Thermal conductivity and compressive strength of carbon fiber concrete

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ABSTRACT

This research includes an experimental study to find out the possibility of benefiting from the addition of Carbon Fiber Reinforced Polymers (CFRP) to the concrete mix in reducing the thermal conductivity of concrete and thereby reducing the heat transferred through the structures and elements of buildings, which leads to increased thermal insulation and reduce the electrical energy consumed to operate air conditioners. Eight rectangular concrete specimens are prepared and poured for thermal conductivity testing, in addition to 12 standard concrete cubes for compressive strength testing. CFRP strips cut in different proportions are added to find out the effect of the amount of these fibers on the thermal insulation of concrete and compare it with their effect on compression resistance. The results of the thermal conductivity tests for a test time of 390 minutes for each model showed that there is an increase in the insulation of concrete with added percentage of CFRP strips. The concrete specimens and cubes are classified into four groups according to the percentage of addition of CFRP, which was (0 %, 0.45 %, 1.1 %, and 1.6 %) by the weight of the cement allocated for the mixture. Despite the increase in insulation with the presence of fibers, there was a decrease in the compressive strength of concrete with an increase in the amount of fibers, where this decrease ranged between (6.4 - 28.5) % relative to the compressive strength of the reference concrete.

Keywords: CFRP, concrete, thermal conductivity, compressive strength.

1. Introduction

Heat is defined as a type of energy that moves from warm regions to cold regions and its transmission is by conduction, transmission, and radiation. The amount of heat transfer depends on several factors, including: the temperature difference between the two surfaces of the element, the thickness of the element, the area of surfaces exposed to heat, and the rate of thermal conductivity of the material (or thermal insulation of the material) [1].

The percentage of electrical energy consumed in summer to cool buildings is estimated at about 66 % of the total electrical energy, and the heat that penetrates walls and ceilings on summer days is estimated about 60-70 % of the heat to be reduced by air conditioners, the rest comes through windows and ventilation holes [2]. Hence the importance of thermal insulation to reduce the consumption of electrical energy used for air conditioning purposes in order to reduce heat leakage through walls and ceilings to achieve a convenient, comfortable, and low-cost living. A good thermal insulation reduces the use of air conditioners, which reduces the health and psychological impact on humans due to the noise generated by the operation of these devices. Good thermal insulation also protects the building from weather changes and weather fluctuations, as the temperature difference resulting from the heat rise due to sunlight during the day, and its decrease at night, and the frequency of this occurrence, leads to thermal stresses that make the outer surface layer of the building lose many of its natural and mechanical properties, and thus the appearance of cracks in the building structure.

A number of researchers have made attempts to reduce the thermal conductivity coefficient of concrete by adding insulating materials with different weight and volume ratios and studied the effect of these additives on the thermal and mechanical properties of the mixture and the extent of the decrease in the compressive strength of concrete when adding these materials. In 1980 (Shirtliffe) [3] conducted a study on heat transfer in fibrous materials and came up with several mathematical and statistical models of the relationship between the coefficient of thermal conductivity and the volumetric ratios of both the fibrous material and the air gaps inside it. Also (Adam) studied (in 1997) [4] the effect of adding weight ratios of reeds to concrete and the effect of the size and density of reed plates and the amount of moisture in them on the coefficient of thermal conductivity of the mixture using a two-sample hot plate type measuring device, where he used laboratory-manufactured samples with dimensions (290 mm x 290 mm), and he came up with an experimental equation for the thermal conductivity of concrete in terms of the volumetric ratios of reeds, moisture content and the average temperature of the sample. Kazem and Hefama in 1998 [5] studied the effect of adding sunflower seeds to Portland cement in weight ratios ranging from (0.0-0.7) % on thermal conductivity and tensile and compression resistances and obtained a decrease in thermal conductivity to 0.7 from the original value before addition, which is a good ratio.

Since the addition of CFRP strips to the concrete mix will improve its tensile strength and crack resistance properties [6], it has become necessary to study the heat transfer through strengthened concrete with these strips and to find out the usefulness inspired by the addition of carbon fiber strips in reducing the thermal conductivity of concrete elements.

2. Laboratory work

The wooden formwork shown in Fig. 1 was prepared for pouring eight concrete models with dimensions of (200 mm x 200 mm) and a thickness of 80 mm and mixing weight ratios of cement, sand, gravel of (2:1.5:1) and a water/ cement ratio of 0.45 in order to find out the effect of adding different amounts and proportions of CFRP strips on heat transfer rates during strengthened specimen. Specimen no. 1 is referred to the control model that do not contain fiber strips, and no. 2 specimen has a weight addition of carbon fiber of 0.45 % of the weight of cement, and no. 3 specimen has a weight addition of carbon fiber of 1.1 % of the weight of cement, and the no. 4 specimen has a weight addition of carbon fiber of 1.6 % of the weight of cement. Table 1 shows the characteristics of the specimens used. Figure 2 shows concrete specimens used for calculating thermal conductivity. Twelve standard concrete cubes with dimensions of (150 mm x 150 mm x 150 mm) have been poured for testing the compressive strength of concrete and the used steel molds are shown in Fig. 1 as three cubes for each of the four mixes. The next day, all the concrete models and cubes were taken out of their molds to be placed submerged in the curing water basin for 28 days to be ready for test. Figure 3 represents a concrete cube prepared for examination inside the compression testing machine

Figure 1. Wooden molds for specimens and steel molds for concrete cubes.

Figure 2. Concrete specimens used for testing thermal conductivity.

Table 1. The characteristics of concrete specimens used for calculating thermal conductivity.

Specimen	CFRP ratio by weight of cement (%)	Weight of the specimen before test (g)	Average weight for two specimens (g)
1	0.00	7470	7483
1	0.00	7495	
2	0.45	7345	7340
2	0.45	7335	
3	1.10	7205	7215
3	1.10	7225	
4	1.60	7160	7148
4	1.60	7135	

Figure 3. A standard concrete cube prepared for testing compressive strength.

2.1 Characteristics of the raw materials used in concrete

In this research, Ordinary Portland cement Type (I) is used, which is manufactured at the Kirkuk cement plant/ Iraq. The largest diameter of the sand (which was dried before mixing) did not exceed 4.75 mm and the largest diameter of the gravel did not exceed 10 mm according to ACI 318-05 Code specifications [7] and the gradation of sand and gravel used in sieves fell within the allowed gradation in the Iraqi specifications No. 45/1984 for Group (2) [8]. Sikawrap Hex-230C CFRP strips are used, as shown in Fig. 4, which is imported from Sika Middle East – Beirut – Lebanon. Since these strips are in the form of a mat with a width of 300 mm and a length of up to 50 m, these strips have been cut into small pieces with fixed dimensions (50 mm x 15 mm) to be mixed in different weight ratios with the other dry components of concrete and water is added to the homogeneous mixture to pour the final mixt into molds intended for testing thermal conductivity and cubes intended for testing the concrete compressive strength.

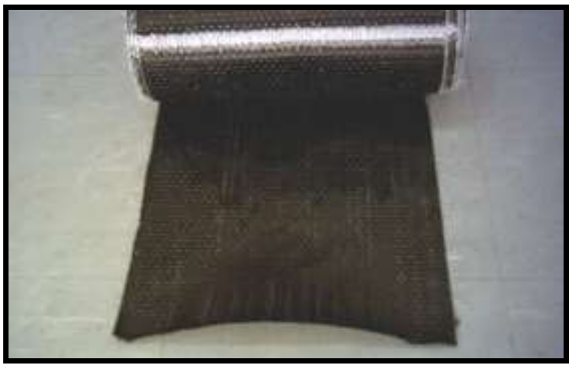

Figure 4. The CFRP mat used.

2.2 Devices used for laboratory tests

An Italian-made digital inspection device is used to test the compressive strength of standard concrete cubes containing different proportions of CFRP strips. This device is located at the National Center for construction laboratories in Kirkuk, as shown in Fig. 5, where the cubes were checked sequentially by placing them between the jaws of the compression inspection device until they cracked and failed. The time required to fail each cube was between (2-3) minutes, as the loading rate was 6.8 kN/s.

Figure 5. The device used to testing concrete compressive strength.

An accurate electronic balance is also used to measure the weights of the materials used in the ordinary and strengthened concrete mix with slides in addition to measuring the weights of the models intended for thermal conductivity tests, and the results obtained from the weight of the eight models of the four mixtures before the thermal conductivity test as shown in Table 1.

The thermal conductivity measuring device shown in Fig. 6 is manufactured and used. The device contains a sample test chamber made of aluminum metal with dimensions (500 mm x 500 mm) and a height of 300 mm, and this chamber is thermally insulated with asbestos and glass wool. The device from the bottom contains an oil cabinet with dimensions of (500 mm x 500 mm) and a thickness of 100 mm and the cabinet contains 30 liters of oil and under the cabinet there is an electric heater with a heat capacity between 50 W/ min to 500 W/ min. As for the front end of the chamber, it can be opened and closed for the input and output the samples. The device also contains eight electronic screens connected to temperature sensors with ranges ranging from 10 ^{o}C to 85 ^{o}C, as shown in Fig. 7. All the models prepared for the test were insulated by glass wool from the sides well to reduce heat leakage and to make it move in one direction, and thermal sensors were connected to the upper and lower surfaces of the models, and the time required to make preparations and conduct the test once was about eight hours, where temperature readings were taken every 15 minutes. Figure 8 shows samples prepared for testing inside the chamber of the thermal conductivity test device.

Figure 6. The device used to measure the thermal conductivity of concrete.

Figure 7. Details of the electronic board of the thermal conductivity measuring device.

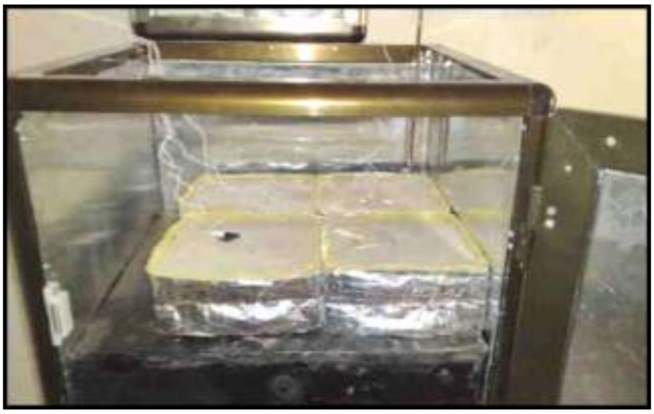

Figure 8. Concrete specimens inside the test chamber.

3. Results and discussion

Thermal conductivity tests were performed on 8 hardened concrete specimens distributed to 4 groups containing different weight ratios of CFRP strips as a strengthening and insulating material cut with dimensions (50 mm x 15 mm) and added to the dry components of the concrete before mixing it with water, the addition ratios ranged from (0 %, 0.45 %, 1.1 %, and 1.6 %) by the weight of the cement used. The tests of these specimens are carried out using a thermal conductivity measuring device, which was manufactured locally for this purpose, at different values of the temperature of the hot surfaces ranged between (20-35) ^{o}C. The compressive strength test of concrete is also carried out on 12 standard concrete cubes and the results of the tests are as shown in Table 2. It is noted that the compressive strength of the cubes when carbon fiber is added will gradually decrease from the compressive strength of the reference concrete cubes and this is due to the presence of carbon fiber material, which has a lower density than the rest of the concrete components, which leads to weakening of the concrete and reducing the cohesion of its components and thus reducing its resistance to compression.

Table 2. The results of testing the concrete cubes compressive strength.

Specimen	CFRP addition by weight of cement (%)	Concrete cube	Compressive strength (N/mm^2)	Mean compressive strength (N/mm^2)	Decrease in compressive strength (%)
1*	0	i	28.4	28.4	-
		ii	28.3		
		iii	28.5		
2	0.45	i	26.7	26.6	6.4
		ii	26.4		
		iii	26.6		
3	1.1	i	23.2	23.2	18.4
		ii	23.4		
		iii	23.0		
4	1.6	i	20.1	20.3	28.5
		ii	20.4		
		iii	20.5		

* Reference specimen

All specimens dedicated to measuring thermal conductivity are examined for a total time of 390 minutes in which the heat source (electric heater) is turned off in a time of 285 minutes, and temperature readings of the hot and cold surfaces were recorded every 15 minutes to get the real and accurate disposition of the amount of heat transfer during each model. The reading rate of each of the two analog models is also taken to obtain a uniform reading of each addition ratio of carbon fiber strips. The data is plotted using the EXCEL computer program in the form of graphs, Figure 9 shows the rate of change in temperatures between the surfaces of the two reference specimens, which are denoted by the symbol (1), as they do not contain carbon fiber strips. It is noted in this figure that the change in the temperature of the cold surface begins after a time of 12 minutes, so that its temperature continues to rise with time until the device is turned off after a time of 285 minutes, after which the temperature of the cold surface continues to increase despite the decrease in the temperature of the hot surface, and the average temperature difference between the two surfaces at the time of turning off the device was 2.5 ^{o}C. It is noted that after a time of 390 minutes, the temperatures of the two surfaces equalize to 32.5 ^{o}C, as this time was considered the end time of the experiment readings.

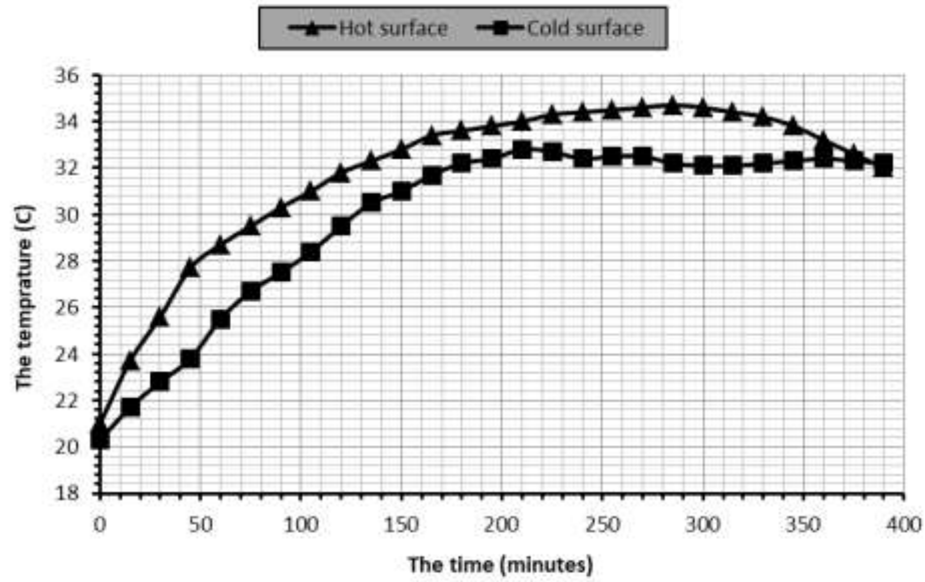

Figure 9. The average temperatures of the two surfaces over time for the two reference specimens (1).

Figure 10 shows the rate of change in temperatures for the surfaces of the two specimens No. 2, where they contain CFRP strips at a 0.45 % by the weight of cement. It is noted that the difference in the temperature readings of the hot and cold surfaces of the two specimens has increased from what was recorded in the testing of the two reference specimens, which means that the presence of CFRP has positively affected the thermal insulation properties of concrete, despite the decrease in compression strength in the testing of cubes by 6.4 % from the reference concrete cubes. It is noted that the amount of the difference between the two surface temperatures is proportional to the amount of fiber added as shown in Fig. 11 for the average readings of the two specimens No. 3, as they contain 1.1 % of CFRP strips, and the average temperature difference between the two surfaces at the time of switching off the device was 3.2 ^{o}C, and this difference is higher than the difference of 2.5 ^{o}C for the reference specimen. It is also noted that at the end of the test, 390 minutes, the temperature readings of the two surfaces were approaching each other and this approach is reduced by increasing the amount of fiber added, which means that the thermal insulation property has improved with the presence of carbon fiber. The rate of decrease in the compression strength of specimens No. (3) was 18.4%, and the rate of difference between the two surface temperatures at the time of switching off the device was 4.5 ^{o}C, which is higher than the difference recorded for reference specimens No. (1) and strengthened specimens No. (2).

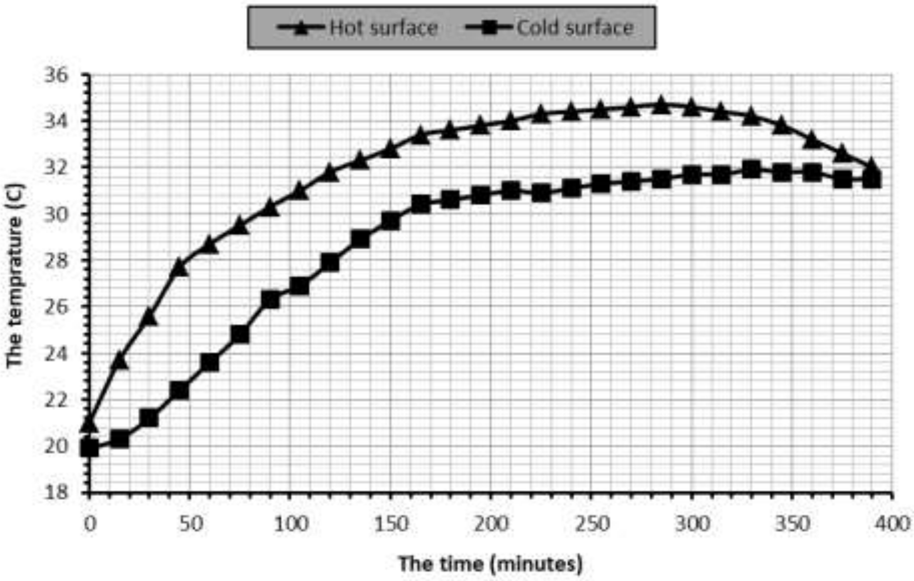

Figure 10. The average temperatures of the two surfaces over time for specimens No. 2 with a carbon fiber ratio of 0.45 %.

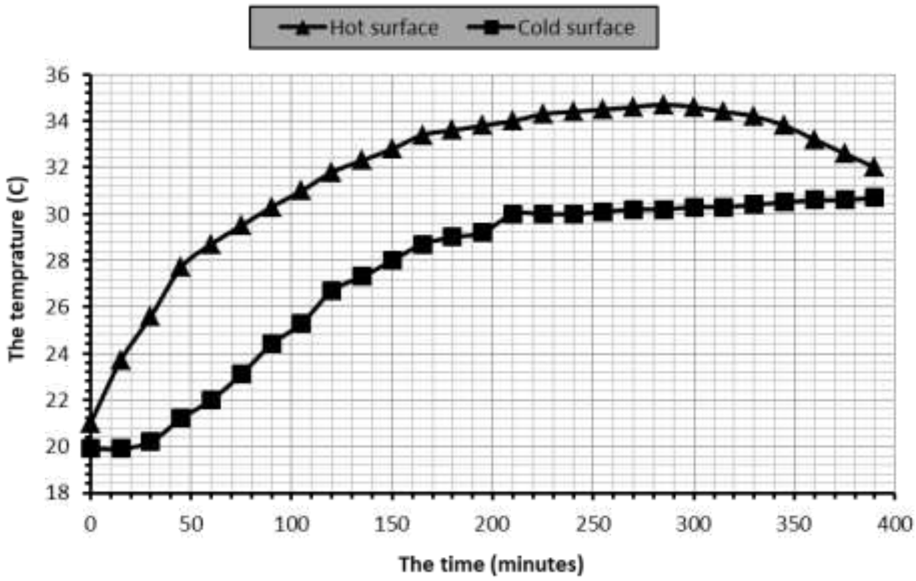

Figure 11. The average temperatures of the two surfaces over time for specimens No. (3) with a carbon fiber ratio of 1.1 %.

When increasing the amount of carbon fiber added to 1.6 % by the cement weight, the increase in the difference in the temperature readings of the two surfaces is evident in Fig. 12, where the average temperature difference of the two surfaces at the time of switching off the device was 5.5 ^{o}C. It is noted that even after switching off the heat source at 285 minute, the heat difference between the two surfaces lasts for a period of time, exceeding the end time of the readings, and this means that the specifications of the concrete in the thermal insulation have improved significantly despite the decrease by 28.5 % in the compressive resistance of this strengthened concrete from the reference concrete, and this decrease is due to the increased amount of fiber additives that, although they have improved the specifications of the concrete for thermal insulation and its resistance to tensile and cracks, but have weakened it in its compressive resistance, as is evident in Fig. 13, which shows the decrease in the temperature readings of the cold surfaces of the specimens with different amounts of fiber added, and Fig. 14 which shows the gradual decrease in the compressive strength of concrete by increasing the amount of added carbon fiber strips.

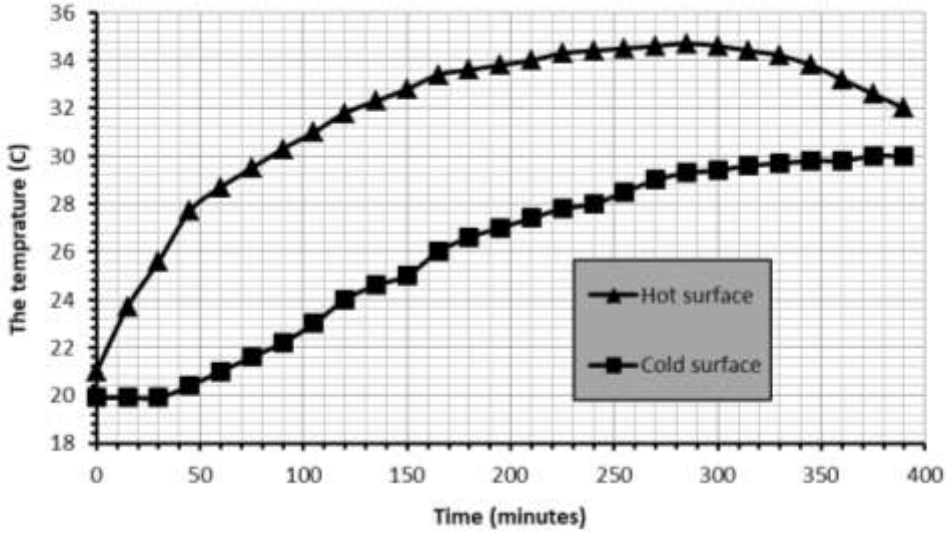

Figure 12. The average temperatures of the two surfaces over time for specimens No. (4) with a carbon fiber ratio of 1.6 %.

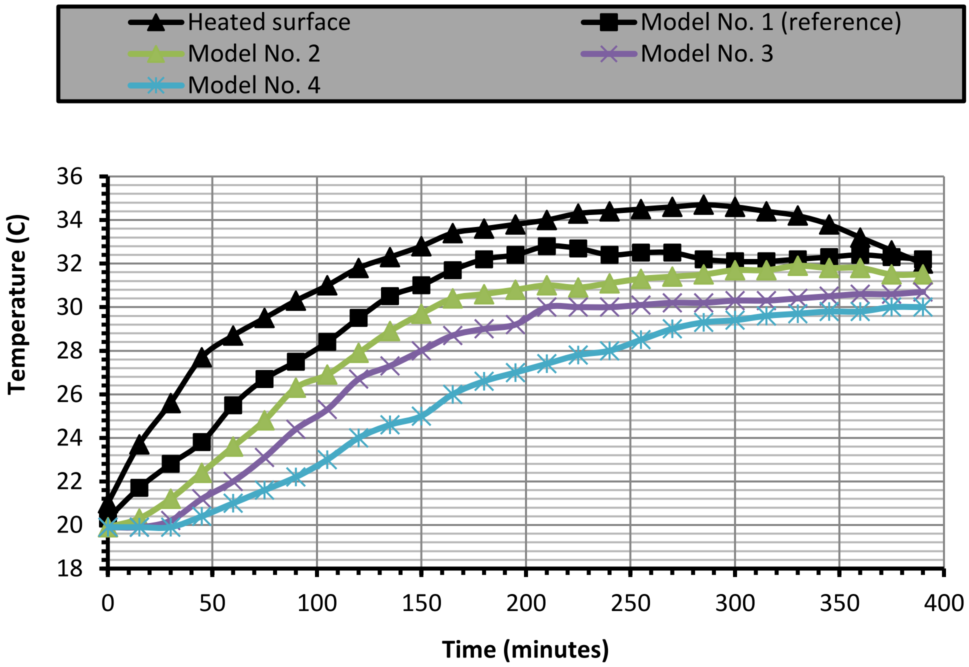

Figure 13. A comparison for the cold surface for the four specimens.

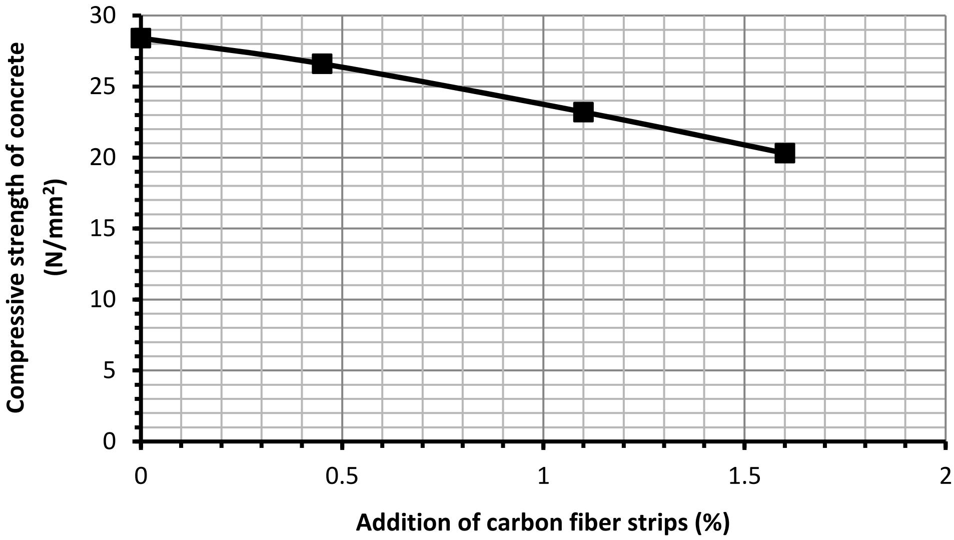

Figure 14. The relationship between the amount of addition of CFRP strips and the compressive strength of concrete.

4. Conclusions and recommendations

From this study we conclude that the addition of carbon fiber strips (CFRP) to the concrete mix to strengthen the structural elements of buildings reduces the thermal conductivity (increases thermal insulation) and at the same time reduces the compressive strength of hardened concrete. The laboratory results in this study indicate that the increase in the percentage of addition of carbon fiber strips from 0% to 1.6% (by the weight of cement) increased the value of the difference in the temperature of the hot and cold surfaces (from 2.5 ^{0}C to 5.5 ^{0}C), which means an increase in the thermal insulation of concrete, and at the same time this increase in the percentage of addition of strips gave a decrease in the values of compressive resistance of concrete (from 6.4% to 28.5%) relative to the compressive resistance of the reference concrete. Although this study is an attempt to find out the extent to which CFRP strips, originally intended for strengthening and rehabilitating concrete elements, can be used to increase the thermal insulation of buildings and thus reduce the electrical energy consumed to operate air conditioners. Therefore, it is recommended using these strips as an additive to concrete to reduce thermal conductivity (increase thermal insulation), taking into account the decrease in the compressive strength of concrete. It is also recommended conducting laboratory studies by adding other available and inexpensive insulating materials such as cork and rubber residues with carbon fiber to concrete, and it is also recommended doing statistical studies of a large number of laboratory models through which mathematical relationships to calculate the coefficient of thermal conductivity and compression resistance of strengthened concrete by adding carbon fiber and comparing them with existing theoretical mathematical relationships can be derived.

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