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Physico-mechanical Behaviors and Durability of Heated Fiber Concrete

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Abstract

The objective of the present manuscript is to describe the impact of polypropylene fibers on the behavior of heated concrete subjected to heating and cooling cycles at temperatures of 200, 450 and 600 °C respectively for six hours, through a series of experimental tests on mass loss, water absorption, porosity, compressive and tensile strength. For this purpose, mixes were prepared with a water/cement ratio with the incorporation of polypropylene fibers with a rate varying from 0.5 to 1.5%. These fibers were added in order to improve the thermal stability and to prevent the concrete from splitting. The results show that a considerable loss of strength was noticed for all tested specimens. The relative compressive strengths of the concretes containing polypropylene fibers were higher than those of the concretes without fibers. Also, a greater loss of mass of the polypropylene fibers compared to those without fibers was noticed when increasing the temperature. The flexural tensile strength of the concrete was more sensitive to elevated temperatures than the compressive strength and a rapid increase in porosity was observed for the fiber-reinforced concrete compared to the reference concrete. Furthermore, water absorption by the fibers is proportional to the fiber content of the concrete.

Keywords: Concrete; Temperature; Polypropylene Fibers; Mechanical Properties; Physical Properties; Heating-Cooling.

1. Introduction

Despite the fact that concrete has a good behavior at ambient temperature, this is not true under fire conditions, as it can exhibit thermal instability which may occur in several forms. Through the outcomes of this research make it possible to explain the observed phenomena on the behavior of concrete at high temperature. The introduction of polypropylene fibers into the concrete composition has been proved to be an effective technique to overcome the risk of thermal instability and possible bursting perils. Several researchers had carried out full experimental studies on the mechanical behavior of concrete and fibrous concrete subjected to high temperatures, particularly in terms of porosity, mass loss, compression resistance, ultrasonic tests and tensile strength. As far as porosity is concerned, authors Kalifa et al. [1] quantified the effect of polypropylene fibers on the behavior of concrete at high temperatures to determine how the fibers contribute to the creation of a network that is much more permeable than the ordinary matrix [2, 3]. Have experimentally studied the effect of polypropylene and metallic fibers on the behavior of concrete subjected to

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high temperature and have resulted in the formulation of improved concretes with high temperature stability and mechanical behavior after cooling, [4, 5] have shown an increase in temperature either for ordinary concrete or high-performance concrete with or without fibers. Mindeguia [2] confirms that low fiber-free concrete damages are more than high concrete. On the other hand, [6, 7] found that in the presence of fibers an additional porosity occurs and increases with the fiber dosage.

Regarding the mass loss, Xiao & Falkner and Phan et al. (2001) [8, 9] notice that the mass loss takes place in three steps. While, in the other hand a small loss of mass from the free water contained in the concrete and from the ambient temperature at 150°C. then A more rapid increase in fiber-free concrete heated up to 300°Chas been reported by Malier (1992) and Noumowe (1995) [10, 11] which is due to the departure of water bound in hydrates essentially from C-S-H gel. Hager (2004) and Noumowe (1995) [7, 11] conclude that the drying rate passes through a maximum which corresponds to the end of evaporative water migration process. Hager (2004) and Khoury and Willoughby (2008) [7, 12] note that beyond 300°C, the rate of mass loss decreases which continues due to the dihydroxylation of the portlandite as well as the decarbonation of the calcium carbonate. In addition, Hager (2004), and Xiao & Falkner (2006) [7, 8] conclude that the addition of polypropylene fibers to concrete does not change the evolution of mass loss process as a function of temperature either during heating or after cooling. According to Phan (2003) [13] the effect of high temperatures on the compressive strength of fiber-free concrete is marked by an increase in its compressive strength, because with heating beyond 200°C, the liquid water converts to steam and the improvement in compressive strength is essentially due to the departure of this water which leads to a re-augmentation of the forces of attractions and reconciliation of hydrated calcium silicate sheets. This strength drops off significantly with a temperature of 600°C as reported by Xiao & Falkner (2001) and Behnood & Ghandehari (2009) [8, 14] which may be explain by the fact that the partial or total melting of polypropylene fibers creating channels within the cement matrix. It is worth to note that the evolution of the compressive strength of ordinary concrete is similar to that of fiber concrete but with lower values. Toumi (2010) and Laneyrie (2014) [15, 16] noted that the cracking density of the heated concrete increases with heating temperature which reflects the decrease in the propagation speed with the temperature rise.

Finally, several researchers namely: Chen and Liu (2004) [17] note a decrease in tensile strength under the influence of temperature. Suhaendi & Horiguchi (2006) and Aydın et al. (2008) [18, 19] found that melting and vaporization of the fibrous components are responsible for the reduction of the residual properties of high strength polypropylene fiber reinforced concrete. Harada et al. (1972) [20] have noted that the decrease in tensile strength is very noticeable compared to the compressive strength. A test program to study the on the normalized residual tensile strength was conducted by Chang et al. (2006) [21] show a decrease in tensile strength with temperature for temperatures higher than 400°C. Relatively, Suhaendi & Horiguchi (2006) [18] noted that the results of the tests for a fiber-free concrete lead to a lower tensile strength loss than that of fiber-free concrete. Also, Khoury and Willoughby [12] prove that the addition of polypropylene fibers in concrete under high temperatures reduces the probability of risk of bursting.

Through a thermo gravimetric analysis Ríos et al. (2018) [22] show that the time of exposition of the samples to high temperatures has no influence on the mechanical properties once the thermal and humidity equilibrium are reached. Thanaraj et al. (2019) [23] studied the effect of elevated temperature on the compressive and flexural behavior of specimens by varying cement strength classes. The effects of concrete age, mass loss, surface characteristics and thermal crack model were also studied. The results confirm that strength class, time exposed and age of concrete are the key parameters affecting the residual strength of concrete. Thanaraj et al. (2019) [24] examined the mechanical properties of concrete subjected to elevated temperatures and found that the water/cement ratio and the porosity of concrete are critical factors in the strength loss of concrete. Also the higher quality concretes show a greater loss of mass and strength than the lower quality ones. In order to compare the effect of fire with that of exposure of normal strength concrete to predetermined temperatures. Suresh and Sachin (2020) [25] observed that specimens exposed to fire had lower residual compressive and tensile strength and higher porosity than specimens heated in an electric furnace at the same temperature. Mathews et al. (2021) [26] carried out an experimental study to observe the effect of elevated temperature on the durability characteristics of ordinary concrete. They found that as the strength of the concrete increased, the mechanical and durability characteristics improved for unheated specimens. However, in the case of heated specimens, a significant decrease in mechanical performance was observed.

This study focuses on the effect of the inclusion of polypropylene fibers in improving the mechanical performance of the concrete and preventing its spalling. Since the heating rate and experimental conditions are not identical. The authors differ on the analysis of the mechanical properties of concrete heated with polypropylene fibers. For this purpose, the present study was carried out by varying several parameters such as temperature (T°c), fiber content (%) keeping constant the ratio (water/cement) and the heating cycle time (t) which represents the novelty of the present study.

2. Experimental Procedure

In the following, some details will be given on the set-up, materials properties, and the process of testing. Flow chart of the present research and characterization methodology is illustrated in Figure 1.

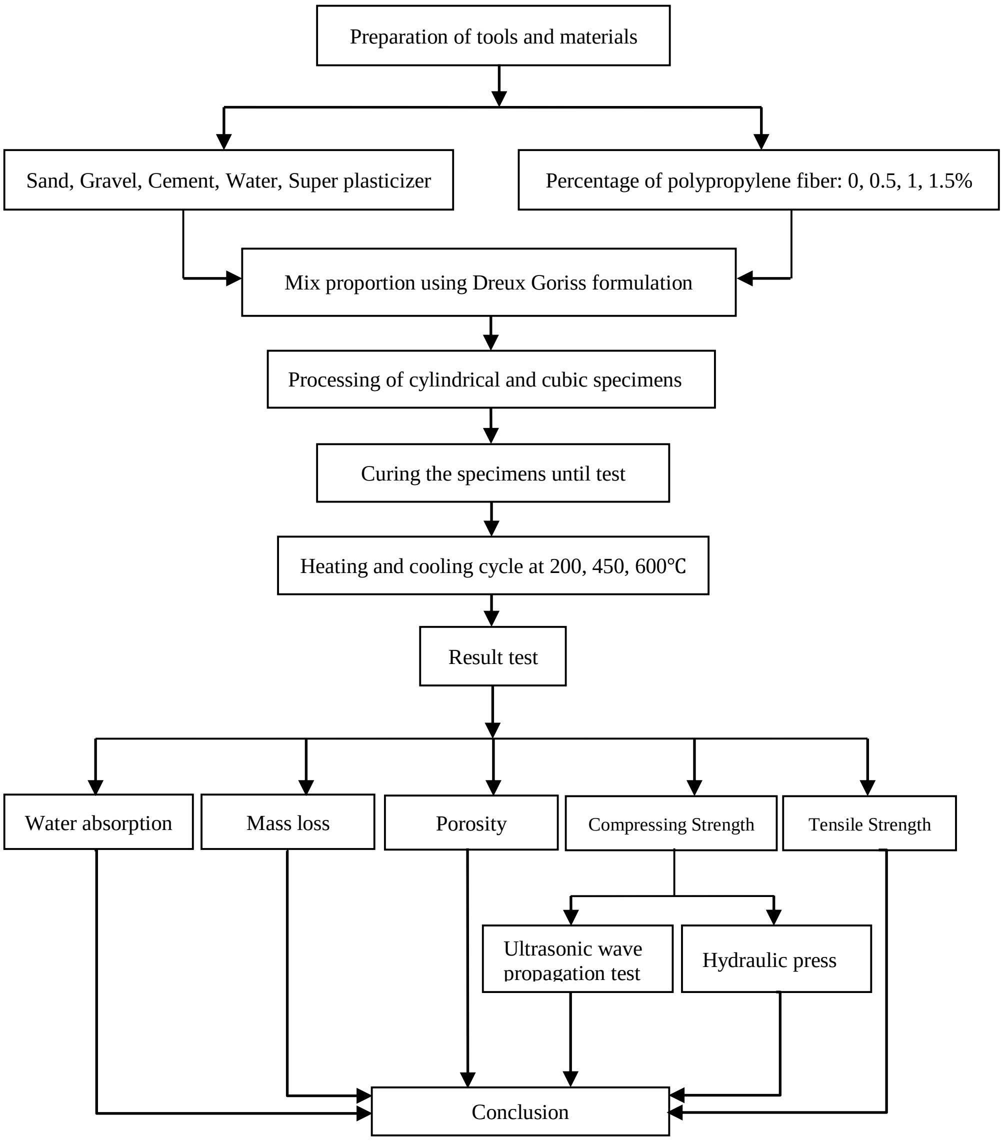


Figure 1. Flow chart of the research study

2.1. Material Properties

2.1.1. Cement

The type of cement used for both ordinary concrete and polypropylene fiber concrete is made by is Djebel Rsass cement company (Tunisia). Physical and mechanical characteristics of this type of cement are shown in Table 1.

Table 1. Physical and mechanical characteristics of cement

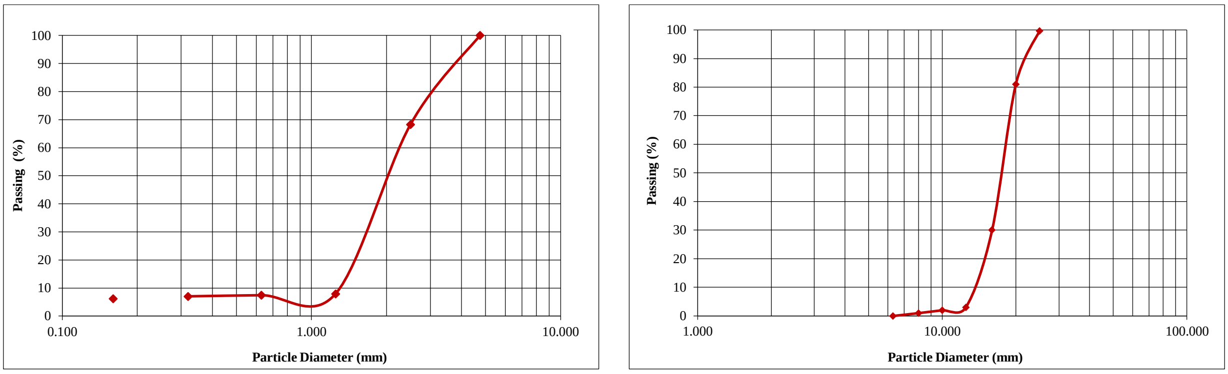
Normal consistency (%)	26.5±2.0
Thickness according to the Blain method (cm^2/g) (NA 231)	3700 -5200
Withdrawal at 28 days (µm/m)	< 1000
Expansion (MPA)	≤ 3.0
Resistance to compression 2 days (MPA)	≥ 10.0
Resistance to the 28-day test (MPA)	≥ 42.5
Start of setting at 20°C (min)	150 ± 30
End of setting at 20°C (min)	230±50

2.1.2. Aggregates

All the concrete was made with aggregates (sand and gravel).

- Identification of aggregates intended for the manufacture of concrete
- Quarry sand from Sotramat (Boulhafdir) Tebessa, Algeria.
- Gravel: 3/8– 8/15 from the quarry of Sotramat (Boulhafdir) Tebessa, Algeria.

The particle size curves for sand and gravel are showed in Figure 2.



(a) (b)

Figure 2. Particle size curve: (a) Sand; (b) Gravel

2.1.3. Superplasticizer

The superplasticizer used in this testing program is the VISCOCRETE TEMPO 12 type high water reducer, marketed by the Algerian company Sika El-DJAZAIR, and complies with NF EN 934-2, French standardization, with a recommended range of use from 0.2 to 3% of binder or cement weight depending on fluidity. The characteristics of the superplasticizer are given in Table 2.

Table 2. Physical and mechanical characteristics of cement

Form	Liquid
Color	Light brown
Density (unity)	1.06
Chlorine content (%)	<0.1
PH	6 1

2.1.4. Water

The mixing water used in this study is potable water from the laboratory tap. The conditions imposed on this mixing water are subject to the NF EN 1008 standard, once again a French standardization. This water must be clean and free from organic substances.

2.1.5. Polypropylene Fibers

The fibers used are polypropylene fibers marketed by the company Algerian GRANITEX see Figure 3. They are used in the concrete to improve the fire resistance of the structures; they are cylindrical and are delivered in the form of a cluster.

Figure 3. Polypropylene fibers

The main characteristics of these fibers are summarized in Table 3.

Table 3. Physical and mechanical properties of propylene fibers

Nominal diameter	18
Length (mm)	12
Density	0.91
Tensile strength (MPa)	300
Elasticity module (MPa)	3000
Melting point (°C)	150

2.2. Evolution of the Porosity

The water-accessible porosity test consists of measuring the porosity of the concrete specimens. In order to determine the overall percentage of void that can be occupied by water. The technique used is a variant of water porosity by hydrostatic weighing recommended by AFPC-AFREM [27].

$$Porosity = \frac{Msa - Mse}{Msa - Msai} \times \rho_e \tag{1}$$

Which (M_{sa}) is mass of sample being saturated and surface dried; (M_{se}) is dry sample mass after steaming; (M_{sai}) is immersed saturated sample mass and (ρ_e) is water density.

2.3. Water Absorption

The absorption capacity is determined by a simple method, the concrete test tubes were completely soaked in water for 24 hours, then removed and weighed at different periods: 0 min, 2 min, 5 min, 10 min, 20 min, 30 min, 1h, 19 h until 20 h where the test tubes will have a constant weight.

Absorption coefficient :

$$CA(\%) = \left(\frac{M_a - M_s}{M_s}\right) \times 100 \tag{2}$$

Where; M_a: saturated mass (g) and M_s: dry mass (g)

2.4. Mass Loss

The mass loss of the test tubes is an important data of the study of the concrete exposed to high temperatures, it makes it possible to follow up the evolution of the weight of the concrete under thermal cycles test pieces when being heated in relation to their initial state, which is the ambient conditions before heating process. The loss mass expressed as a percentage is obtained as follows:

$$Mass\ loss = \left(\frac{M_a - M_{ap}}{M_a}\right) \times 100 \tag{3}$$

Where; M_a: The mass of the test piece at ambient temperature before heating and M_{ap}: the mass of test tube after cooling following exit from the furnace.

2.5. Compressive Strength

Twelve cubic test tubes of (10×10×10) cm were carried out to determine the compressive strength of concrete at 28 days. The ends of the test tubes have to be rectified by surfacing with Sulphur in accordance with NF EN 12390-324, AFNOR, 2003. The test tube is placed in center of an IBERTEST hydraulic press of 1000 kN capacity and subjected to a loading rate of 0.5 $MPa.s^{-1}$ up to failure see Figure 4. The maximum load reached is recorded and the tensile compressive stress at break is obtained by the following formula: $\sigma = F_{max}/A_1$, which F_{max} refers to the compression failure load and A_l is the cross section of the test tube.

Figure 4. The crash tests

2.6. Tensile Strength by Bending

This test is carried out on prismatic test tubes of dimensions (10×10×40) cm as shown in Figure 5, as per AFNOR, 2001, EN12390-5 standard, Part 5 Grade Rating Test P18-433. The two-point loading is conducted at a speed rate of 1N/s until failure.

Figure 5. Tensile test by bending

2.7. Ultrasonic Wave Propagation Speed Test

The main objective of this method is to obtain as much information as possible on the quality of the concretes subjected to a temperature rise. The ultrasonic test represented by its apparatus in Figure 6 according to the French standard AFNOR, Sonic auscultation measurement of the propagation time of sonic waves in the concrete classification index P18-418 is used to assess material homogeneity and detect cracking, voids and fire caused damages.

Figure 6. Ultrasonic test apparatus

2.8. Mix Proportions

Fiber-free concrete composition is obtained using the Dreux-Gorisse formulation method, Dreux and Festa (1998) [28]. The adjuvant dosage is adjusted by execution of preliminary tests to get a mixture that ensures good handling. The consistency class of the concrete obtained is characterized by a subsidence to the Abrams cone Between 75 and 50mm for concrete reinforced with polypropylene fibers, the percentage of fibers relative to the total weight of the concrete was set at three values: 0.055–0.11 and 0.17%. The composition detail is shown in Table 4 below:

Table 4. Concrete composition

Materials	Weights per one cubic meter (kg/m^3)			
Cement	400	400	400	400
Polypropylene fiber	0.00	0.5	1	1.5
Water	180	180	180	180
Superplasticizer%	1	2	2.1	2.2
Superplasticizer kg	4	8	8.40	8.80
Coarse aggregate	1131	1131	1131	1131
Fine aggregate	654	654	654	654

2.9. Mixing, Casting and Curing Procedures

The mixing is done at the beginning of dry from the largest aggregate to the finest in a tilting drum mixer, the 10% of the quantity of water is primary poured as a result of the mixing and then the 90% of the remaining quantity of water is sequentially poured to the composition of the mixture, while polypropylene fibers are gradually added during the mixing process. P18400 will be kept at ambient temperature for 24 hours before being released and placed in a curing tank until the beginning of the test. The slumping test is used to determine the workability of the concrete according to the French standard AFNOR (P18-400).

2.10. Mixing, Casting and Curing Procedures

The tests are carried out on twelve (10×10×10) cm cubic specimens to determine the compressive strength at 28 days. The ends of the test tubes are rectified by surfacing with Sulphur in accordance with NF EN 12390-324, (AFNOR, 2003). Details on test tubes are summarized in Table 5.

Table 5. Number of test tubes details

PP Fiber Content	200 C°	6 hrs.
0% PP		03
0.5% PP		03
1% PP		03
1.5% PP		03
	450 C°	**6 hrs.**
0% PP		03
0.5% PP		03
1% PP		03
1.5% PP		03
	600 C°	**6 hrs.**
0% PP		03
0.5% PP		03
1% PP		03
1.5% PP		03

2.11. Heating Procedure

After 28 days of curing, the test tubes are subjected to a cooling cycle of 200, 450 and 600°C for 6 hours' time. Later, the specimens remain inside the furnace for cooling and will be tested in compression as per NF EN 12390-324 (AFNOR, 2003). The furnace used for the cooling heating cycle is shown in Figure 7.

Figure 7. The furnace used for heating the specimens

3. Results and Discussion

3.1. Fresh Concrete Tests

The slump test results based on the French standard AFNOR(P18-400) are given for the four mixing cases namely: ordinary concrete and concretes with respectively (0.055, 0.11 and 0.17) % reinforcement polypropylene fibers, the values obtained are respectively (75, 60, 55 and 50) mm relative to a plastic concrete and the values are gradually decreased relatively to the fibers ratio.

3.2. Hardened Concrete Tests

3.2.1. Mass Loss

As it can be seen from the Figure 8, with the rise in temperature, consequently the concrete its mass. This loss of mass is due essentially to the water departure which occurs with temperature less than 600°C and taking place usually throughout three stages. These stages can be summarized as follows:

For the case of ambient temperature ranging between 100-150 °C, a low mass loss is observed due to free water in the concrete. With a temperature ranging between 150 and 300°C: a rapid increase in mass loss due to water contained in hydrates and mainly from hydrated calcium silicategel. According to Kanéma (2007) [29], at 300 °C, concrete can lose approximately 65 to 80% of the total water mass. Beyond 300°C: Small mass loss corresponding to the dehydroxylation of the portlandite (450-550 °C), the decomposition of silanols (Sioh), flint (400 to 570 °C) and $Caco_3$ limestone decarbonization (600 to 800 °C). It is can be observed from Figure 8 that for polypropylene fiber concretes, an increase in kinetics mass loss is noticeable and the three domains characterizing the evolution of mass loss in terms of temperatures can also be remarked.

Also the addition of fibers leads to an increase in mass loss compared to concrete without fibers. This additional mass loss is related to the melting of fibers during the rise in temperature. Because the melting of fibers facilitates the transport and evacuation flow.

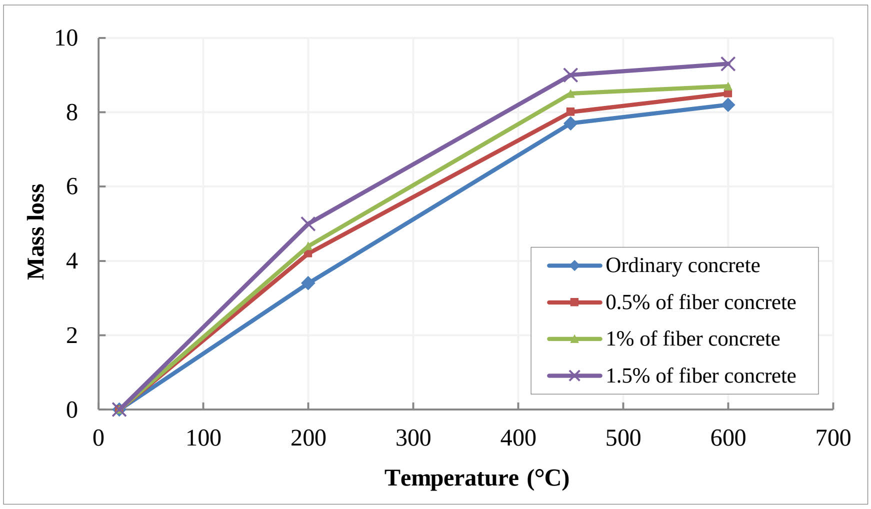


Figure 8. Variation of mass loss in % vs. temperature in °C

3.2.2. Water Absorption

As shown in Figure 9, the water absorption increases gradually depending on two parameters which are porosity and absorptivity i.e. absorption speed) and the higher the moisture contains in the concrete, the higher the measured volume of absorptivity is low Assié (2004) [30]. The fibers absorption of water is proportional to the fiber's ratio in the concrete.

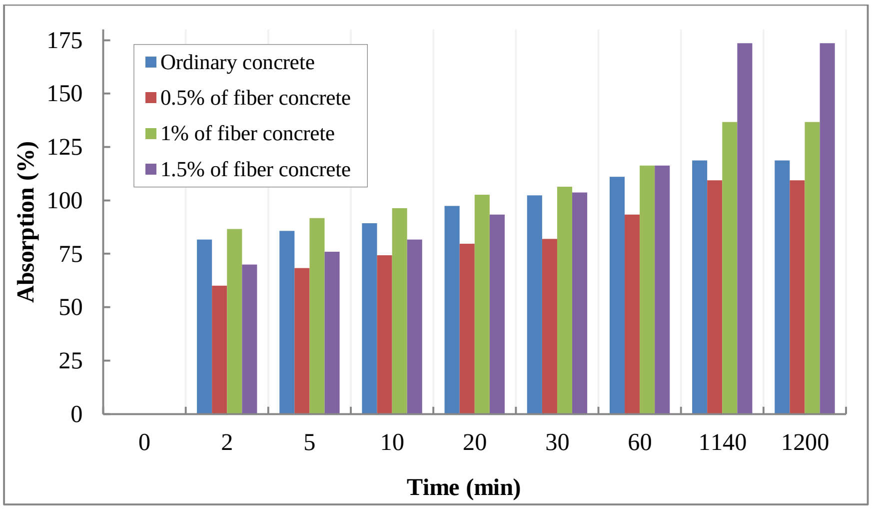


Figure 9. Variation of absorption degree vs. Time

3.2.3. Porosity Evolution

The results of the experimental tests carried out by the various authors showed an increase in porosity with temperature for both ordinary and high-performance concretes in the presence or in absence of fibers [4, 5]. From the results presented in Figure 10, the inclusion of polypropylene fibers in heated concrete leads to an increase in pore volume and changes the kinetics of porosity development. Moreover, the polypropylene fibers show the appearance of an additional porosity. This porosity is related to the micro cracking generated by the expansion of the polypropylene and also to the channels formed after the fiber melts. In addition, as the fiber dosage increases, another void is created during heating. Also according to the obtained graph, the porosity of the heated concrete measured with 1.5% fiber increases significantly compared to the other two measurements.

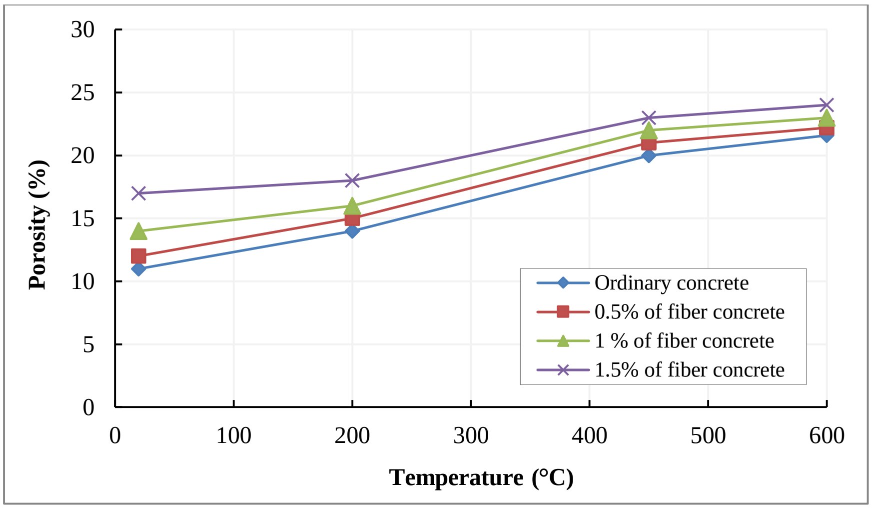


Figure 10. Variation of Porosity (%) vs. Temperature (°C)

3.2.4. Compressive Strength

For different temperatures cases and as shown in the Figure 11, the compressive strength of concrete having 0.5, 1, and 1.5% polypropylene fiber ratios increases, due to effect of heating and beyond 200°C the liquid water converts to steam and the improvement of strength is a consequence of the departure of this water allowing a re-increase of the tension forces and reconciliation of the sheets of hydrated calcium silicate which was found to decrease significantly at 600°C because of the partial or total melting of polypropylene fibers creating channels within the cement matrix. It is worth noting that the evolution of the compressive strength of ordinary concrete is similar to that of fiber concrete but remains lower than this one. Similar results were observed by other researchers [8, 14].

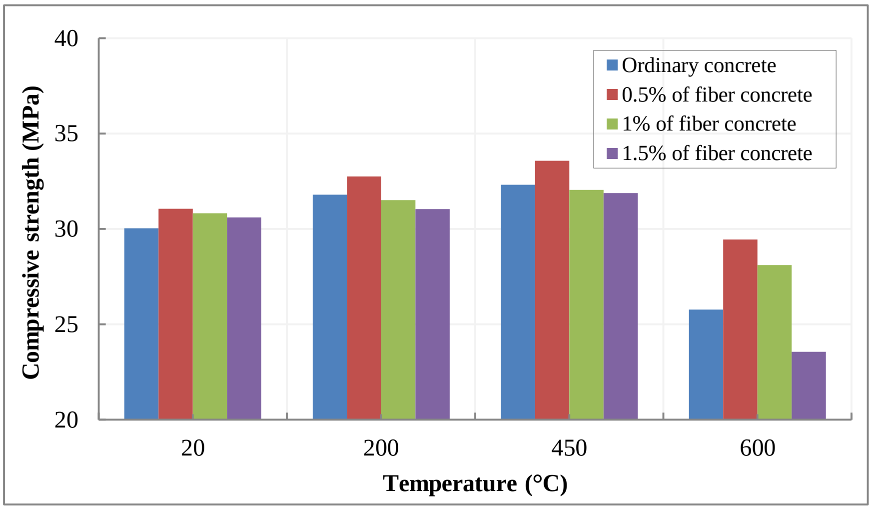


Figure 11. Variation of compression strength (MPa) vs. Temperature (°C)

3.2.5. Tensile Strength

Based on the previous studies such as Chen & Liu (2004) and Suhaendi & Horiguchi (2006) [17, 18], there is a decrease in tensile strength due to temperature. Figure 12 involving the flexural tensile strengths of polypropylene fiber concretes for different heating-cooling cycles reveals a progressive decrease in the flexural strength of concrete with polypropylene fibers as the heating temperature increases. This strength decreases with increasing temperature for all the concretes studied; With the exception or then above 300°C, the decrease in tensile strength becomes more important, all concretes losing more than half of their initial flexural strength due to the degradation of the cementitious matrix (decomposition of the portlandite).

Similar results were observed by other researchers for ordinary concrete and fibrous concrete Chang et al. (2006) [21]. The results of the tests for fiber-free concrete lead to a lower tensile strength loss than that of fiber concrete see Figure 12.

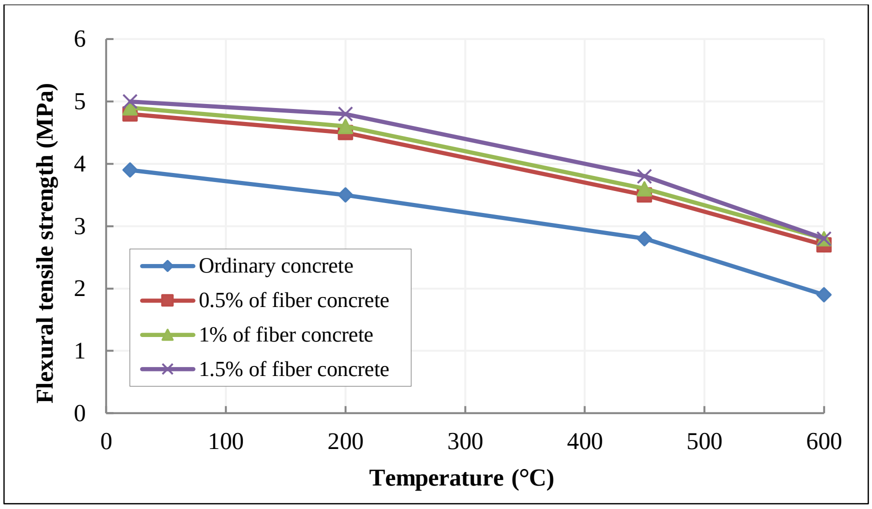


Figure 12. Variation of compression strength (MPa) vs. Temperature (°C)

3.2.6. Ultrasonic Testing

On the basis of the results obtained from the ultrasonic tests for the different types of concrete, namely ordinary concrete and fibrates concrete with 0.5, 1 and 1.5% fibers.

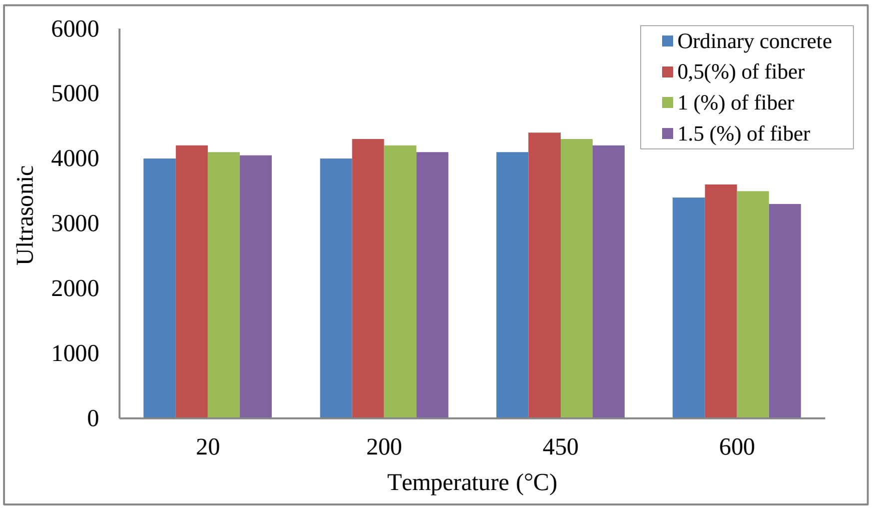


Figure 13. Variation of ultrasound vs. Temperature (°C)

On examination of Figure 13, it can be noticed that the results of the wave velocity variation increase at a temperature ranging from 200 to 450 °C and decrease gradually when the temperature reaches 600°C in a manner similar to the results provided by Toumi (2010) and Laneyrie (2014) [15, 16]. These authors find that the cracking density of heated concrete increases with increasing heating temperature. Therefore, the sound propagation velocity of concrete decreases as the heating cycle increases. This decrease in sound propagation speed is attributed to the fact that there is an expulsion of water bubbles contained in the concrete.

4. Conclusions

According to the obtained results in tests carried out in this study on ordinary concrete specimens, the following concluding remarks can be drawn:

- A reduction in the concrete mass (or mass loss) with the increase in temperature was observed by weighing the test tubes before and after each single heating cycle.
- An increase of porosity increases when the temperature rises to 450°C and then slowing down under 600°C.
- The mechanical behavior relative to the compression strength is divided into two areas. The first, ranging from ambient temperature up to 450°Cwhich is marked by a slight decrease or improvement in resistance. The second one, when the ambient temperature is higher than 450°C, resulting in a significant loss of strength.
- The obtained results from tensile tests are characterized by a drop in the tensile strength.

- The obtained results from the tests carried out on the polypropylene fiber-containing concretes show that:
    - It was observed that a concrete mass loss increases with temperature, with an additional loss of mass on polypropylene fiber concretes.
    - It was observed that the porosity measurements show a rapid increase in porosity for concrete reinforced with fiber than unreinforced concrete.
- The addition of polypropylene fibers in the concrete results in an increase in resistance up to 450°C and a remarkable fall to 600 °C due to the melting and vaporization of the fibers.
- The influence of the fibers on the tensile behavior is negative because the melting of the fibers causing a loss of their tensile strength. Among the dosages of polypropylene fibers studied the dosage of 0.5% leads to better mechanical performance particularly for compressive strength.

5. Declarations

5.1. Author Contributions

R.B.: Methodology, investigation, data collection. M.M.: development and orientation. M.B.: review and editing. T.M. and R.B.: validation, data analysis. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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