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Research Article

Effect of carbon fibers on the mechanical properties of steam-cured concrete

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ABSTRACT

While the use of the steam-curing method in the precast concrete can result in an early high compressive strength and thus can increase the production rate of structural elements, it should be noted that the steam-curing method has some negative effects on the mechanical properties of concrete due to the fact that the high-temperature steam causes micro-cracks. On the other hand, the inclusion of carbon fibers enhanced the overall mechanical properties in terms of high tensile strength and modulus of elasticity. This paper aimed to investigate the effect of adding carbon fibers to steam-cured concrete. Twenty-seven cube specimens of 15 cm dimensions were used to investigate the unit weights, the ultrasonic pulse velocity, the compressive strength, and the split tensile strength of the concrete. Three different mixes were made by adding carbon fibers (0%, 0.12% and 0.24%) by weight to the concrete. Three of each were kept in a standard curing environment for 3, 7 and 28 days. Three specimens of each mix were steam-cured for 4 hours, and three specimens were steam-cured for 8 hours. The result showed a significant increase in the rate of gaining compressive strength under steam-curing with an enhancement in the tensile strength due to the presence of fibers, all without compromising the integrity of the concrete and without increasing the amount of voids.

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1. Introduction

As a result of the rapid development around the world, there is always a need to build structures at a lower cost and in a shorter time without compromising the quality. Therefore, researchers focus on developing the production process of structural elements rather than relying on improving project execution techniques. Using precast concrete is one of the best ways to achieve this in reinforced concrete structures (Ba et al. 2011). One of the main advantages of precast concrete is to increase the production rate in many ways. One of the most cost-effective ways is by accelerating the concrete curing process (Shi et al. 2020; Hanif et al. 2017).

Various methods are used for accelerating the concrete hardening process, to gain higher early-age performance. Steam-curing is one of the most widely used accelerated curing methods, which proved numerous advantages in terms of the material characteristics such as less permeability, intent microstructures, high mechanical properties, and more hydrated products at early stages (Ba et al. 2011). However, the steam curing method demonstrated disadvantages in terms of long-term compressive strength, micromechanical properties. Based on Liu et al. (2020), a dense region around the cement particles formed as a result of the rapid hydration caused by the steam curing heating result in an expansion of the gas-liquid phase inside the concrete which produces micro-cracks.

One of the methods used to improve the mechanical properties of concrete is to add fibers to the concrete mix (Yang et al. 2017; Guo et al. 2021). Fiber admixture con-

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tributes to increasing the concrete's resistance to compressive and tensile loads, as well as its resistance to cracks expansion. The behavior of fiber reinforced concrete varies according to the type, length, and density of the fibers used (Zhang et al. 2019). Considering its corrosion and high-temperature resistance, as well as high tensile strength and modulus of elasticity, carbon fiber is recommended over other types of fibers.

The effect of fibers on the behavior of concrete has been tested by many researchers. According to Mastali et al. (2017), the mechanical properties of fiber reinforced concrete, as well as the impact resistance, can be improved by increasing the length of carbon fiber and the volume fraction. (Rangelov et al. 2016) investigated the differential impact of carbon fiber sizes and combine them with cement mortar mixtures. The result showed an increase by (4–11%) of the 28-day compressive strength and 7-day tensile strength increased by (11–46%). Xiong et al. (2019) demonstrated that when carbon fiber dosage increases a clear improvement in Vickers hardness, fracture toughness, and the ultimate capacity when they studied the mechanical behavior of carbon fiber reinforced concrete. Yakhlaf et al. (2013) investigated carbon fibers effect on the physical properties of self-consolidating concrete. The study concluded that (filling ability and passing ability) inversely correlated with the amount of carbon fibers. However, the amount of carbon fibers had no negative impact on the segregation resistance of concrete.

On the other hand, other studies focused on the mechanical properties of carbon fiber reinforced concrete that has been exposed to high temperatures. The effect of post high temperature on the elastic modulus, compressive strength, and toughness of fiber reinforced concrete have been researched by Dügenci et al. (2015). The study found that 1.0% fiber additive had a minimum loss of compressive strength of fiber reinforced concrete that exposed to a high temperature. Varona et al. (2018) and Wang et al. (2021) suggested a formula to the progression of mechanical behavior post exposure to high temperatures, as a result of their investigation of the mechanical behavior of fiber reinforced concrete,

Most of the above-mentioned studies focus on investigating the mechanical properties of fiber reinforced concrete under standard curing conditions or after exposure to high temperatures, while carbon fiber reinforced concrete was not investigated under steam curing conditions. This paper aims to investigate the effect of steam curing on the compressive strength, the Ultrasonic pulse velocity, unit weights, and the split tensile strength of concrete for cubic specimen of concrete reinforced with different ratios of carbon fibers under different steam curing periods and comparing it with specimens tested 28 days later under standard curing conditions.

2. Experimental Study

2.1. Materials

Three types of crushed aggregates were used in casting concrete cube specimens. The particle size analysis of the aggregate mixture used can be seen in Fig. 1. The density of the fine aggregate of sizes (0-4 mm), (4-11.2 mm) and (11.2-22.4 mm) were 2.69, 2.70 and 2.71 g/cm^3, respectively.

Table 1 shows the properties of the new generation of superplasticizers that were used as an admixture for the concrete.

Carbon fibers added to the concrete mix are shown in Fig 2. The properties of fibers are given in Table 2. The fibers have been used up to 0.24% by weight of the concrete.

The type of cement used is CEM I.42.5 R Portland cement, the chemical and physical properties of the cement used are given in Table 4. Tap water was used for mixing the specimen, the physical and chemical properties of the water used can be shown in Table 3.

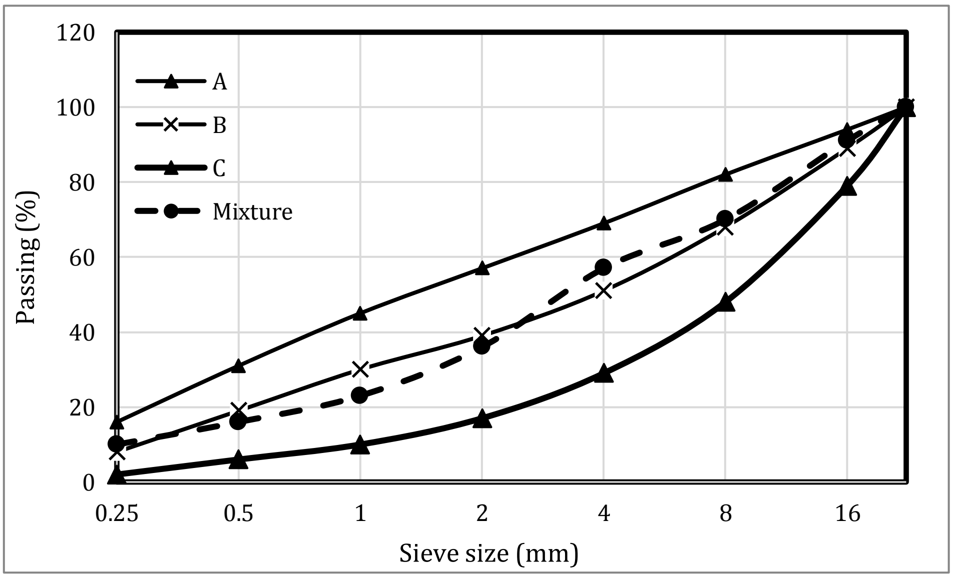

Fig. 1. Granulometry of aggregate mixture according to EN 12620.

Table 1. Properties of admixture.

Chemical Structure	Appearance	Cl, %	pH	Density, g/cm³	Alkali, %
Polycarboxylic ether	Brown	≤ 0.10	5-7	1.069-1.109	≤ 3.00

Table 2. Properties of carbon fiber.

Tensile Str., MPa	Tensile Mod., GPa	Strain, %	Density, g/cm³	Yield, g/1000m
240	4200	1.8	1.78	800

Fig. 2. Carbon fiber.

Table 3. Properties of mixing water.

Chemical Property, mg/l						Physical property	
Al	0.04	Cu	0.016	Ni	5.07	Conductivity, μS/cm	628
NO_3	11.1	Fe	0.007	K	6.8	Hardness, Fd⁰	30.11
NH_4	0.06	Mn	0.015	As	1.19	pH	7.35

Table 4. Properties of cement.

Chemical properties				Physical properties	
SiO_2	19.20	K_2O	0.63	Density, g/cm³	3.09
Al_2O_3	4.56	Na_2O	0.31	Specific surface, cm²/g	3190
Fe_2O_3	3.09	SO_3	3.21	Setting Time(initial), min	163
CaO	62.90	CI-	0.01	Setting Time(final), min	228
MgO	1.88	LOI	3.80	Soundness, mm	1

2.2. Method and tests

The concrete was mixed according to the ratios given in Table 5. Three different mixes were made by adding carbon fibers (0%, 0.12% and 0.24%) by weight to the concrete mixture as can be seen in Fig 3. Cube specimens of 15 cm dimensions were cast. Nine specimens of each mix were cast, three of each were kept in a standard curing environment for 3, 7 and 28 days. Three specimens of each mix were steam cured for 4 hours, and three specimens were steam cured for 8 hours.

Table 5. Mix ratio of 1 m³ of concrete mixture.

Cement, kg	Water, l	Superplasticizer, l	Aggregate, kg		
			0-4 mm	4-11.2 mm	11.2-22.4 mm
435	125	3.5	967	333	555

At the end of the curing process, unit weight, ultrasonic pulse, split tensile strength and compressive tests were carried out on the specimens as shown in Fig 4. Examination of the changes in the unit weight, ultrasonic pulse velocity, splitting tensile strength and compressive strength for each fiber ratio, curing condition and curing duration was carried out and the results will be discussed in further sections.

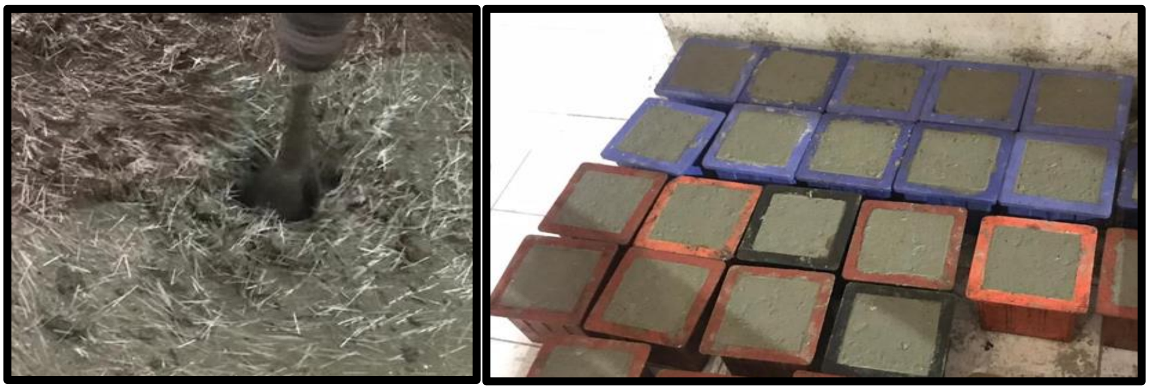

Fig. 3. Adding carbon fiber to the fresh concrete (left), and cube specimens (right).

Fig. 4. Ultrasonic pulse velocity and mechanical tests.

Fig. 5. Steam curing.

3. Discussion

Average unit weight test results are shown in Fig 6. Specimen unit weights varied from 2407 to 2480 kg/m^3. As it can be seen from the figure, the increase in the fibers caused the unit weight values to increase. In 0.12% fiber concrete mix, the unit weights of the specimens increased by 1.4% compared to the mix without fibers, while in 0.24% fiber concrete mix, the increase in unit weights reached 2.1%. Moreover, since the fiber addition affects the workability of the fresh mix, the voids formed during the setting caused the unit weights to increase at different rates for each fibre content. As the curing time increased, the unit weights for fibrous specimens increased up to 2.2%, which is a significant increase compared to the non-fibrous specimens. The increase in unit weight was caused by the formation of cement reaction structures that filled the voids.

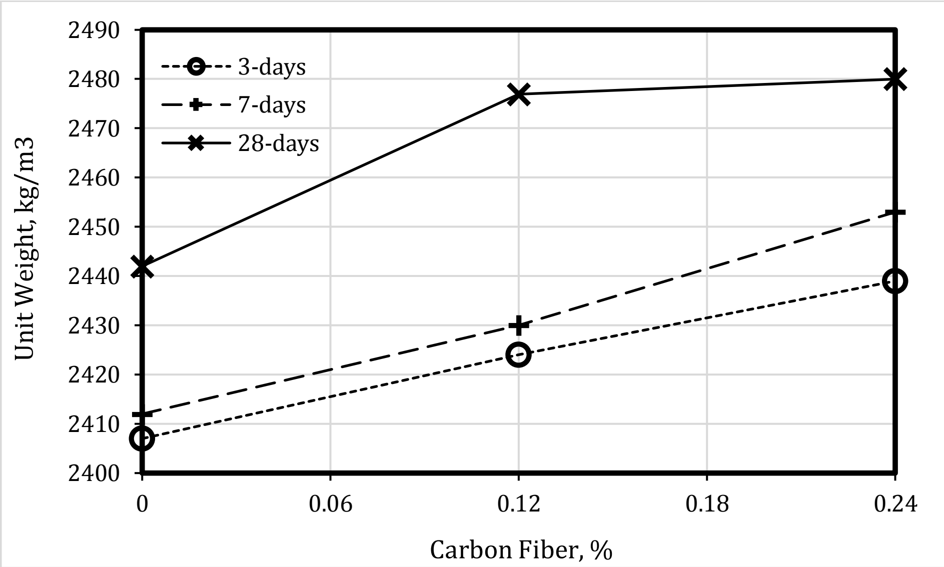

Fig. 6. The effect of fiber ratio on unit weights of concrete specimens.

Changes in ultrasonic pulse velocity for carbon fiber content mix are shown in Fig 7. It can be noted that the ultrasonic pulse velocities were increased with increasing carbon fiber content. While this increase was 0.9% in the case of 0.12% carbon fiber mix, the increase rate reached 5.7% when the carbon fiber ratio was 0.24%. This increase can be due to fibers acting as bridges, allowing ultrasound vibrations to be transmitted through the fibers instead of being transmitted through the pores. As the curing time increased, the ultrasonic pulse velocities increased up to 4.7%, this might be caused by filling of the voids by the hydration reaction products formed over a longer hydration time. The highest ultrasonic pulse velocity value was observed in specimens containing 0.24% fiber for 28 days, the increase in ultrasonic pulse velocities with the increase in fiber content was more pronounced in specimens tested after 28 days.

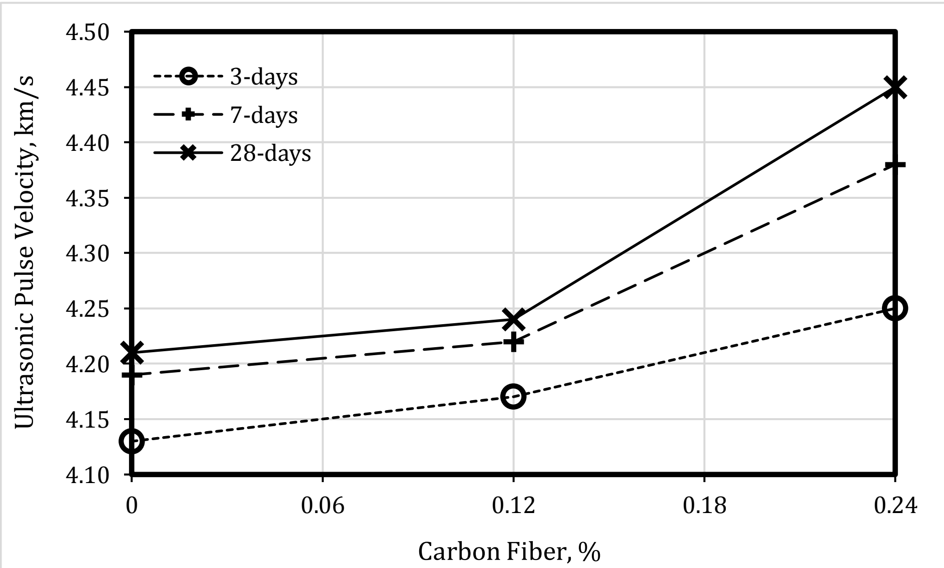

Fig. 7. The ultrasonic pulse velocity rate of concrete under various carbon fiber ratios.

The resulting compressive strength values for each curing time and fiber content can be seen in Fig 8. Compressive strength results were shown to increase with increasing fiber content, this was caused due to the crack growth and branching of micro-cracks formed as the loads were increased in the fiberous mix specimens. While this increase was 7.6% in the case of using 0.12% fiber, the strength reached 14.2% in the 0.24% fiber mix. Examination of the changes of the compressive strength with the curing time showed that the specimens reached 64.1% of the 28-day compressive strength on the 3rd day, and 81.7% on the 7th day. It can also be observed that in the case of 0.24% fiber content mix, the effect of increasing the fiber content is more notable at early ages.

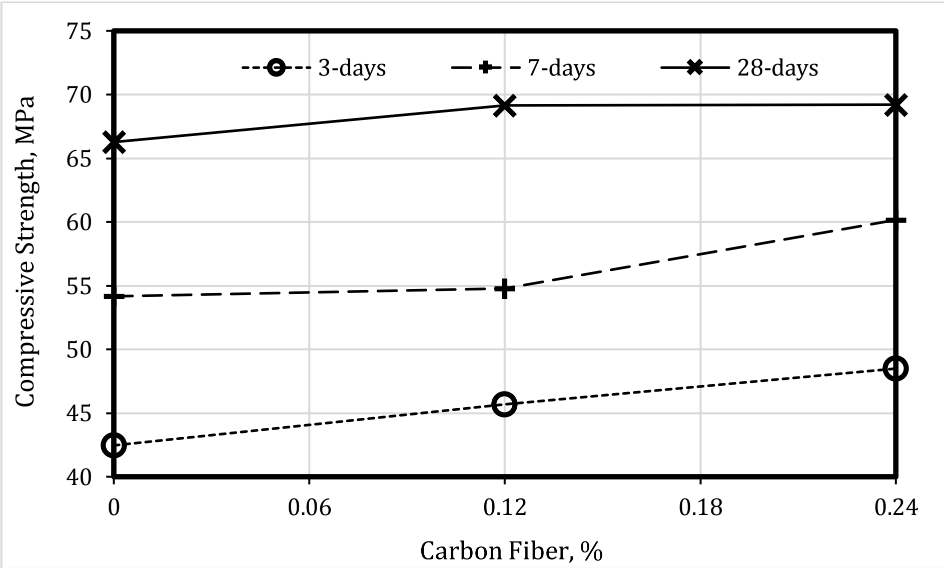

Fig. 8. The compressive strength of concrete under various carbon fiber ratios.

Variation in split tensile strengths for the mixes are shown in Fig. 9. It can be seen that the increase in splitting tensile strength of the specimens increased by 12.1% when the fiber ratio was 0.12%, while it reached a 23.1% increase when the fiber ratio was 0.24%. Due to the brittleness of concrete, there is a sudden loss of strength, particularly after the development of the first crack under the tensile effect. Although the fibers could not prevent the formation of the first crack, they prevent the crack growth and propagation until fibers lose their bond with the binder. This explains the increase in splitting tensile strengths. Therefore, the use of fibers is advantageous as it reduces the brittleness of the concrete mixture under tensile stresses. Cement hydration reactions over time caused an increase in the calcium silicate hydrate gels, this not provided compressive strength gains but also enhanced the tensile strength, which explains the increase in the tensile strength over longer curing times. The tensile strength of the fibrous mixes significantly had a significant enhancement in early splitting strength, a similar effect was noted in the compressive strength behavior discussed earlier. However, unlike compressive strength, the increase in fiber ratio caused a significant increase in splitting tensile strength in 28 days.

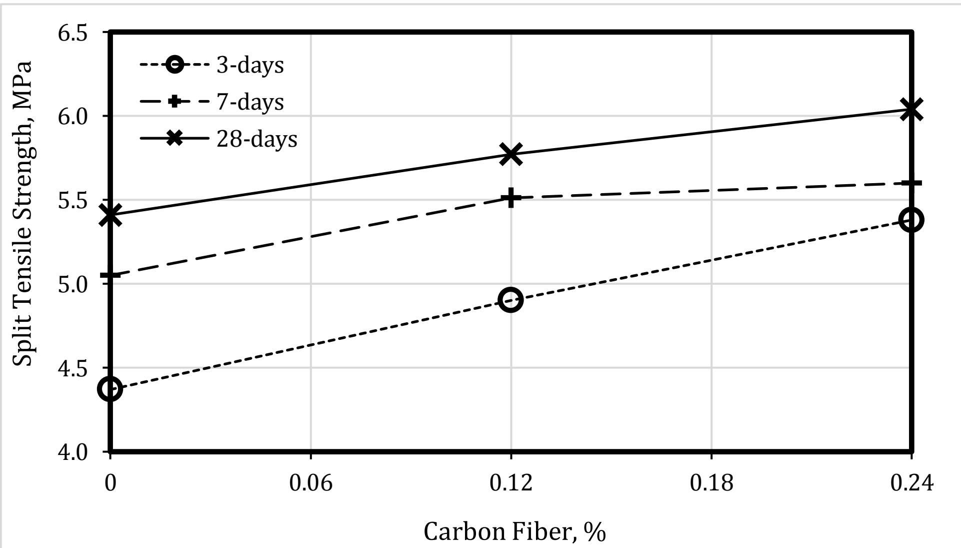

Fig. 9. The split tensile strength of concrete under various carbon fiber ratios.

Variation of unit weight values under the effect of steam curing for each mix are shown in Fig. 10. While the unit weights of the steam cured specimens reached 98% of the reference specimen, a negligible increase of 0.4% was observed in the unit weights of the specimens with the increase in the steam curing application time, therefore there was no negative effect of steam curing on the unit weights of the specimens. It also should be noted that with the increase in the fiber content with steam curing, the unit weights of the specimens increased by 1.3%.

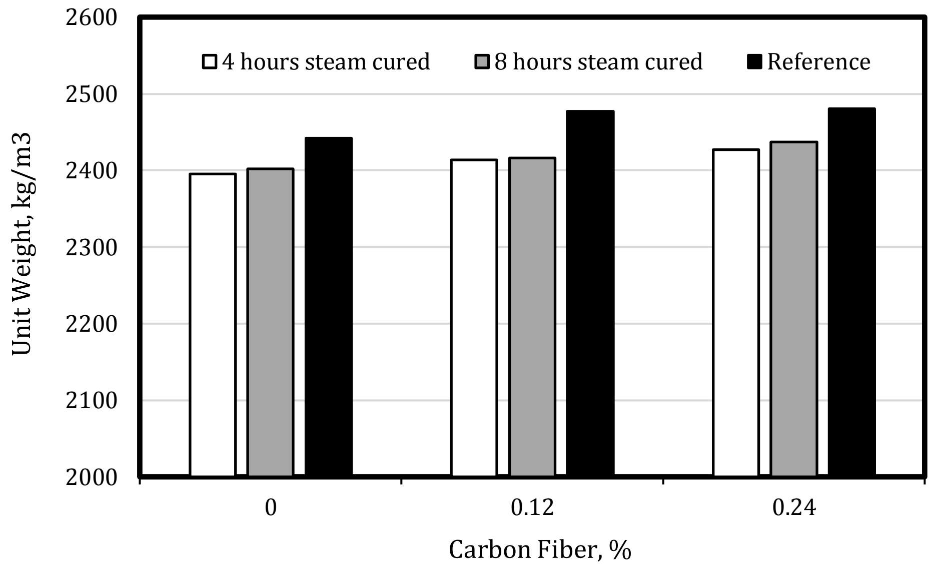

Fig. 10. Comparing the unit weight of steam-cured concrete under various curing durations and carbon fiber ratios to the reference specimens.

Variation of ultrasonic pulse velocity of specimens with steam curing time and fiber ratio is shown in Fig 11. The ultrasonic pulse velocity of the 4 hours steam cured specimens was 95.7% of the ultrasonic pulses of the reference specimen, while this rate reached 97.9% when the steam curing time was 8 hours. With the increase in fiber content, there was a decrease in the variation between the ultrasonic pulse velocity for different steam curing application times, notably for fiber content of 0.24%, this rate decreased to 0.2%. However, a decrease in rates up to 6.4% was observed for the specimen of steam cured specimens with fiber content of 0.24% compared to the reference specimen. This effect might be due to the increase in the hydration reaction rate in the concrete with the application of steam curing, causing the filling of the internal structure and the formation of cement products in a short time, which in turn caused a significant rate of ultrasonic pulse velocities compared to the reference.

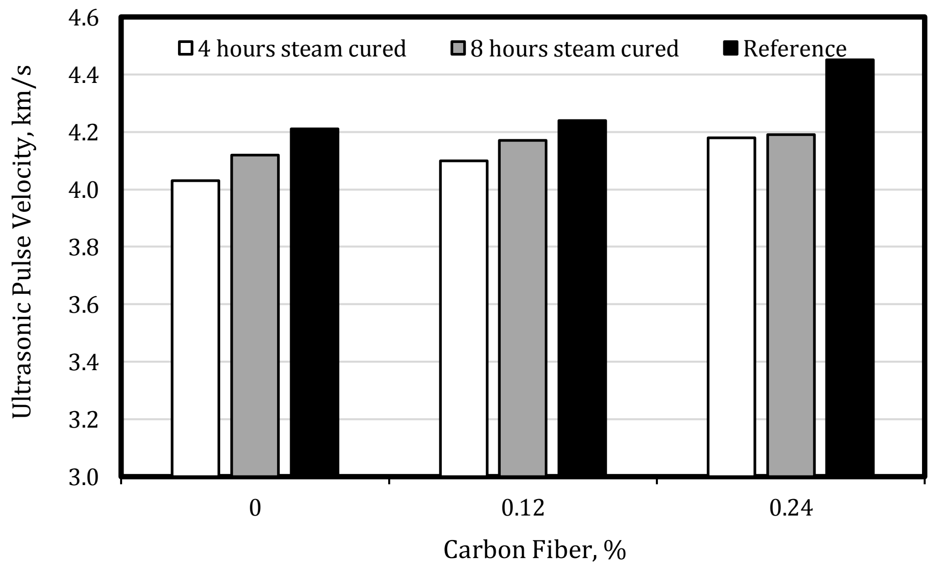

Fig. 11. The ultrasonic pulse velocity rate of steam-cured concrete under various carbon fiber ratios.

In Fig. 12, the change in compressive strength of specimens with fiber ratio and steam curing time are shown. In the case of the compressive strengths of non-fibrous specimens, and when taking the compressive strength of the 28-day normal concrete as a reference, around 45.7% of this strength was reached when the 4 hours-steam curing was applied, and 56.7% of the compressive was reached when steam curing for 8 hours. In precast concrete applications, it is important to reach about half of the 28-day strength in a short time (e.g., 4 hours). The strengths obtained for steam cured specimens are accelerated by the effect of curing temperature due to the formation of calcium silicate hydrate gels with a more robust structure. In addition, the water loss that would have resulted due to this temperature is prevented as a result of the saturation of steam. In the case of different fiber content specimens, the 5% compressive strength increase in the reference specimens was reduced to 3% in steam cured specimens. When the steam curing time increased from 4 hours to 8 hours, the compressive strengths increased by 25% even when fibers are added. Therefore, increasing the steam curing time does not increase the strength at the same rate.

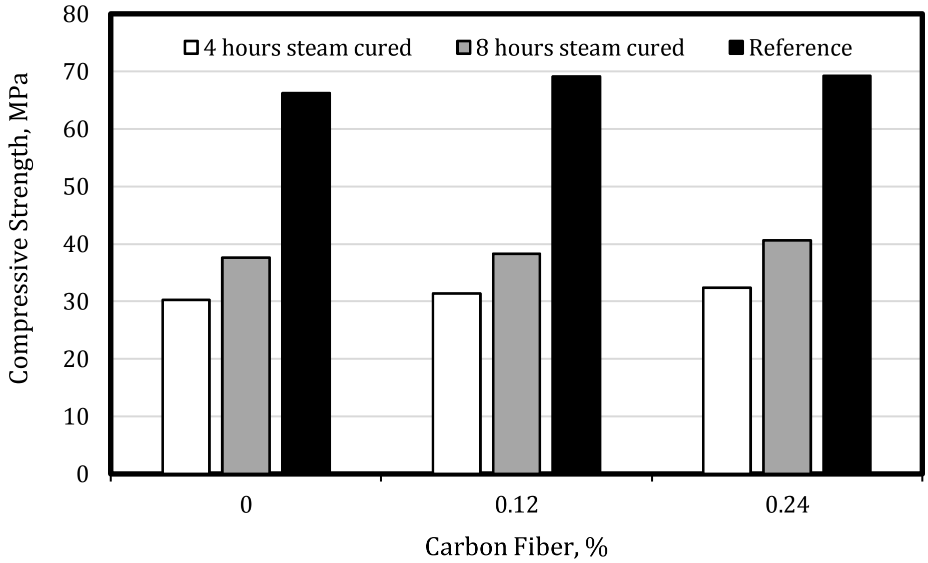

Fig. 12. The compressive strength of steam-cured concrete under various curing duration and carbon fiber ratios.

The effect of steam curing and carbon fiber ratio on the splitting tensile strength is illustrated in Fig. 13. An increase of 27% was observed in the split tensile strength of the fibrous specimens kept in steam curing for 4 hours, while the increase rate reached 17% in the specimens kept in steam curing for 8 hours. With the addition of fiber, crack control in the hardened cement paste was achieved. Although it is important to gain strength quickly with steam curing, particularly after the concrete has hardened, the split tensile strengths of the fibrous specimens with 4 hours and 8 hours steam curing gave close results. It is evident that the fibers have a very significant effect on the tensile effect, it can be observed that the split tensile strength of the non-fibrous specimens, which were steam cured for 4 hours, reached 47.5% of the split tensile strength of the reference concretes, while this ratio was 64.8% in the 8-hour steam curing.

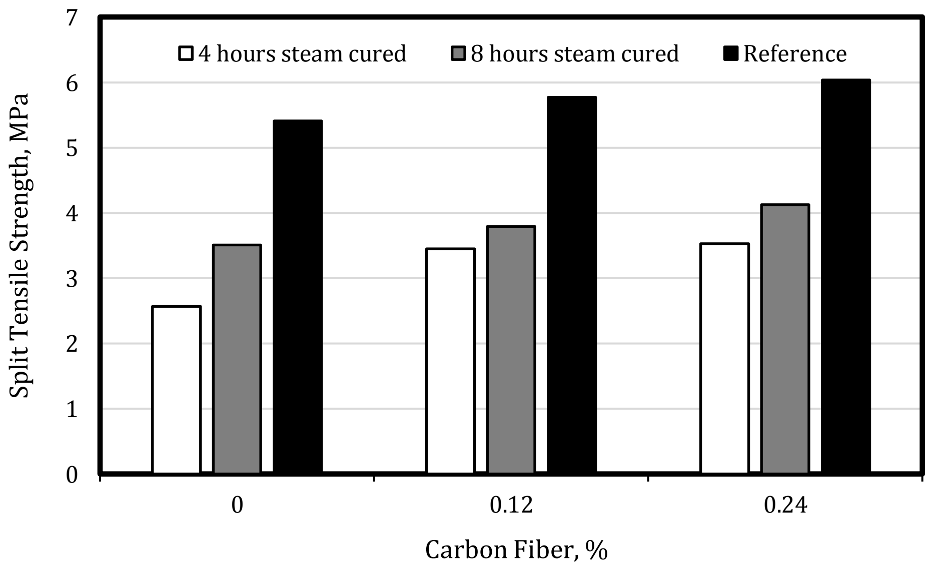

Fig. 13. The split tensile strength of steam-cured concrete under various curing duration and carbon fiber ratios.

4. Conclusions

The following results have been achieved with the experimental study conducted:

- The addition of carbon fiber increased unit weights, Ultrasonic pulse velocity, compressive strength, and split tensile strength of the concrete. Interestingly, the largest increase has occurred in the split tensile strength. The evidence from this study suggests to use 0.24% carbon fiber for tensile strength, while 0.12% fiber is sufficient for compressive strength. An implication of this is the possibility that carbon fiber can be used in places where strength is important at early ages, since fibers positively affect the mechanical properties of concrete at an early age.
- As the steam curing application time increased, very low increases were observed in the unit weights of the specimens, around 0.2%, and very low increases in the Ultrasonic pulse velocity around 2.2%. This finding suggests that steam curing does not impair the integrity of the concrete and does not increase the amount of voids. Steam curing is especially applied to improve the early age mechanical properties of concrete. This study has shown that as the steam curing time increased, the compressive strengths increased by 25% and the splitting tensile strengths increased by 36.5%. This study has also found that compressive strengths of 30 MPa have been reached with 4 hours of steam curing. According to the results of compressive strength under normal conditions, additional steam curing is not recommended unless very high compressive strength is required, since 8-hour steam curing does not increase much compared to 4-hour application.
- The unit weight of the specimens increased by 1.5%, the ultrasonic pulse velocity by 3.7%, the compressive strength by 8.2%, and the splitting tensile strength by 37%, with the increase in the carbon fiber ratio used in the steam cured specimens. While the effect of steam curing on the rate of gaining compressive strength is very high, it has been observed that it has a positive effect of the fibers on the tensile strength of the specimens. For the fact that stem curing imposes the precast elements under aggressive conditions, the use of carbon fiber is recommended to control cracks caused by internal tensile stresses that may arise from these effects.

The results of this study indicate that the addition of carbon fiber to improve the concrete mechanical properties did not adversely affect the strength gain rate under the effect of steam curing. While steam curing is highly preferred in the precast sector in practice, it has been observed that fibers are not used in the production of concrete or reinforced concrete elements. The results of this research support the idea of increasing the use of fibers in this sector, especially in order to increase the mechanical properties and crack control performance. A further study could assess the long-term effects of steam curing performance of fiber use and the control of cracks that may occur in an aggressive environment, especially in precast concrete, with fiber.

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Conflict of Interest

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