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The Effect of High Temperatures on the Compressive Strength of Fly Ash Pozzolanic Concrete

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Abstract.
The mechanical property of compressive strength in concrete is an essential factor that is indicative of structural stability, which cannot be denied. Recently, the utilization of pozzolanic material, namely fly ash, has attracted considerable attention due to its numerous advantages in tackling environmental and economic phenomena. Consequently, the implementation of this approach has the potential to reduce CO_2 emissions and conserve raw materials for sustainable construction. The goal of this study is to find out how replacement different amounts of fly ash to cement (0%, 20%, and 30%) affects the compressive strength of concrete when it is heated to high temperatures (20°C, 200 °C, 400 °C, 600 °C, 800 °C and 1200°C). The present investigation employed non-destructive compressive strength tests using Schmidt's hammer and direct compressive strength. The specimens were designed to detect compressive strength under different degrees of temperature with a constant water-bender ratio of W/B = 0.452. The study involved a total of 63 concrete cubes, each with dimensions of 150 * 150* 150 mm, divided into different categories. The average compressive strength of three cubes at each temperature level has been measured after 28 days of concrete casting. The results exhibited a significant increase

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in compressive strength with the addition of fly ash up to 400 °C, accompanied by cracks. This indicates an increase in the durability of construction exposed to high temperatures.

Key words: High temperature, Fly ash, Compressive strength, Concrete.

تأثير درجات الحرارة المرتفعة على قوة الضغط للخرسانة البوزولانية ذات الرماد المتطاير

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الملخص.

تعتبر خاصية مقاومة الخرسانة للضغط من الخواص الميكانيكية التي تدل على استقرارية المنشآت. وفي الآونة الأخيرة، تم استخدام المواد البوزولانية والتي منها الرماد المتطاير، اهتماماً كبيراً لما له العديد من المميزات في معالجة المشاكل البيئية والاقتصادية نتيجةً لتقليل كميات الاسمنت المستخدم في الخرسانة. إن عملية إحلال الاسمنت بمواد بوزولانية في صناعة الخرسانة يقلل بشكل ملحوظ من انبعاثات ثاني أكسيد الكربون أثناء عملية صناعة الاسمنت ويحقق التنمية المستدامة من خلال المحافظة على المواد الخام الموجودة في الطبيعة. إن الهدف من هذه الدراسة هو معرفة مدى تأثير إضافة كميات مختلفة من الرماد المتطاير إلى الاسمنت كنسب احلال بنسب وزنية (0%، 20%، و30%) ودراسة تأثيرها على مقاومة الضغط للخرسانة عند تعرضها إلى درجات حرارة مختلفة تتراوح (من 20 إلى 1200 درجة مئوية). حيث تم اجراء في هذا البحث اختبار مقاومة الضغط للخرسانة بطريقة غير إتلافيه باستخدام اختبار الموجات فوق الصوتية والذي يعتمد على تحديد سرعة انتشار الموجة ومقارنتها مع مقاومة الضغط المباشر. تم تصميم العينات لتحديد قوة الانضغاط تحت معدلات مختلفة من درجات الحرارة مع نسبة الماء للمادة الرابطة W/B = 0.452. حيث شملت الدراسة 63 مكعبًا خرسانيًا، أبعاد كل منها 150*150*150 ملم، مقسمة إلى فئات مختلفة. تم قياس متوسط قوة الضغط لثلاثة

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مكعبات عند كل مستوى درجة حرارة بعد 28 يوما من صب الخرسانة. أظهرت النتائج زيادة ملحوظة في مقاومة الضغط مع إضافة الرماد المتطاير حتى 400 درجة مئوية، مصحوبة بتشققات. وهذا يدل على زيادة متانة المنشأ المعرض لدرجات الحرارة المرتفعة.

الكلمات المفتاحية: ارتفاع درجة الحرارة، الرماد المتطاير، مقاومة الضغط، الخرسانة.

1. Introduction

High temperatures in fire construction are one of the most extreme conditions that cementitious composites may encounter during their service life [1][2]. Fire may also contribute to the deterioration of the bearing capacity of concrete structures, hence causing substantial hazards to both human lives and assets [3]. Portland cement is widely utilized as a primary material in the construction industry. Despite the fact that the manufacturing process of Portland cement is responsible for generating approximately 5-7% of the overall carbon dioxide emissions[4][5]. Fly ash is considered one of the most important energy wastes that effect on the environment. The utilization of fly ash in concrete elements has the potential to reduce energy consumption and decrease CO_2 emissions in the manufacturing process [6]. It can be obtained from the combustion of both hard coal and lignite as well as by co-combustion of these materials with biomass, which, due to increasing restrictions related to the emission of carbon dioxide into the atmosphere, will increase its share in fly ash production [7][8][9]. The basic component of fly ash is glass, similar to glass silica and alumina silicate glass. Active SiO_2 content determines the pozzolanic activity of the ash and its ability to bind in the environment of wet calcium hydroxide to form phases with binding properties [10][11]. According to previous research, the additive material in the concrete network structure exhibits a significant transformation within the temperature ranging from 600 to 800 °C. This alteration involves the total removal of water and the crystallization of stages, resulting in a simultaneous drop in strength, as documented in previous studies [12][13]. Numerous tests have been conducted to assess the potential of combining fly ash in construction applications and investigate its

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mechanical characteristics. However, the current study gap relates to the correlation between compressive strength and thermal properties, resulting in a highly interesting area for further investigation. Therefore, the investigation of the impact of high temperatures on building construction, particularly in relation to waste materials, is of significant importance in preserving structural integrity.

2. Experimental Program

2.1Material Properties

The tests carried out were aimed at demonstrating the effect of the mineral supplement, which is fly ash, on the quality and strength of concrete that has been exposed to high temperatures between 20 °C and 1200 °C. They included sclerometric examinations, performed with a hammer by Schmidt, ultrasonic tests made using a concrete scope and tests devastating in compression. The experiments were carried out on cubic concrete samples with a side of 150 mm, for which Portland cement, gravel aggregate with a size range of 2–8 mm, and fly ash were produced in a combined heat and power plant. The cement used in this study is cement type I (44 N) with a specific gravity of 3.15. The coarse and fine aggregates were sieved according to BS 812-1992 [14], as shown in Figure 1 and Figure 2, respectively, and the specific gravity was 2.68.

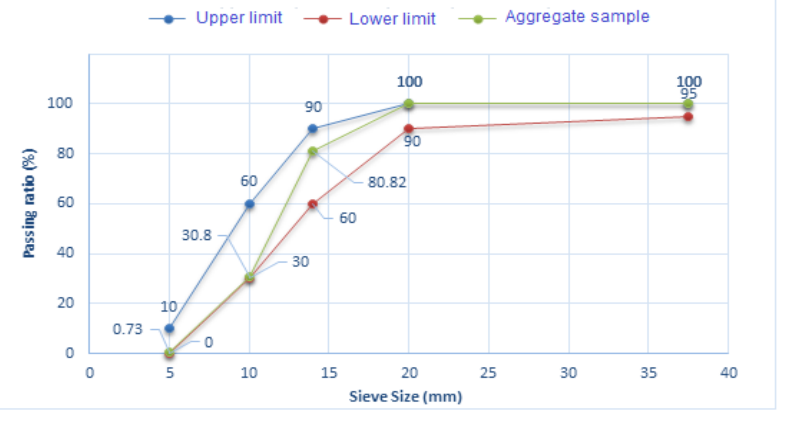

Figure 1. Sieve analysis of coarse aggregate

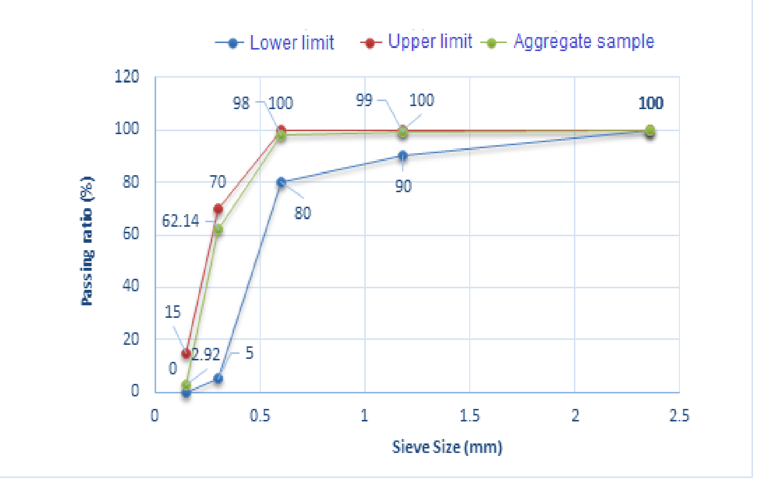

Figure 2. Sieve analysis of fine aggregate

2.2Sample Preparation

Three different concrete mixes were prepared, namely mixture I, mixture II, and mixture III, differing in percentage of ash additive as a partially replacement cement (0%, 20%, and 30%, respectively). The exact composition of the individual mixtures has been determined as presented in Table 1. Each type of mix consisted of three identical categories with a volume of 0.071 m^3.

Table1. Concrete mix design

Concrete Components	Mix I	Mix II	Mix III
	1 m^3 (Kg/m^3)	1m^3 (Kg/m^3)	1m^3 (Kg/m^3)
Cement	353.5	282.8	246.7
Fly ash	0.0	70.7	106.05
Water	160	160.0	160.0
Sand	680	680.0	680.0
Gravel	1206.7	1206.7	1206.7
Plasticizer	4	5.3	5.3

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After the mixture was prepared, it was placed in molds with dimensions of 150x150x150 mm, as shown in Figure 3. Then it was compacted on a vibrating table. From any type of mix, 63 identical samples were made of concrete. Thus, the series was created in concretes I, II and III. The samples prepared in this way were moistened and left in the mold to prevent them from drying. After 24 hours of casting samples as displayed in Figure 4, they were placed in a tap of water, where they cured for 14 days. For the next 14 days, samples cured in an environment with a humidity level of about 90%.

Figure 3. Casting cubes of different concrete mixtures

Figure 4. Samples before being subjected to high temperature

2.3 Exposing Samples to High Temperature

Annealing of concrete samples was carried out using a PKTS-type furnace (3/1200) with a power of 100 KW. The maximum temperature that can be reached is 1200 °C. The tests were carried out on 54 samples that were subjected to temperatures of 200 °C, 400 °C, 600 °C, 800°C, 1000 °C, and 1200°C. The heating of concrete was carried out at a constant rate of 0.5 °C per minute. After reaching the intended temperature in the furnace, it was held constant horizontally for the next 2 hours to obtain an even temperature distribution inside the entire volume of the sample. For temperatures

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of 200 °C, 400 °C, and 600 °C, the cooling process exposing samples was carried out automatically outside the furnace, as illustrated in Figure 5.

Figure 5.Process of cooling concrete samples

On the other hand, samples were annealed at temperatures of 800 °C, 1000 °C, and 1200 °C for the first few hours after the end of the process. The anneals remained in the furnace. The tests took place 24 hours after completion, exposing samples to high temperatures. For comparison, experiments were also performed on samples that were not subjected to high temperatures. The temperature was controlled by thermometer at 20 °C.

2.4 Sclerometer Test

The sclerometric method is an indirect method of testing concrete strength; for this purpose, it uses the value of the near-surface hardness of the material. It is based on the energy difference before and after the impact of a standardized movable hammer on the concrete surface. The measured value is the reflection number L, read from the scale of the hammer. Hardness measurement also allows test measurements in terms of the homogeneity of the material [15]. The DIGI-SCHMIDT 2000 Type N hammer was used for the tests shown in Figure 6. Diagnostics for using this type of device start with a thorough cleaning of the test piece surface from any impurities, dust, detached fragments of the tested material, and possible surface grinding

Figure 6.Schmidt's hammer for Sclerometric examinations

The test conducted according to BS-EN: 13791,[16] which can obtain compressive strength according to reflection L, can be formulated as follows:

$$fc' = 1.25\,L - 23 \qquad if\ 20 \le L \le 24 \qquad (1)$$

$$fc' = 1.73\,L - 34.5 \qquad if\ 24 \le L \le 50 \qquad (2)$$

$$L = L\alpha + \Delta L \qquad (3)$$

Where:
L: Reading obtained from Schmidt hammer
fc′: Compressive strength (N/mm^2)
Lα
: reading when the hammer is titled an angle α to the horizontal
ΔL : reading correction as shown in Table2

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Table 2. Approximate values of correction of non-horizontal position [16]

The No. of Reflection	Hitting Up		Hitting Down	
	ΔL=+90^0	ΔL=+45^0	ΔL=-45^0	ΔL=-90^0
20	-5.1	-3.5	+2.5	+3.4
30	-4.7	-3.1	+2.3	+3.1
40	-3.9	-2.6	+2.0	+2.7
50	-3.1	-2.1	+1.6	+2.2
60	-2.4	-1.6	+1.3	+1.7

Figure7 shows the method of taking measurements with Schmidt's hammer on the concrete samples, where the test is done vertically with correction of values due to non-horizontal position depending on reflection, which can be translated into reading in Schmidt's hammer [17]. This can be used to determine the compressive strength of a concrete cube, as explained in equations 1 and 2, based on reflection.

Figure 7. Schmidt's hammer measurement on concrete specimen

2.5 Ultrasonic Test

One of the non-destructive techniques for evaluating the quality of concrete is a measurement-based technique that uses ultrasonic wave propagation in the material that is bound directly with its modulus of elasticity and compressive strength. Ultrasonic methods belong to the acoustic category. In material concrete research, waves in the range of vibration frequencies from about 30 kHz to about 500 kHz are used. The test setting is illustrated in Figure 8.

Figure 8. Test setting and measurements of ultrasonic waves

Obstacles in the path of an ultrasonic wave that propagates in a solid can cause the reflection of different types of waves. The test applied according to BS-EN: 13791 [16], which can employ the speed wave to obtain the compressive strength, has the following formula:

$$V = \frac{L}{T} \dots \dots \dots \dots (Km/Sec) \qquad (4)$$

Where:

V: ultrasonic wave propagation speed (Km/sec)

L: path of the ultrasonic pulse at the measurement point (mm)

T: transit time of the ultrasonic pulse at the measurement site (μs)

The quality of the concrete can be estimated from the result of the measurement made using a concrete scope according to the assumptions contained in Table 3.

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Table 3.Classifications of concrete quality based on the speed of ultrasonic wave propagation [18]

Ultrasonic wave speed (Km/sec)	Concrete quality
>4.5	Very Good
3.5-4.5	Good
3.0-3.5	Questionable
2.0-3.0	Poor
<2.0	Very Poor

From calculating the average wave propagation speed, the compressive strength can be calculated, as displayed in the following formula:

$$fc^{\backslash} = 62.5\ V^2 - 497.5V + 990 \quad (5)$$

2.6 Axial Compression Test

After performing sclerometer and ultrasonic tests, the samples were subjected to compression and they were loaded to failure for the determination of their actual compressive strength. Therefore, it is a destructive test, which can demolish the samples after testing. The samples conform to specification BS-EN: 196-1[16] with a loading rate of 0.5 N/sec, as illustrated in Figure 9. The samples that were exposed to axial compressive strength are shown in Figure 10.

Figure 9.Compressive strength test

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Figure 10. Images of failure under the influence of axial compression of the tested samples

3. Results and discussions

In the tests carried out, the influence of high temperatures on quality and the residual strength of concrete was observed. Figure 11 shows the course of changes in the average value of the measured reflection number, and in Figure 11 and Table 4, the average compressive strength calculated on its basis.

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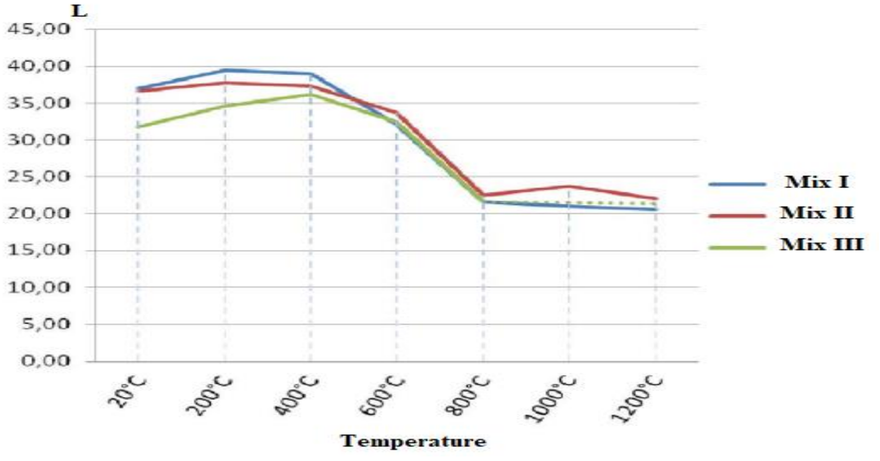

Figure 11.The average value of the reflection number

Table 4. The average value of the reflection number

Temperature (C ˚)	The reflection number		
	Mix I	Mix II	Mix III
20˚	36.5	36	31.7
200˚	39.4	37.6	35
400˚	39	36.9	36.2
600˚	32.6	33.7	32.5
800˚	21.7	22.4	21.8
1000˚	21.2	23.6	21.8
1200˚	20.6	22.3	21.9

As illustrated in Figure 12 and Table 5, the variability of the average propagation velocity as a function of temperature of the ultrasonic wave in the tested samples only in the study of sclerometric, the number of tested samples, and the relationship statistical values included to determine the residual strength compression of the tested concretes based on the ultrasonic method. The method of determining the f'_c in Figure 13 and Table 6, the value proposed in the standard has validity for use in temperatures between 20°C and

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200 °C, and the ultrasonic wave propagation velocities were within the requirements for the application of this method.

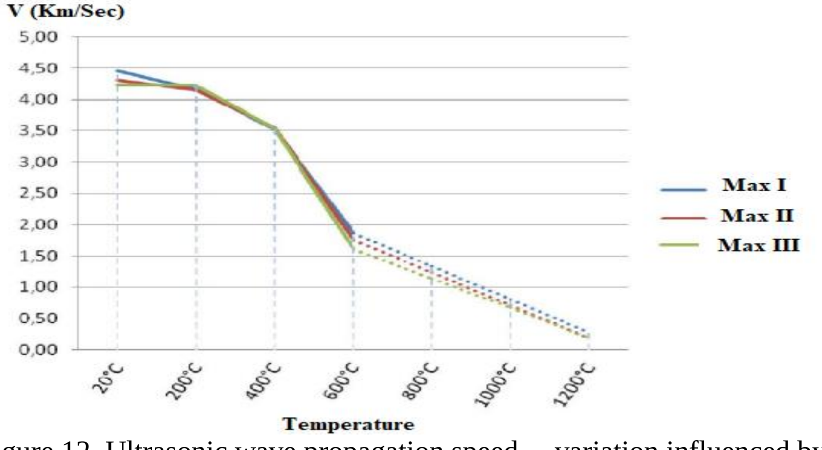

Figure 12. Ultrasonic wave propagation speed variation influenced by temperature.

Table 5. The comparison of ultrasonic wave propagation speed variation influenced by temperature.

	Ultrasonic wave propagation speed (Km/sec)		
Temperature (C ˚)	Mix I	Mix II	Mix III
20˚	4.45	4.32	4.28
200˚	4.23	4.16	4.19
400˚	3.52	3.54	3.51
600˚	1.88	1.73	1.64
800˚	1.35	1.26	1.18
1000˚	0.78	0.69	0.63
1200˚	0.41	0.32	0.33

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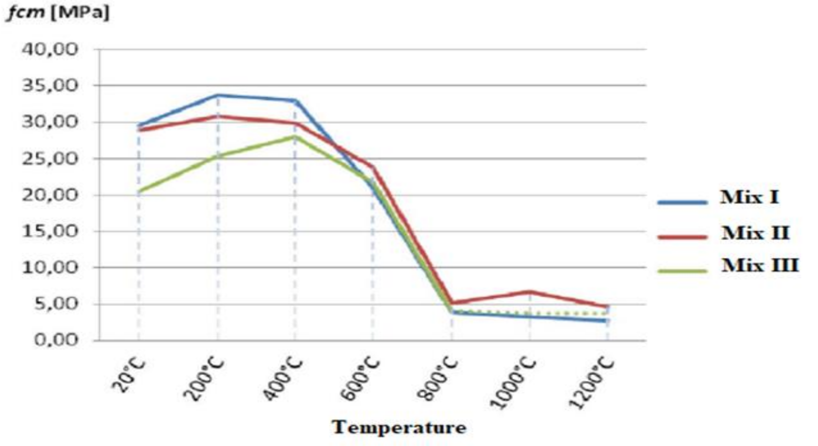

Figure 13. Average compressive strength based on sclerometer test.

Table 6. The values of the average compressive strength based on sclerometer test.

	Average compressive strength fcm(MPa)		
Temperature (C ˚)	Mix I	Mix II	Mix III
20˚	29.6	29.4	21.1
200˚	33.4	30.9	25.2
400˚	32.8	30.1	28.6
600˚	21.6	23.7	22.4
800˚	3.83	5.08	3.65
1000˚	3.15	6.71	3.25
1200˚	2.53	4.92	2.85

Tests with the use of a Schmidt hammer, based on the measurement of hardness close to the surface material, showed that at approximately 400 °C, the influence of high temperature increases the compressive strength of concrete. After exceeding this limit, the strength value drops sharply. In addition, the study shows that the addition of fly ash in this temperature range has a positive effect on concrete strength. The average change in strength from the initial

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value is illustrated in Figure 14 and Table 7.On the other hand, Figure 15 and Table 8 shows the dependence of the actual compressive strength of the samples compared to the processing temperature.

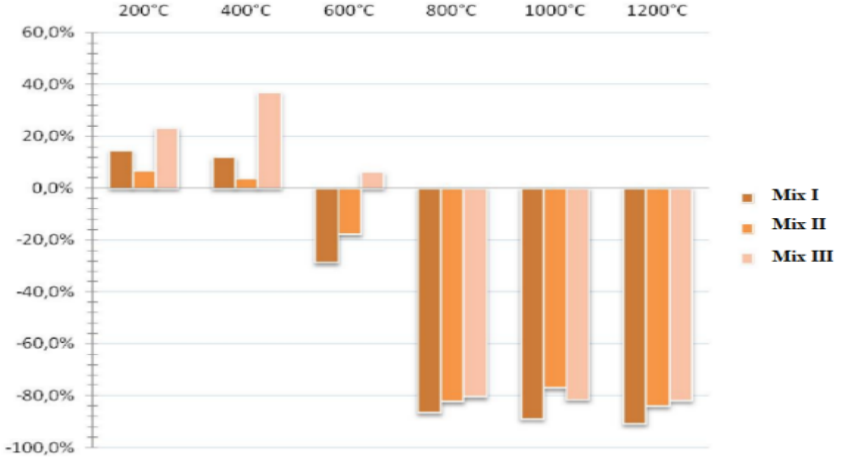

Figure14. Sclerometer examination reveals strength change percentage.

Table 7. The comparison of percentages of Sclerometer examination

	Strength change percentage		
Temperature (C ˚)	Mix I	Mix II	Mix III
200˚	14%	7%	23%
400˚	12%	3%	36%
600˚	-28%	-18%	6%
800˚	-88%	-83%	-80%
1000˚	-90%	-76%	-82%
1200˚	-93%	-82%	-81%

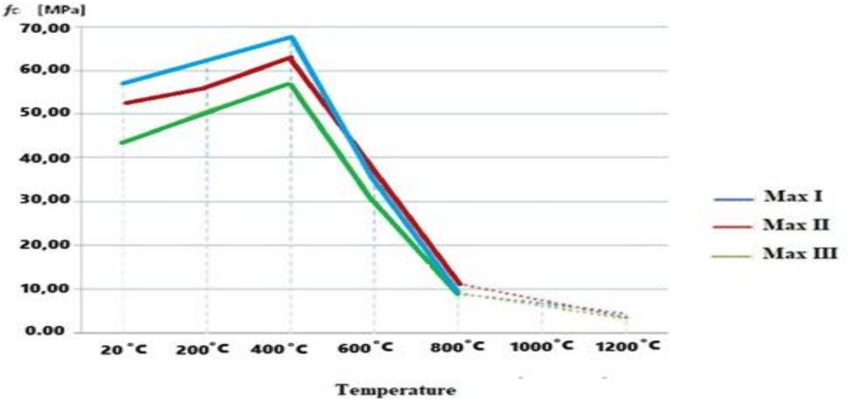

Figure 15. Compressive strength determined during destructive tests

Table 8. Values of compressive strength determined during destructive tests

	Strength change percentage		
Temperature (C ˚)	Mix I	Mix II	Mix III
200˚	14%	7%	23%
400˚	12%	3%	36%
600˚	-28%	-18%	6%
800˚	-88%	-83%	-80%
1000˚	-90%	-76%	-82%
1200˚	-93%	-82%	-81%

The high temperature to which the tested samples were subjected has a very large impact on the change in the basic properties of the material, which is concrete, as displayed in Figure 16. And Table 9. It can be noticed that such action significantly affects the damage to the internal structure of the concrete.

The gradual reduction of the compressive strength is mainly due to the progressive dehydration of the CSH phase and the decomposition of Portland cement as a result of the destruction of the contact zone between grout and aggregate due to opposite thermal deformations. Mineral additives in the form of fly ash reduce the strength of concrete under normal conditions, while from the perspective of the possibility of high temperatures,

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depending on the percentage of the additive, they significantly affect the improvement in quality and durability

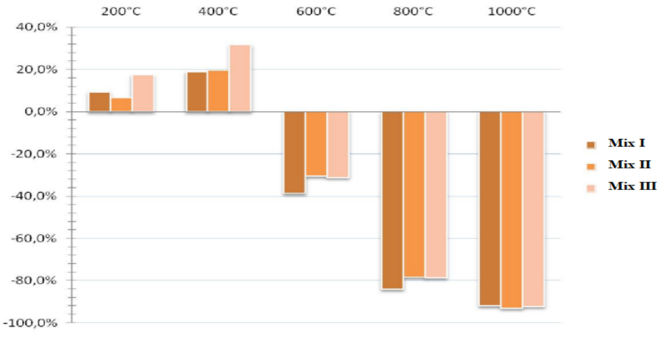

Figure 16. Percentage change of sample strength based on destructive testing

Table 9.Values of percentage change of sample strength based on destructive testing

	Percentage change of sample strength (%)		
Temperature (C ̊)	Mix I	Mix II	Mix III
200˚	9%	6%	16%
400˚	18%	19%	31%
600˚	-39%	-32%	-34%
800˚	-85%	-77%	-79%
1000˚	-92%	-94%	-92%

.4. Conclusions

In conclusion, the impact of incorporating fly ash as a partial replacement to cement on the properties of concrete, specifically in relation to its response to varying temperature conditions, can be briefly expressed as follows:

- Concrete without the addition of fly ash at a temperature of 20 °C exhibits a higher compressive strength when compared to mixtures containing 20% and 30% fly ash. However, the

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presence of fly ash could improve the long-term tests such as durability of the constructed environment.

- The compressive strength of all mixtures exhibited enhancement as temperatures escalated, reaching its maximum at 400°C. Subsequently, a notable decline in strength was observed with further increases in temperature.
- An agreement exists among various methodologies for estimating concrete strength, encompassing both destructive and non-destructive approaches. This agreement holds significance for the estimation of in situ compressive strength.
- A higher wave speed is indicative of elevated porosity, which exerts a substantial impact on the compressive strength.

5. Recommendations for Future Studies

Based on the conducted experiments, it is advisable to further expand the scope of the study by directing attention towards the following aspects:

- It is advisable to prioritize the examination of the freezing of concrete incorporating fly ash in order to safeguard its structural integrity over time.
- The investigation of the microstructure of additives through the utilization of X-ray diffraction (XRD) and scanning electron microscopy (SEM) due to exposure to high temperatures could have significant impacts on the structural behavior through the utilization of X-ray diffraction (XRD) and scanning electron microscopy (SEM).
- It is recommended to conduct a comprehensive examination of the mechanical properties of concrete under controlled temperature conditions by using fly ash as a geopolymer concrete and a convenient alkali activator and detecting the high temperature in its mixing design.

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