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# A COMPARATIVE EXPERIMENTAL INVESTIGATION OF HIGH-TEMPERATURE EFFECT ON FIBRE CONCRETE AND HIGH STRENGTH CONCRETE USING UT AND CM METHODS

Javad Royaei*, Kabir Sadeghi, Fatemeh Nouban

*Near East University, Department of Civil Engineering, Lefkosa, Via Mersin 10, Turkey*

* corresponding author: royaei.j1975@yahoo.com

Abstract. In this paper, a 28-day compressive strength test has been performed on samples including normal fibre concrete and high-strength concrete. The ultrasonic test (UT) as a non-destructive and compression machine (CM) as a destructive test were applied, and the results were compared. To investigate the effect of temperature, the samples were subjected to 200, 400, 600, 800, 1000, and 1200 degrees Celsius and the exposure time was equal to 30, 45, 60, 90, 120, and 180 minutes. Based on the results, it was observed that the minimum error observed between the UT and CM tests was 2.9 % and the maximum error between the two methods was 10.9 %, which shows the high accuracy of the ultrasonic testing method in determining the specimen's strength. The average probable error of the method is determined to be around 6.8 %.

Based on the results of the average decrease in compressive strength versus the heat exposure time, it is observed that the trend of changes and decrease in resistance over time for both types of tests is almost the same and has a negligible difference. At the end of 180 minutes of exposure, the resistance ratio for the ultrasonic test is 69.8 %, and 71.1 % for the compression machine. Furthermore, according to the average reduction in compressive strength due to heat exposure time, it has been observed that the results of the UT and UM tests have slight numerical differences, however, the trend of changes and reduction in resistance over time for both types of tests is almost the same. Finally, the accuracy of the UT in determining the compressive strength of specimens at high temperatures is fully confirmed.

Keywords: Fibre concrete, high strength concrete, temperature, ultrasonic text.

## 1. Introduction

High temperatures resulting from a fire are considered a serious threat to most buildings, whether steel or concrete. Due to the widespread use of concrete as a building material, it is very necessary to fully investigate the effect of heat on it in order to achieve a safe design [1]. Since human safety against fire is one of the most important considerations in building design, research on the effective factors on the resistance of concrete exposed to high temperatures began in 1920, and since then, much research has been carried out on the resistance of concrete to fire [2]. Many explanations have been proposed for the behaviour of concrete exposed to high temperatures due to differences in three factors, namely, high-temperature conditions, concrete constituents, and laboratory equipment used [3]. Researchers have recognised that many factors affect the actual behaviour of concrete exposed to high temperatures, with the most important being environmental factors, such as heating rate and final temperature, and the constituent materials [4–10].

Extensive research has been carried out on the subject of fire for structures, especially reinforced concrete buildings, and then studies and research on the effects of high temperatures on concrete, as well as the problems and disadvantages of reinforced concrete structures during a fire, which have been carried out so far, were reviewed [11]. Research on the factors affecting the resistance of concrete exposed to high temperatures began in 1920, and since then a great deal of research has been carried out on the resistance of concrete to fire. Many explanations have been proposed for the behaviour of concrete exposed to high temperatures due to differences in three factors, namely, high-temperature conditions, concrete constituents, and laboratory equipment used [12–18]. Zhang's experiments [1] showed that concrete will lose its compressive strength as the temperature increases, but the rate of this reduction in strength is different according to the type of granular materials used in the concrete mixing plant and the density of the hardened concrete. Ramachandran's laboratory studies [19] also concluded that concrete loses some of its compressive strength at a temperature of about 200 to 250 degrees Celsius. As the temperature increases beyond 300 degrees, the concrete starts to crack. In this case, concrete will lose approximately 30 % of its compressive strength, and as the temperature increases, the resistance will continue to decrease. The research of Otieno et al. [20] on the effect of fire on concrete with light aggregate materials showed that in reinforced concrete structures with the possibility of fire, the use of light concrete in covering the members can prevent the phenomenon of thermal bursting and to maintain the members' resistance. Elsalamawy's studies [21] in the field of destructive effects of explosive bursting of the peripheral layer of reinforced concrete members due to fire and considering this phenomenon in safe design conditions show the importance of this discussion. Accuracy in the microtexture of concrete with the help of electro-optic equipment also corroborates this statement. In their research, Wang and Zheng [22] showed that all concrete structures are classified into two categories (in terms of covering) with regard to fire: 1 – non-combustible, 2 – combustible (burnable). In this classification of Sousa coatings, it is the common mode of reinforced concrete structures. But the non-flammable group is based on creating a protective coating layer on the concrete surfaces to dissipate the high temperature resulting from a fire. Several tests were also conducted in the field of protective coatings used as thermal insulation in concrete structures during a fire, which can be referred to in the research conducted by Kong et al. [23].

In this research, high-strength fibre concrete samples were made and then, by controlling the temperature in laboratory furnaces, conditions such as fires of varying durations were simulated. The heated samples were subjected to an ultrasonic test and then re-tested for mechanical properties using the compressive machine. Establishing a meaningful relationship between these two types of tests will help us to make a scientific opinion about the amount of damage and reduction in fire resistance in concrete structures using non-destructive tests.

## 2. Materials and Methods

The main purpose of this article is to do a comparative experimental investigation of the high-temperature effect on fibre concrete and high-strength concrete using UT and CM methods. The routine procedure in all concrete construction projects is to carry out compressive machine tests (CM) for determining the mechanical compressive behaviour of the specimens. Also, if the project is already built and there are uncertainties about the concrete design parameters, the only common way is using destructive methods such as getting sample cores. Therefore, if we are able develop a non-destructive method, which is an ultrasonic test (UT), in this research, all the possible extra costs and damages to structures that come with destructive methods will be eliminated.

A literature dealing with the relation of ultrasonic tests with compressive properties for normal concrete specimens is already available, yet the lack of concise research for other types of concrete mix designs, such as fibre concrete or high-strength concrete mixtures, is needed. In this paper, the relationship between the speed acquired from UT with the compressive strength obtained by CM is determined. The experiments are performed for various temperatures to further help us broaden our knowledge for all concrete infrastructures and ordinary structures affected by the occurrence of fire incidents during their operational life.

| Item | Value |
|---|---|
| Water | $150\,\mathrm{kg{\cdot}m^{-3}}$ |
| Cement | $350\,\mathrm{kg{\cdot}m^{-3}}$ |
| Water/cement ratio | 0.43 |
| Coarse aggregates | $810\,\mathrm{kg{\cdot}m^{-3}}$ |
| Fine aggregates | $990\,\mathrm{kg{\cdot}m^{-3}}$ |
| Fiber (steel/plastic) | 1 % by volume of cement |
| Superplasticizer | 1 liter |

Table 1. Specification of mix design of normal concrete.

| Item | Value |
|---|---|
| Water | $300\,\mathrm{kg{\cdot}m^{-3}}$ |
| Cement | $846\,\mathrm{kg{\cdot}m^{-3}}$ |
| Water/cement ratio | 0.32 |
| Coarse aggregates | $1500\,\mathrm{kg{\cdot}m^{-3}}$ |
| Fine aggregates | $1325\,\mathrm{kg{\cdot}m^{-3}}$ |
| Micro silica | $35\,\mathrm{kg{\cdot}m^{-3}}$ |
| Superplasticizer | 1 liter |

Table 2. Specifications of mix design of high-strength concrete samples.

The concrete samples have been prepared for tests using Portland cement type 2 (based on ASTM C 150 standard) according to ACI 211.1 standard. Two types of tests have been conducted, the compressive strength test with a compression machine and the non-linear ultrasonic (NLU) measurement test.

Table 1 shows the specifications of the sample mix design. It should be noted that the concrete samples are made in two versions: normal concrete with fibre (steel fibre, plastic fibre) and high-strength concrete (Table 2).

Fresh concrete is poured into the mould and cured at room temperature. After opening the moulds, the samples were stored in a chamber with a temperature of 23 degrees Celsius and 95 % humidity to accelerate the hydration process and this process continued until the concrete was 28 days old.

According to the software of the heating furnace, the time-temperature standard curve of ISO 834 was used (Figure 1). After heating the samples to the desired temperature, the samples remained in the closed furnace for three hours until the furnace temperature reached the ambient temperature so that they did not suffer from thermal shock and sudden cracks due to the decrease in temperature.

In this paper, the concrete samples (normal, metal fibres, plastic fibres, high resistance) were kept in humid conditions after being poured into the mould and compacted until reaching the test age. The samples were kept in humid conditions and after 24 hours, they were removed from the moulds and placed in a water tank with a temperature of 20±2 degrees Celsius. Samples were processed according to the ASTM C 192 standard.

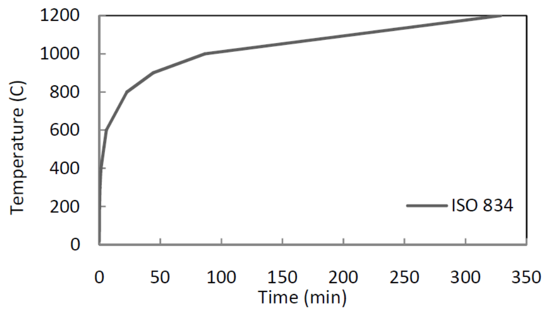


FIGURE 1. Time-temperature curve.

The prepared samples were placed in the furnace at different temperatures and durations. Then, the samples were first subjected to a non-destructive ultrasonic test, and their compressive strength was determined, after which they were subjected to a destructive pressure machine test, and their strength was measured again.

In this study, the compressive strength test based on ASTM C39-86 standard was used. The compressive strength tests have been performed on cube samples. In the compressive strength tests, the cubes were placed in the compression machine in such a way that the two opposite surfaces that were adjacent to the mould during curing were in contact with the upper and lower stirrups of the machine. The loading speed should be in the range of 0.14 to 0.34 MPa per second. In this study, the loading speed was set to 0.25 MPa·s$^{-1}$.

One of the most common methods in the field of quantitative and qualitative assessment of concrete on site is the use of the non-destructive method of ultrasonic waves, which is known as the ultrasonic method. In this experiment, the speed of longitudinal (pressure) waves is determined. This process involves measuring the time required for a pulse to travel a certain distance, the test method is suggested by ASTM C 597-83. Ultrasonic pulse testing has the significant advantage of providing information about the interior of a concrete element, including concrete uniformity. The basis of the device's work is that the electro-acoustic generator, which produces pulses of longitudinal vibrations, is placed on the concrete surface and emits pulses. After the pulse passes a certain length (L) of the concrete, the pulse vibrations are converted into electronic signals by the second generator. The electronic circuit of the device is able to measure the pulse transit time in microseconds (T). In this thesis, the speed of ultrasonic waves was tested by the Pundit device (with a frequency of 54 kHz).

## 3. RESULTS

The results of the compressive strength of concrete samples obtained by two methods, concrete compression machine (CM) and ultrasonic test (UT), have

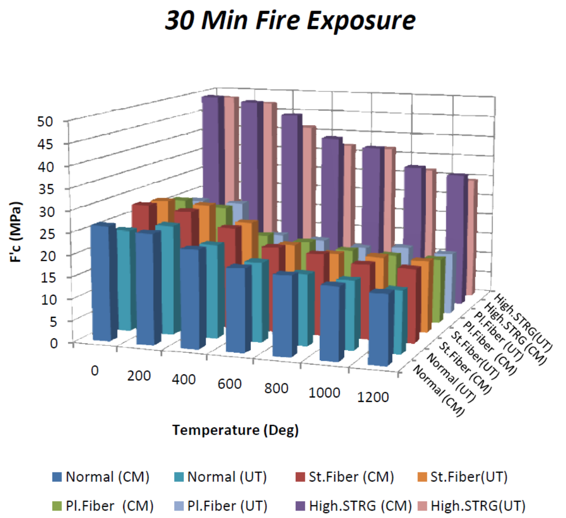


FIGURE 2. Comparing the results of the compression machine test and ultrasonic test for concrete samples exposed to different temperatures for 30 minutes.

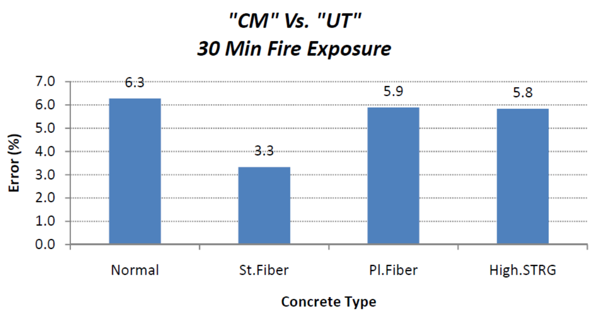


FIGURE 3. Ultrasonic test error for samples exposed to different temperatures for 30 minutes.

been investigated to determine the limits of the difference in the accuracy of the two methods.

Figure 2 shows the comparison of the results of the compression machine test and the ultrasonic test for concrete samples exposed to different temperatures for 30 minutes.

In Figure 3, the average difference between the results of the two methods is presented.

Based on the results of the ultrasonic test error for samples exposed to different temperatures for 30 minutes, it has been observed that a 6.3 % error has been observed for concrete samples with a conventional mix design. The lowest observed error was 3.3 % for the concrete samples with steel fibres, and the highest error was 6.3 % for samples of a conventional mix design. The observed error for high resistance concrete is also determined at about 5.8 %.

Figure 4 shows the comparison of the results of the compression machine test and the ultrasonic test for concrete samples exposed to different temperatures for 45 minutes.

In Figure 5, the average difference between the results of the two methods is presented.

Based on the results of the ultrasonic test error for

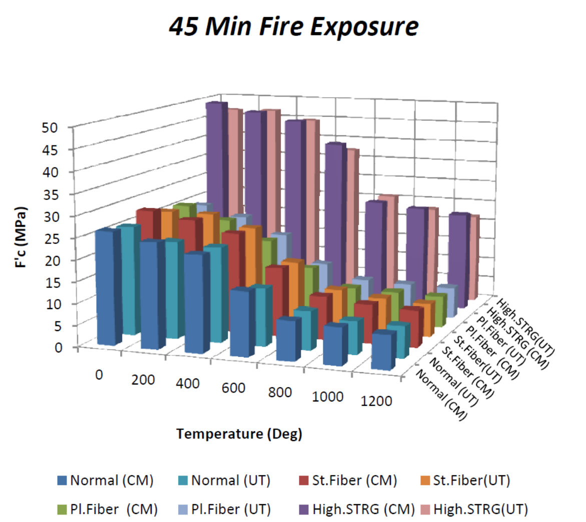


Figure 4. Comparing the results of the compression machine test and ultrasonic test for concrete samples exposed to different temperatures for 45 minutes.

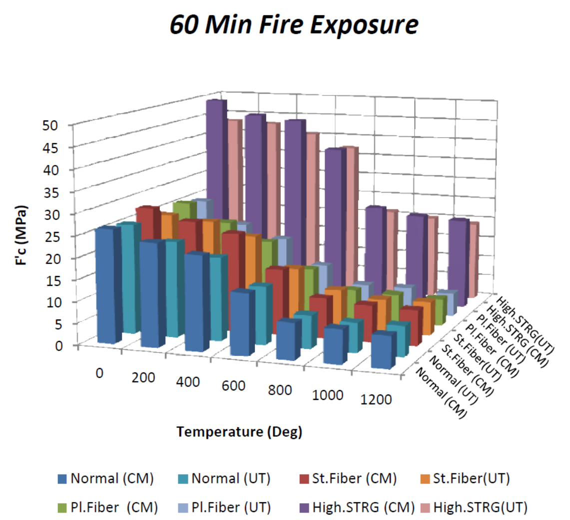


Figure 6. Comparing the results of the compression machine test and ultrasonic test for concrete samples exposed to different temperatures for 60 minutes.

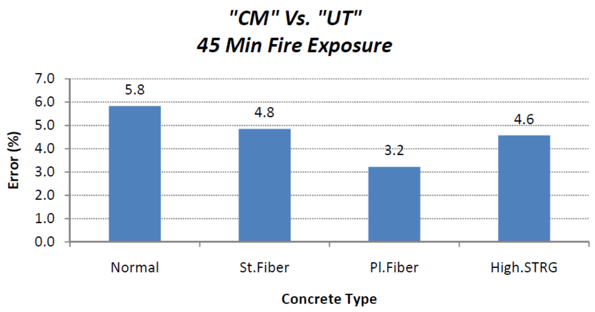


Figure 5. Ultrasonic test error for samples exposed to different temperatures for 45 minutes.

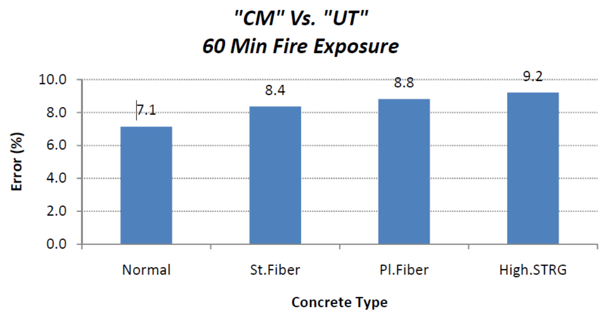


Figure 7. Ultrasonic test error for samples exposed to different temperatures for 60 minutes.

samples exposed to different temperatures for 45 minutes, it has been observed that a 5.8 % error has been observed for concrete samples with a conventional mix design. The lowest observed error was 3.2 % for concrete samples with plastic fibres, and the highest error was 5.8 % for a conventional mix design samples. The observed error for high resistance concrete is also determined, at about 4.6 %.

Figure 6 shows the comparison of the results of the compression machine test and the ultrasonic test for concrete samples exposed to different temperatures for 60 minutes.

In Figure 7, the average difference between the results of the two methods is presented.

Based on the results of the ultrasonic test error for samples exposed to different temperatures for 60 minutes, a 7.1 % error has been observed for concrete samples with a conventional mix design. The lowest error value for the concrete samples with a common mix design was 7.1 % and the highest error for high-strength samples was 9.2 %. The observed error for steel and plastic fibre concretes was 8.4 % and 8.8 %, respectively.

Figure 8 shows the comparison of the results of the compression machine test and the ultrasonic test for concrete samples exposed to different temperatures for 90 minutes.

In Figure 9, the average difference between the results of the two methods is presented.

Based on the results of the ultrasonic test error for the samples exposed to different temperatures for 90 minutes, a 7.7 % error has been observed for the concrete samples with a common mix design. The lowest error value was 2.9 % for high-strength concrete samples and the highest error was 9.3 % for samples with steel fibres. The observed error for the concrete with a common mix design was also determined, at around 7.7 %.

Figure 10 shows the comparison of the results of the compression machine test and the ultrasonic test for concrete samples exposed to different temperatures for 120 minutes.

In Figure 11, the average difference between the results of the two methods is presented.

Based on the results of the ultrasonic test error for samples exposed to different temperatures for 120 minutes, it has been observed that a 7.4 % error has been observed for concrete samples with a common

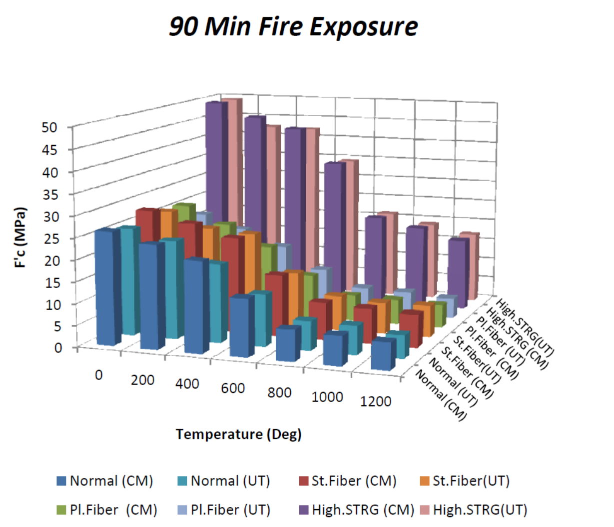


Figure 8. Comparing the results of compression machine test and ultrasonic test for concrete samples exposed to different temperatures for 90 minutes.

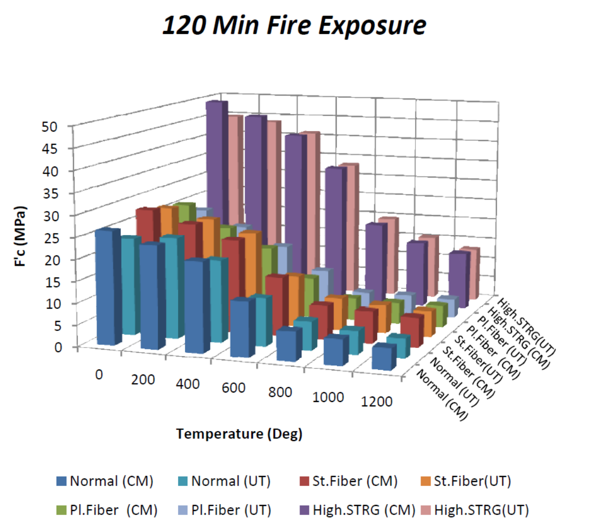


Figure 10. Comparing the results of the compression machine test and ultrasonic test for concrete samples exposed to different temperatures for 120 minutes.

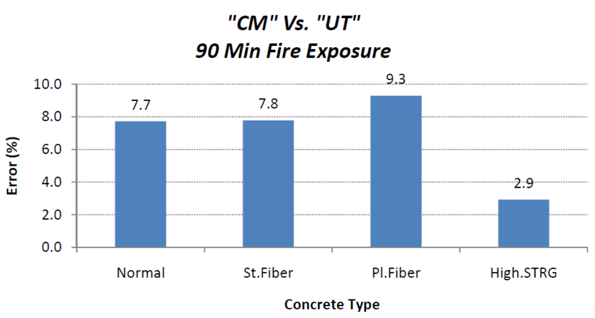


Figure 9. Ultrasonic test error for samples exposed to different temperatures for 60 minutes.

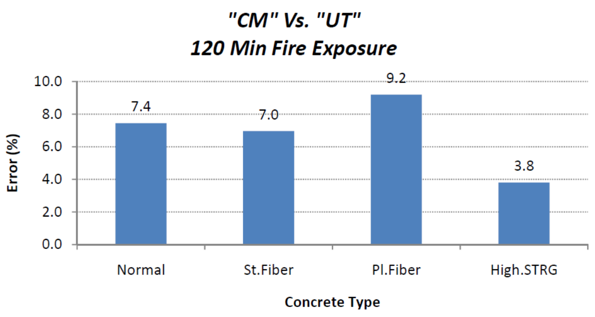


Figure 11. Ultrasonic test error for samples exposed to different temperatures for 120 minutes.

mix design. The lowest error value was 3.8 % for high-strength concrete samples and the highest error was 9.2 % for samples with plastic fibres. The observed error for concrete with a common mix design was also determined, at around 7.4 %.

Figure 12 shows the comparison of the results of the compression machine test and the ultrasonic test for concrete samples exposed to different temperatures for 180 minutes.

In Figure 13, the average difference between the results of the two methods is presented.

Based on the results of the ultrasonic test error for samples exposed to different temperatures for 180 minutes, a 9.2 % error has been observed for concrete samples with a common mix design. The lowest error value was 4.7 % for concrete samples with steel fibres and the highest error was 10.9 % for samples with plastic fibres. The error value for high resistance concrete was also determined, at about 10.3 %.

## 4. Comparison of two compressive test methods

In the following, a summary of the changes and losses of compressive strength over the time of exposure to heat is presented in Figure 14.

Based on the findings and results of the average drop of compressive strength against the heat exposure time, it has been observed that although the results of the compressive strength test based on the compressive machine and the ultrasonic test have slight numerical differences, the trend of changes and reduction in resistance over time for both types of tests is almost the same and has a minimal difference. For example, at the time of 180 minutes of exposure, the resistance ratio for the ultrasonic test was 80.3 %, and 79.1 % for the concrete breaker machine. This is despite the fact that the fracture resistance of the sample was less than 10 % different in the two cases. Therefore, the accuracy of the ultrasonic test in determining the decreasing trend of compressive strength is fully confirmed.

From the results of the compressive strength tests of concrete at different temperatures, we conclude

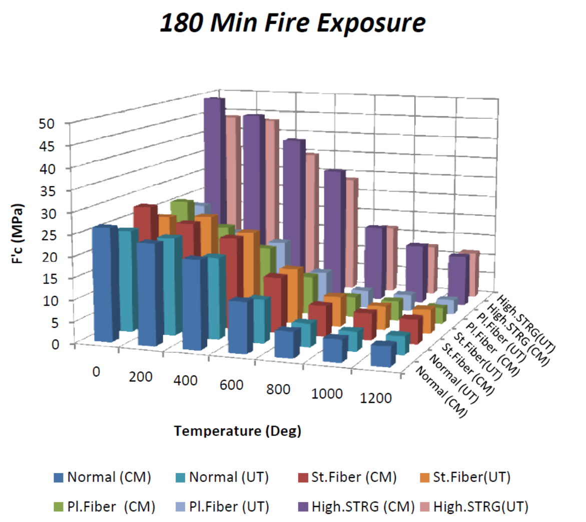


Figure 12. Comparing the results of the compression machine test and ultrasonic test for concrete samples exposed to different temperatures for 180 minutes.

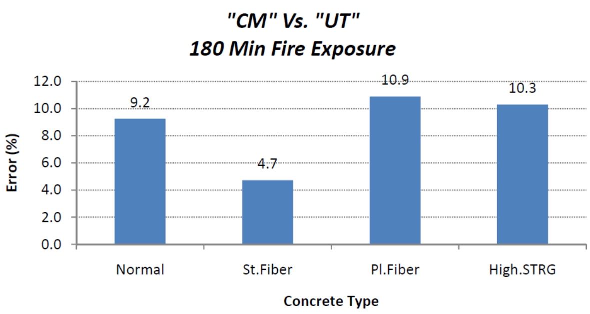


Figure 13. Ultrasonic test error for samples exposed to different temperatures for 180 minutes.

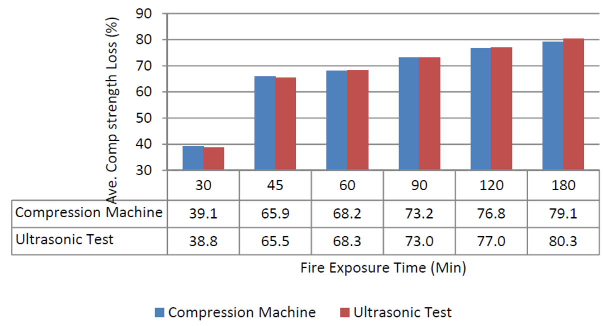


Figure 14. The average drop in compressive strength against heat exposure time.

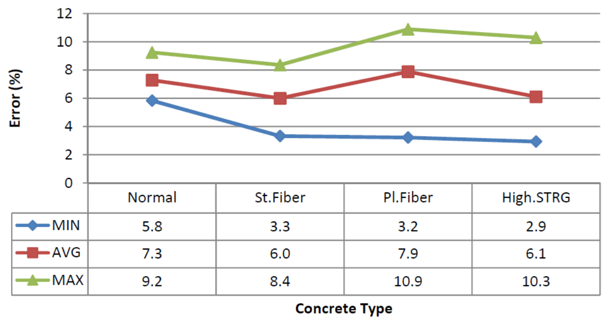


Figure 15. Summary of comparing the results of compressive strength tests of concrete samples with compression machine and ultrasonic test.

that with the increase in temperature, the compressive strength decreases, the reason being that in the range of 100 to 200 degrees Celsius, free water in the concrete starts to evaporate and leads to water vapour pressure, this water vapour pressure creates a network of microcracks inside the concrete, this process then continues in the range of 200–400 degrees Celsius, where the microcracks turn into larger cracks and lead to a decrease in compressive strength Several other factors reducing the strength can be the growth of the structure and the diameter of the pores in the concrete, and the difference in the coefficient of thermal expansion of the components that constitute the concrete (expansion in aggregate and contraction in cement paste) and the non-linear expansion of these components, which causes stress concentration in concrete components.

Finally, the summary of the comparison of the results of compressive strength tests of concrete samples with a compression machine and the ultrasonic test is as follows in Figure 15.

Based on the summary of the comparison of the results of compressive strength tests of concrete samples with the compression machine and ultrasonic test, it has been concluded that the minimum error recorded in the tests was 2.9 % and the maximum error between the two methods was 10.9 %, which shows the high accuracy of the ultrasonic test method in determining the compressive strength of concrete samples exposed to fire. The average probable error of the method is determined to be around 6.8 %. Also, the best performance and lowest error were observed for concrete samples with steel fibres and high strength, and the worst performance and the highest error of the method were observed for concrete samples with plastic fibres (7.9 % error).

The reason for the lower compressive strength of concrete containing plastic fibres as compared to other concretes at normal temperatures is that the use of plastic fibres reduces the compressibility of concrete. This causes weak points in the concrete texture (due to local porosity caused by the penetration of air bubbles) and is the reason why the amount of compressive strength decreases with the presence of plastic fibres.

From the temperature of 400 to 600 degrees Celsius, we can see a noticeable decrease in compressive strength for all samples, which can be because, at the temperature range of 400 to 600 degrees Celsius, the decomposition of cement paste and calcium hydroxide $Ca(OH)_2$ in concrete takes place as a result of this porosity reaction. The cement matrix increases and the mechanical properties of concrete, including strength and hardness, decrease. This range can be considered as the critical temperature range for resistance reduction.

Also, the greater decrease in strength in the concrete containing plastic fibres is caused, in addition to the reasons mentioned so far, which also occur in concrete containing plastic fibres, by the fact that plastic fibres start to melt in the temperature range of 160 to 180 degrees Celsius and cause voids. Additional particles are inside the concrete, which causes a greater decrease in the compressive strength of concrete containing plastic fibres at high temperatures as compared to concrete without plastic fibres. This issue was also present for concrete with steel fibres at temperatures higher than 800 degrees.

## 5. Conclusions

To investigate the effect of temperature increase on the compressive strength of concrete, concrete samples were subjected to temperature increase. Temperature changes include 200, 400, 600, 800, 1000, and 1200 degrees Celsius. Each compressive strength test result is the average result of three samples. The results obtained from the compressive resistance test against temperature increase were obtained for all four mixtures at the age of 28 days. The most important results and findings of this part of the research are as follows:

- Based on the summary of the comparison of the compressive strength test results of concrete samples by compression machine and ultrasonic test, it has been observed that the minimum error recorded in the tests was 2.9 % and the maximum error between the two methods was 10.9 %, which shows the high accuracy of the ultrasonic test method in determining the compressive strength of concrete samples exposed to fire. The average probable error of the method was found to be about 6.8 %. Also, the best performance and lowest error were observed for concrete samples with steel fibres and high strength, and the accuracy of the method for concrete samples with plastic fibres had the worst performance (7.9 % error).
- Based on the findings and results of the average decrease in compressive strength against the time of exposure to heat, it has been observed that although the results of the compressive strength test based on the compressive machine and the ultrasonic test have slight numerical differences, the trend of changes and reduction in resistance in the amount of time for both types of tests is almost the same and has a minimal difference. For example, at the time of 180 minutes of exposure, the resistance ratio for the ultrasonic test was 80.3 %, and 79.1 % for the compressive machine. This is despite the fact that the fracture resistance of the sample was less than 10 % different in the two cases. Therefore, the accuracy of the ultrasonic test in determining the decreasing trend of compressive strength is fully confirmed.
- Based on the findings and results of the average decrease in compressive strength against the heat exposure time, it has been observed that although the results of the compressive strength test based on the compressive machine and the ultrasonic test have slight numerical differences, the trend of changes and reduction of resistance against the time for both types of tests is almost the same and has a minimal difference. For example, at the time of 180 minutes of exposure, the resistance ratio for the ultrasonic test was 69.8 %, and 71.1 % for the compressive machine. This is despite the fact that the fracture resistance of the sample was less than 6.2 % different in the case of the maximum possible error for the two cases. Therefore, the accuracy of the ultrasonic test in determining the decreasing trend of compressive strength is fully confirmed.

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