297 | 0.156 | 0.320 |
| 300 | 0.493 | 1.346 | 0.782 | 1.409 |
| 400 | 1.878 | 2.074 | 1.941 | 2.230 |
| 500 | 2.465 | 3.209 | 2.504 | 2.951 |
| 600 | 2.778 | 3.718 | 2.857 | 3.835 |

5. Conclusions

Based on the above, the following can be concluded:

1. The external strengthening with CFRP sheets enhanced the compressive strength of the low strength concrete. The percentage of compressive strength increases in the wrapped specimens when the laboratory temperature reached (60.2%) compared to the un-wrapped specimens.
2. The effect of temperature did not appear on the wrapped concrete specimens until after (200ºC), and it is also noticed that their compressive strength decreased and returned to its initial value (18.1 MPa) when the temperature reached (600 ºC).
3. The external strengthening with CFRP sheets provides adequate protection for the low strength concrete, as it is noticed that the decrease in the compressive strength of the wrapped specimens with high temperature is less than the decrease in the un-wrapped specimens.
4. In general, the external strengthening with carbon fiber sheets had a positive effect on the rest properties of low strength concrete when exposed to high temperature than the un-wrapped specimens.
5. The dynamic modulus of elasticity (Ed) is related to the ultrasonic velocity (UPV) and the density of the concrete, as it is noticed that with increasing temperature, the UPV decreases and the density decreases, which leads to a decrease in the values of the Ed, but the Ed of the wrapped specimens remains higher than the un-wrapped.
6. The heating period and the increase in temperature negatively impacted the behavior of the low strength concrete.
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