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RELATIONSHIPS BETWEEN MECHANICAL PROPERTIES (COMPRESSIVE STRENGTH) AND PHYSICAL PROPERTIES (POROSITY) AT HIGH TEMPERATURES

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Abstract
Introduction: This research is a part of a broader study on the evolution of concrete properties when exposed to high temperatures. **It aims** to analyze the behavior of ordinary concretes at elevated temperatures, incorporating either organic or synthetic fibers in the same dosage. **Metods**: Three concrete compositions were formulated: plain concrete without fibers (CO1), polypropylene fiber-reinforced concrete (CFP), and chicken feather fiber-reinforced concrete (CFC1), with both fiber-reinforced types containing an identical fiber dosage of 0.9 %. The prepared specimens were subjected to a heating-cooling cycle at 150 °C, 300 °C, 450 °C, and 600 °C, with a heating rate of 1 °C per minute. The residual physical and mechanical properties of the different concretes were then analyzed. **Results**: The concretes studied exhibited similar initial mechanical properties. However, the concrete reinforced with chicken feather fibers demonstrated superior residual physical and mechanical performance compared to the other concretes. Overall, the residual mechanical performance of the fiber-reinforced concretes was greater than that of the plain concrete, confirming the positive contribution of fibers to strength retention at temperatures up to 600 °C. Finally, a correlation between compressive strength and porosity was established for the three concrete types. This correlation provides a reliable method for estimating the compressive strength of concreted containing different types of fibers when exposed to high temperatures.

Keywords: ordinary concrete; chicken feather fibers; polypropylene fibers; high temperature; compressive strength–porosity correlation.

Introduction

This work aims to understand the behavior of ordinary concrete incorporating synthetic fibers (polypropylene fibers) and organic fibers (chicken feather fibers) at an identical dosage under high temperatures, using a slow heating rate of 1 °C per minute.

Numerous studies have explained the phenomena observed in the behavior of heated concrete and identified key parameters influencing concrete performance at elevated temperatures. Among these, the nature of the aggregates and the incorporation of fibers are considered crucial. The addition of various fibers (polypropylene, steel, glass) has been proposed by several researchers to enhance the residual physical and mechanical performance of concrete. Polypropylene fibers improve thermal stability, while steel fibers enhance residual mechanical strength (Sahnoun and Toumi, 2024).

Noumowe (2005) provided significant data on the mechanical properties and microstructure of high-strength concrete containing polypropylene fibers exposed to temperatures up to 200 °C. When such concrete is heated to 170 °C, the polypropylene fibers melt and volatilize, creating additional porosity and microchannels. Differential Scanning Calorimetry (DSC) and Thermogravimetric (TG) analyses revealed the decomposition temperature ranges of the material. Scanning Electron Microscope (SEM) analysis confirmed the formation of supplementary pores and microchannels due to fiber melting. Mechanical testing showed minor changes in compressive strength, modulus of elasticity, and splitting tensile strength, likely caused by fiber decomposition. Importantly, the inclusion of polypropylene fibers improved the spalling resistance of high-strength concrete, which is crucial for application in thermally demanding environments, especially in nuclear facilities.

Nonna (2015) conducted a comparative study on the physical properties and residual mechanical behavior of three types of concrete: plain concrete (Créf (C)), steel fiber-reinforced concrete (CS 60), and hybrid fiber concrete incorporating both polypropylene and steel fibers (CPPS 0.75-60). Tests were conducted at 300 °C, 600 °C, 750 °C, and 900 °C. At ambient temperature, the differences among the concretes were minor. The porosity of the fiber-reinforced concretes was similar (CS 60 at 8.5 %

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and CPPS 0.75-60 at 8.6 %), while plain concrete (Créf(C)) had higher porosity (11.2 %). During heating, CS 60 exhibited delayed water release between 200 °C and 500 °C, whereas Créf(C) and CPPS 0.75-60 experienced gradual mass loss up to 750 °C (9.2 % and 8.7 %, respectively). Beyond 750 °C, significant mass loss was observed due to the decarbonation of limestone aggregates (19.8 % for Créf(C) and 17.6 % for CPPS 0.75-60). Mechanical properties such as compressive strength, elastic modulus, and flexural tensile strength decreased with increasing temperature. However, steel fibers mitigated performance loss, with average mechanical degradation around 10 % in the fiber-reinforced concretes. Despite the development of cracks and increased porosity at elevated temperatures, steel fibers helped maintain tensile performance and reduced crack propagation, preserving ductility up to 750 °C. At 900 °C, the concrete became more brittle due to oxidation and corrosion of the steel fibers. The elastic modulus also showed a continuous decline as the temperature increased.

Hamoush and El-Hawary (1994) explored the use of feather fibers in concrete to enhance strength and durability, proposing them as a cost-effective and environmentally friendly alternative to traditional steel or glass fibers. Their experimental investigation involved incorporating feather fibers at volumetric ratios of 1 %, 2 %, and 3 % into concrete mixtures. Results showed that while compressive and tensile strength decreased with feather addition, flexural strength improved at certain ratios, especially at 1 % and 2 % after 56 days. The study also pointed out issues related to feather decay and reduced strength, suggesting that additional treatments may enhance performance. Overall, the study highlights the promising potential of feather-reinforced concrete for construction applications, with ongoing research focusing on long-term durability and fiber strength retention.

Adetola et al. (2021) conducted a study in which the compositions of chicken feather fiber (CFF) and synthetic hair fiber (SHF) were varied by weight at 0 %, 1.5 %, 2.5 %, 3.5 %, and 5 % for samples A to E, respectively. The physical and mechanical properties assessed included water absorption (WA), thickness swelling (TS), compressive strength (CS), and splitting tensile strength (STS). The results indicated that both WA and TS decreased with lower percentage of CFF and SHF, as well as with increased curing time. WA ranged from a maximum of 10.01 % to a minimum of 0.14 %. Compressive strength for sample A increased with curing time, from 16.98 MPa at 7 days to 20.66 MPa at 28 days, while sample B achieved its highest CS of 9.98 MPa at 14 days, with other samples showing a progressive decline. Similarly, STS for sample A increased with curing time from 9.84 MPa to 13.64 MPa, while sample B exhibited a decrease from 5.43 MPa to 4.79 MPa between days 7 and 21, followed by a slight increase to 4.92 MPa at 28 days. Samples C, D, and E followed a trend similar to sample B. An SEM analysis revealed that interlocking concrete block (ICBs) with 0 % CFF and SHF exhibited brittle characteristics, while samples incorporating varying percentages of fibers displayed ductile behavior. Overall, the inclusion of CFF and SHF improved the WA, TS, CS, and STS of fiber-reinforced concrete.

Abdelsamie et al. (2021) investigated the use of keratin fibers — waste by-products from the poultry industry (CFFs) — in fiber-reinforced concrete composites. One of the key challenges with high-strength concrete (HSC) is its brittleness, which leads to sudden failure at ultimate capacity. This study examined the impact of CFFs on improving the ductility of HSC. Two experimental scenarios were explored. In the first scenario, HSC was prepared with different volume ratios of CFF (0 % as control, 0.5 %, 1 %, 1.5 %, 2 %, and 3 %). In the second scenario, CFFs were replaced with glass fibers (GF). Tests were conducted on fresh, hardened, and morphological properties of the concrete. Tests were conducted on fresh and hardened concrete, its morphological properties were analyzed. The results showed improved ductility in HSC with the addition of both types of fiber. The optimal fiber content was found to be 1 % by volume for both CFF and GF. Flexural and splitting tensile strengths increased by approximately 44.9 % and 42.65 % for the mix containing 1 % GF, and by 21.6 % and 21.16 % for the mix containing 1 % CFF, respectively.

The current work is primarily experimental and aims to deepen the understanding of the behavior of ordinary concrete exposed to high temperatures, incorporating synthetic (polypropylene) and organic (chicken feather) fibers at the same dosage. The study also seeks to establish a correlation between porosity and residual compressive strength, enabling the estimation of compressive strength in fiber-reinforced concrete subjected to elevated temperatures.

Materials and Methods

Raw Materials

The cement used in this study is a locally sourced Portland cement, classified as CEM I 42.5 R, from Lafarge, branded as EL MOUKAWEM. It has a 28-day compressive strength exceeding 42.5 MPa but below 62.5 MPa, and a specific gravity of 3,140 kg/m³. The aggregates used are of calcareous (limestone) origin and include 0/4 fraction (sand) and 8/16 fraction (aggregate), both sourced from the EL KHROUB quarry located in the northern region of Constantine. The sand has a specific gravity of 1,440 kg/m³, while the aggregate has a density of 1,350 kg/m³. The water absorption rates are 0.78 % for the sand and 0.72 % for the aggregate.

The polypropylene fibers used in this study are manufactured by FIBERTEK. These fibers are cylindrical in shape, 6 mm in length, and have a nominal diameter of 18 µm. They are characterized by a density of 0.91 g/cm³, a melting point of 160 °C, a tensile strength of 400 MPa, and an elastic modulus of 3.7 GPa. The CFFs used are semi-crystalline, with a diameter of approximately 5 µm and lengths ranging from 4.2 to 15 mm (Menandro, 2010), giving a length-to-diameter ratio of about 25. They have a specific gravity of 0.85 g/cm³. The chicken feathers were collected from Al-Ihsan poultry farm in Constantine. All raw materials are shown on the Fig. 1.

Experimental Methods

Three concrete compositions were prepared (Table 1). A constant water-to-cement ratio of 0.50 was maintained for all mixtures. The mix design was determined using the Dreux-Gorisse method (Dreux and Festa, 1998), which guided the calculation of the quantities of each concrete constituent. The first composition, designated as CO1, is ordinary concrete without any fibers. The second composition, designated as CCF1, is ordinary concrete incorporating chicken feather fibers at a dosage of 0.9 % by volume. The third composition, designated as CFP, is ordinary concrete with polypropylene fibers, also added at a dosage of 0.9 % by volume.

Each concrete mixture was cast into cylindrical molds with a diameter of 10 cm and a height of 20 cm, as well as into prismatic molds measuring 7 × 7 × 28 cm. After 24 hours, the specimens were demolded and stored in ambient laboratory air for 90 days prior to testing (Noumowe et al., 2009) (Fig. 2). All specimens were subjected to four different temperature cycles, with target temperatures of 150 °C, 300 °C, 450 °C, and 600 °C. Each cycle began with a heating phase at a rate of 1 °C/min until the target temperature was reached. This heating rate is commonly used for specimens of these dimensions.

The target temperature was then maintained for one hour to ensure uniform internal distribution. Finally, the specimens were allowed to cool back to ambient temperature. This thermal cycle procedure follows the guidelines recommended by the RILEM Technical Committee TC-129 (RILEM, 1995). For mass loss determination, the specimens were oven-dried at 105 °C for several days until their mass stabilized. They were weighed before and after each heat treatment to determine mass loss. Direct weighing was performed to avoid rehydration from ambient humidity. Porosity was also measured before and after each temperature cycle. The physical and mechanical properties (Figs. 5, 7) of the concrete specimens were evaluated at ambient temperature and after each heating-cooling cycle (150 °C, 300 °C, 450 °C, and 600 °C).

Results and Discussion

Physical Properties

Mass Loss

Fig. 3 illustrates the variations in mass loss of the 7 × 7 × 28 cm prismatic specimens after the heating-cooling cycles. The mass loss is similar across all

Fig. 1. Raw materials

Fig. 2. Preservation of test specimens

three types of concrete studied and shows closely aligned trends.

From the figure above, two distinct ranges in the evolution of mass loss with temperature can be observed. The first range extends from ambient temperature up to 300 °C. The mass loss in this range is 0.76 %, 0.83 %, and 0.89 % for concretes CO1, CCF1, and CFP, respectively. This loss is primarily due to the evaporation of free water from the pores, desorption of water from the surface of solid components, loss of bound water, and dehydration of C-S-H gels and ettringite.

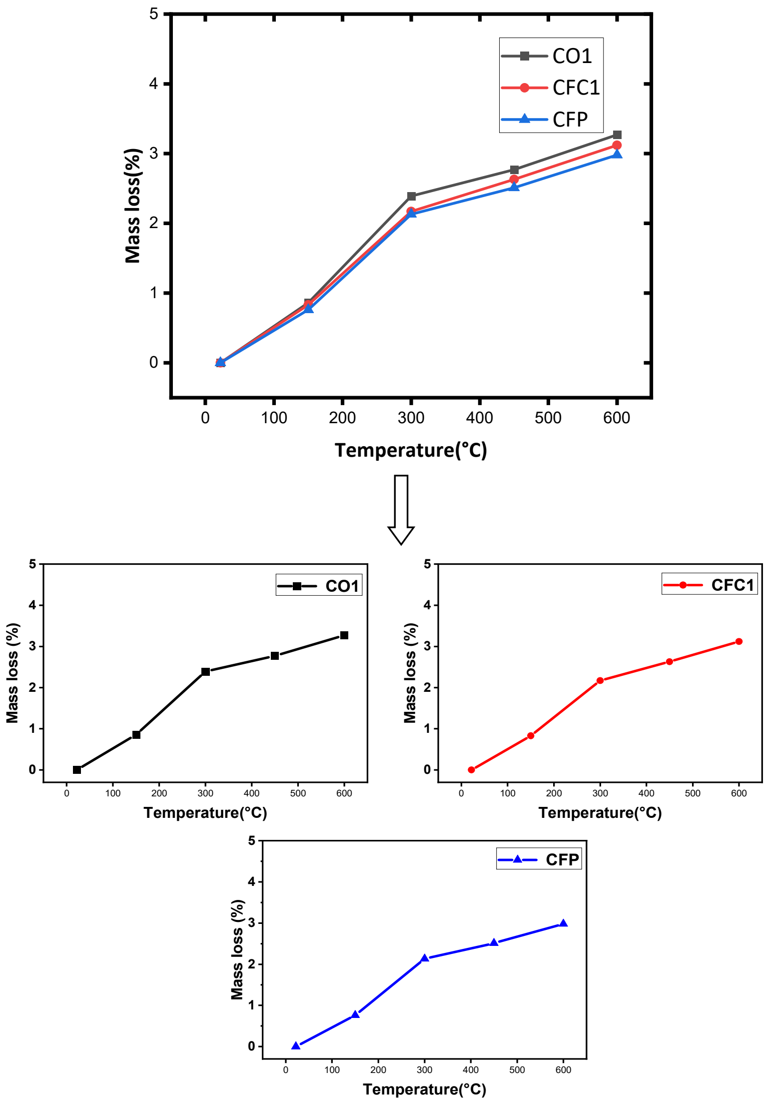

Fig. 3. Evolution of mass loss for CO1, CCF1, and CFP with respect to the temperature of the heating-cooling cycle

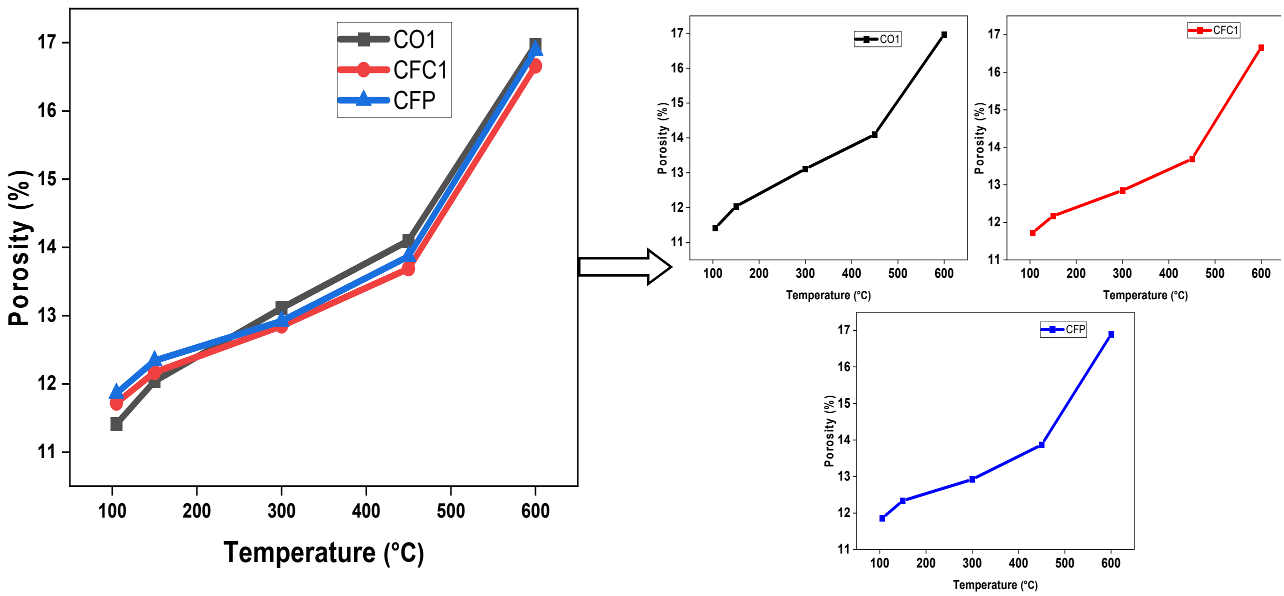

Fig. 4. Evolution of residual porosity of concretes with different fibers as a function of temperature

The second range, from 300 °C to 600 °C, shows only a slight variation in mass loss compared to the first range. This range is characterized by the dehydroxylation of portlandite (Menandro, 2010). The mass loss trends for all three concretes follow a similar slope. At 300 °C, concrete CO1 loses 2.39 % of its mass, CCF1 loses 2.17 %, and CFP loses 2.13 %. The small differences in mass loss among the concretes can be attributed to the varying water contents in their initial compositions.

At 600 °C, the mass loss is 3.27 % for CO1, 3.12 % for CCF1, and 2.98 % for CFP. Overall, the addition of chicken feather fibers or polypropylene fibers reduces the mass loss compared to concrete without fibers (Pliya, 2010). This is likely due to the partial replacement of aggregates with fibers, which reduces the amount of free or adsorbed water in the mix.

Porosity

The porosity of the studied concretes (Fig. 4) increases with heating temperature. All three types of concrete exhibit a similar trend in porosity development up to 600 °C.

Between 105 °C and 150 °C, the porosity of concrete with polypropylene fibers (CFP) and concrete with chicken feather fibers (CCF1) increases more significantly than that of ordinary concrete (CO1). Beyond 300 °C, a rapid increase in porosity is observed in concrete without fibers, whereas concretes with fibers show a slower rate of increase.

At 300 °C, the porosity of concrete without fibers is 13.11 %, while the porosity of CCF1 and CFP is 12.86 % and 12.92 %, respectively.

Between 300 °C and 450 °C, a sharp increase in porosity is recorded, reaching 14.1 %, 13.69 %, and 13.87 % for CO1, CFC1, and CFP, respectively.

From 450 °C to 600 °C, porosity continues to rise rapidly. This could be due to the decomposition of portlandite ($Ca(OH)_2 \rightarrow CaO + H_2O$) and the allotropic transformations of α-quartz to β-quartz.

Mechanical Properties

The mechanical properties of the specimens were evaluated after undergoing the heating-cooling cycles. The average residual strength values were obtained from three specimens.

Residual Compressive Strength of Concrete at Elevated Temperatures

According to Fig. 6, compressive strength decreases as temperature increases — an observation widely reported in the literature (Hassiba, 2019; Kanéma, 2007; Nonna, 2015; Pliya, 2010), stating that this reduction may be attributed

Fig. 5. Cylindrical specimens (100 × 200 mm) for compressive strength testing

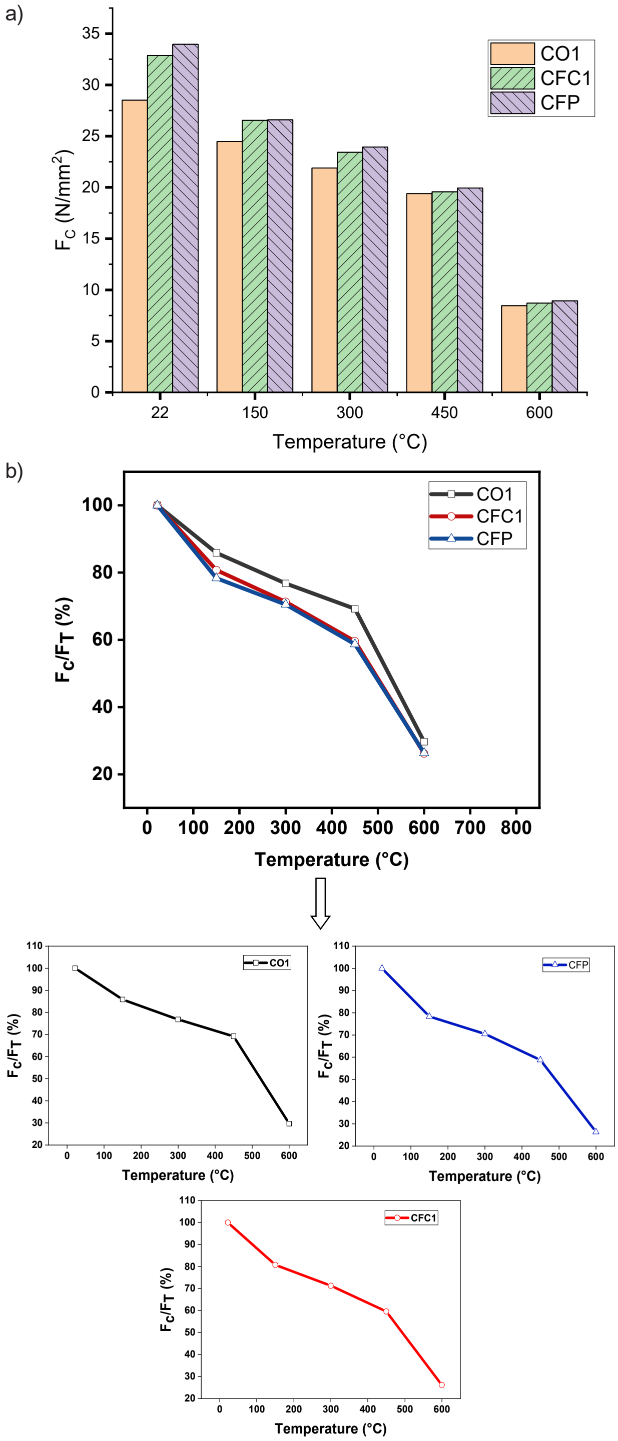

Fig. 6. Evolution of (a) residual and (b) relative compressive strength of CO1, CCF1, and CFP as a function of temperature

to degradation of the cement paste and aggregate microstructure as well as water loss.

The trend in compressive strength reduction is similar across all three concretes — those with and without fibers. However, concretes with fibers exhibit better residual compressive strengths compared to the one without fibers. The reduction in residual compressive strength can be divided into three distinct temperature ranges:

1. Ambient to 150 °C: A moderate decrease in strength.
2. 150 °C to 300 °C: A medium-level decrease in strength.
3. Above 450 °C: A significant decrease in strength.

Between ambient temperature and 150 °C, CCF1 and CFP concretes exhibit higher residual compressive strengths than CO1. From 150 °C to 300 °C, there is a slight reduction in relative strength, with a loss of 23.22 %, of concrete without fibers, while CCF1 and CFP lose around 28.72 % and 29.51 %, respectively. The low decrease is attributed to the loss of water due to temperature, which causes the C-S-H gel sheets to separate, reducing the attraction forces between the sheets and leading to the formation of microcracks. This reduction is attributed to water loss due to temperature increase, which causes the C-S-H gel layers to separate, weakening inter-particle forces and leading to microcrack formation (Pliya, 2010).

Between 400 °C and 600 °C, all three concretes experience a steady decline in residual strength. The losses are similar across the board, indicating material degradation — particularly in the cement matrix — as previously noted by Kanéma (2007).

Concrete without fibers appears less damaged that the other types. Both fiber-reinforced concretes (CCF1 and CFP) show nearly identical loss patterns. This suggests that the type of fiber does not significantly influence the overall shape of the compressive strength curve. Microcrack formation, as discussed by Bidossessi and Prosper (2010), Hachemi (2015), and Hassiba (2019), decreases mechanical performance.

Flexural Tensile Strength

At ambient temperature, concrete generally exhibits higher compressive strength than tensile strength; however, the inclusion of fibers improves its tensile capacity.

Fig. 7. Prismatic specimens of dimensions 7 × 7 × 28 cm for tensile strength testing

Fig. 8 illustrates the evolution of residual and relative flexural tensile strength as a function of temperature. For all concretes (CO1, CFC1, and CFP), flexural strength consistently decreases as temperature increases.

In general terms, the evolution of tensile strength with temperature can be divided into two behavioral zones: the first ranges from ambient temperature to 300 °C, and the second — from 300 °C to 600 °C. The presence of fibers does not alter the shape of the curve. From 22 °C to 300 °C, the bending resistance flexural strength of CFC1 decreases by about 12 %, while CFP loses about 14 % and CO1 loses about 19 % of the initial strength.

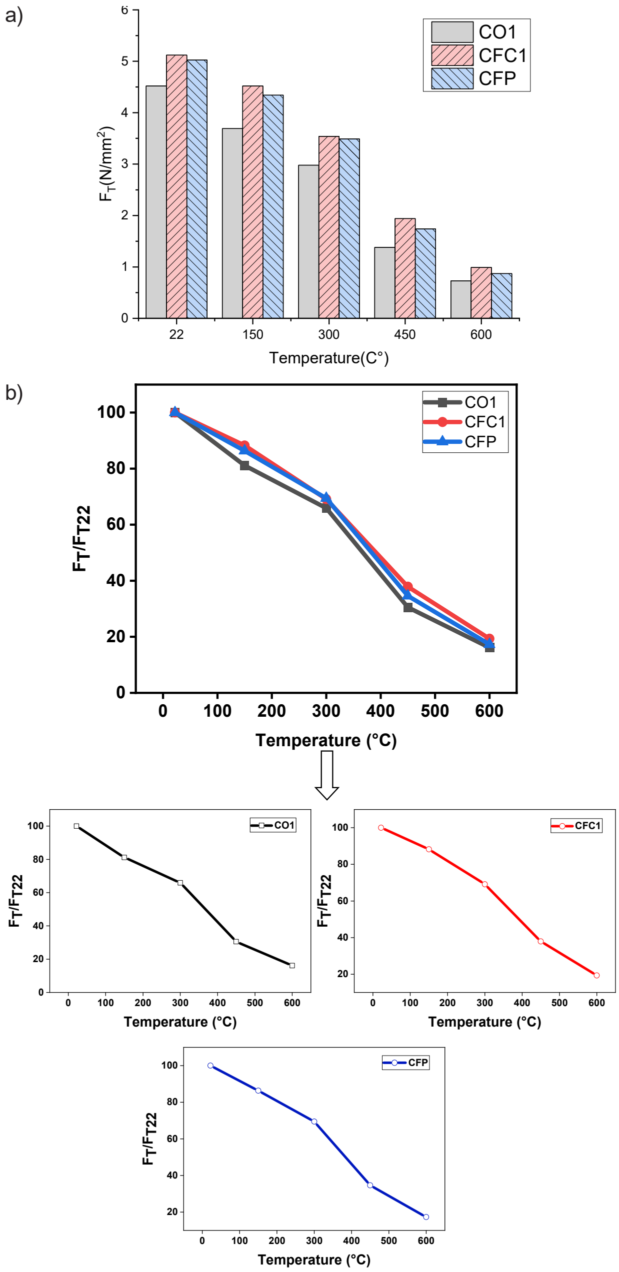

Fig. 8. Evolution of (a) residual and (b) relative flexural tensile strength of concretes CO1, CFC1 and CFP as a function of temperature

Beyond 300 °C, all types of concrete exhibit a significant loss in flexural tensile strength. Concrete with chicken feather fibers (CFC1) and concrete with polypropylene fibers (CFP) lose more than 30 % of their initial strength, while concrete without fibers (CO1) loses more than 35 %.

Above 450 °C, the reduction in residual strength becomes more pronounced for all formulations.

At 600 °C, concrete containing chicken feather fibers shows the least loss compared to CO1 and CFP. The loss of tensile strength in bending occurs in concrete with a water-to-cement (W/C) ratio of 0.5. The use of fibers makes concrete more ductile. The various bending tests, from ambient temperature up to the heating-cooling cycle at 600 °C, show that the ductility of concretes with polypropylene and chicken feather fibers is preserved.

Correlation

The relationship between compressive strength and porosity can be influenced by increasing temperature and the incorporation of fibers.

Correlation Between Porosity and Compressive Strength

The assessment of compressive strength is based on empirical correlations between compressive strength and porosity. Figs. 9 and 10 present this relationship for the three concrete types: CO1, CFC1, and CFP. The best-fit model is a linear equation with a high correlation coefficient (R^2 = 0.996).

It is observed that the coefficient of determination (R^2) is nearly identical for all three concrete types: plain concrete, and those with chicken feather and polypropylene fibers. As residual compressive strength increases, porosity decreases. However, the residual compressive strength of concrete with various fiber types exposed to high temperatures can be estimated using the relationship between

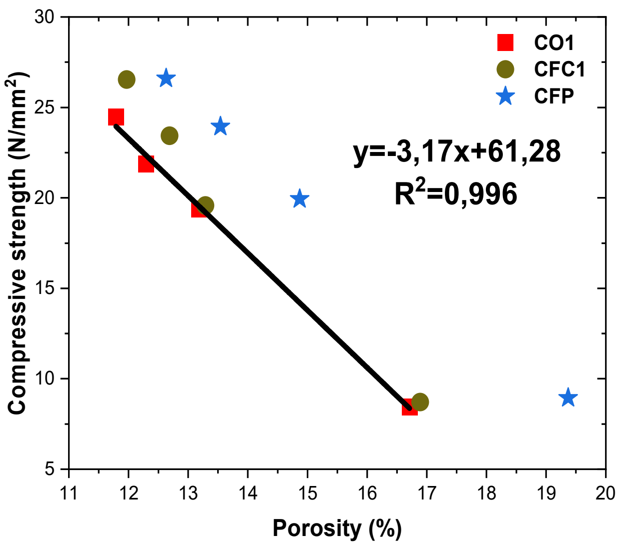

Fig. 9. Relationship between the compressive strength and porosity

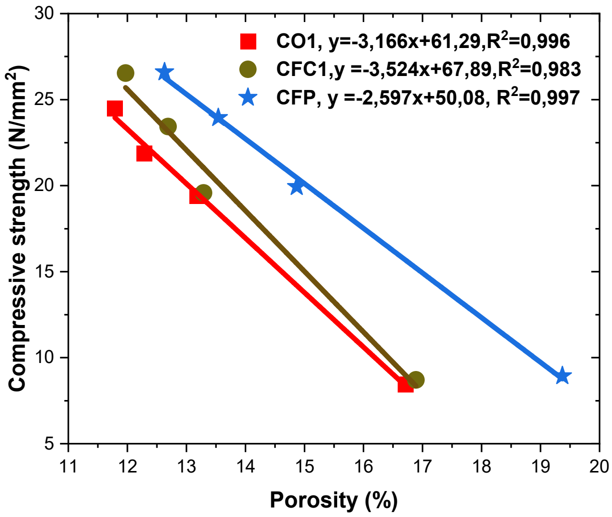

Fig. 10. Correlation between compressive strength and porosity for CO1, CFC1, and CFP at 150 °C, 300 °C, 450 °C, and 600 °C

porosity and residual compressive strength. This correlation implies that porosity can be used as a reliable predictor of residual compressive strength for concrete exposed to high temperatures.

A strong inverse relationship is evident across all formulations: compressive strength improves as porosity decreases. These findings are consistent with previous studies (Cheng et al., 2008; Erniati et al., 2015).

Conclusions

This study aimed to enhance the understanding of the behavior of concrete exposed to high temperatures. It evaluated the influence of two fiber types — polypropylene and chicken feather — added at an equal dosage of 0.9 % by volume, with a constant water-to-cement (W/C) ratio of 0.5. Both physical (mass loss, porosity) and mechanical (compressive strength, flexural tensile strength) properties were measured at ambient temperature and after exposure to elevated temperatures.

For the three types of concrete, it was observed that both mechanical and physical properties decrease with increasing temperature. Mass loss is more significant in ordinary concrete compared to the other types. Porosity measurements confirm that high-performance concretes are more porous and suffer greater damage than ordinary concretes. Several key findings can be noted from this study:

• Exposure to high temperatures directly affects both the physical and mechanical properties of concrete.

• A heating rate of 1 °C/min facilitates more complete chemical transformations within the concrete, resulting in a more pronounced reduction in strength.

• Mass loss increases with temperature. It was observed that concretes without fibers exhibit higher mass loss compared to those containing chicken feather or polypropylene fibers. Thus, the variation in mass loss among the concretes depends on the type and dosage of fibers used.

• Mechanical and physical properties consistently decline as temperature rises.

• The addition of fibers generally enhances mechanical properties at ambient temperature compared to ordinary concrete without fibers.

• Concrete with chicken feather fibers at a dosage of 0.9 kg/m³ shows improved initial and residual compressive strength.

• The improvement in compressive strength correlates with the reduction in porosity observed across the different types of concrete.

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ВЗАИМОСВЯЗЬ МЕХАНИЧЕСКИХ (ПРОЧНОСТЬ НА СЖАТИЕ) И ФИЗИЧЕСКИХ СВОЙСТВ (ПОРИСТОСТЬ) ПРИ ВЫСОКИХ ТЕМПЕРАТУРАХ

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Аннотация
Введение: Данная работа является частью более широкого исследования, посвященного изучению изменений свойств бетона при воздействии высоких температур. **Цель работы** — проанализировать характеристики обычного бетона с добавлением органических или синтетических волокон в одинаковой дозировке при воздействии высоких температур. **Методы**: Разработаны три состава бетона: обычный бетон без волокон (CO1), бетон с полипропиленовыми волокнами (CFP) и бетон с волокнами из куриных перьев (CFC1), при этом объем добавленных волокон в армированном бетоне составил 0,9 %. Подготовленные образцы подвергались нагреву и охлаждению при температурах 150 °C, 300 °C, 450 °C и 600 °C со скоростью нагрева 1 °C в минуту. Далее анализировались остаточные физико-механические свойства различных типов бетона. **Результаты**: Исходные механические свойства исследованных типов бетона были схожи, однако бетон, армированный волокнами из куриных перьев, показал лучшие остаточные физико-механические характеристики по сравнению с другими типами бетона. В целом, остаточные механические характеристики бетонов с добавлением волокон оказались выше, чем у обычного бетона, что подтверждает положительное влияние волокон на сохранение прочности при температурах до 600 °C. Наконец, была установлена корреляция между прочностью на сжатие и пористостью для трех типов бетона. Эта зависимость позволяет надежно оценивать прочность бетона, содержащего различные типы волокон, при воздействии высоких температур.

Ключевые слова: обычный бетон; волокна из куриных перьев; полипропиленовые волокна; высокая температура; корреляция между прочностью на сжатие и пористостью.