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Post Heat Exposure Properties of Steel Fiber Reinforced Concrete

Lect. Sallal Rashid Al-Owaisy
Civil Engineering Department, College of Engineering
Al-Mustansiriya University, Baghdad, Iraq

Abstract

In this work, five destructive and nondestructive tests using three different types of specimens were carried out to study the mechanical properties of steel fiber reinforced concrete before and after exposure to elevated temperatures. Forty-five (100 mm) concrete cubes were used to investigate both concrete compressive strength and ultrasonic pulse velocity (UPV), while the flexural strength and dynamic modulus of elasticity (ED) were studied using forty-five (100x100x500 mm) prisms. Also, the splitting tensile strength was studied using (100 mm) diameter and (200 mm) height cylinders. These specimens were heated to four temperature levels of (150, 350, 500 and 700 ^{o}C). A single concrete mix with three steel fiber contents (Vf %) of (0.0, 0.5 and 1.0 %) by weight was adopted.

The test results of this study show that the use of steel fibers enhance the brittle mode of failure of concrete both before and after exposure to high temperatures and that exposure to elevated temperatures affects all concrete properties, however, the amount of strength decrease depends mainly on the type of stresses in each test and on the level of temperature. Another observation is that the presence of steel fibers enhances splitting tensile strength, flexural strength, and ED significantly, while this effect seems to be less significant or even insignificant for compressive strength and UPV.

الخلاصة

أجريت في هذا البحث خمسة أنواع من الفحوص الإتلافية واللاإتلافية باستخدام ثلاثة أنواع من النماذج الخرسانية لدراسة بعض الخواص الميكانيكية للخرسانة المسلحة بالألياف الحديدية قبل وبعد التعرض إلى درجات الحرارة المرتفعة. تم استخدام خمسة وأربعين نموذجاً خرسانياً مكعباً بقياس (١٠٠ملم)لدراسة مقاومة إنضغاط الخرسانة وسرعة الأمواج فوق الصوتية، بينما تم دراسة مقاومة الإنثناء ومعامل المرونة الديناميكي باستخدام خمسة وأربعين من النماذج الخرسانية الموشورية بأبعاد (١٠٠x١٠٠x٥٠٠ملم). كما تم دراسة مقاومة الإنفلاق للخرسانة باستخدام خمسة وأربعون نموذجاً اسطوانياً بقطر (١٠٠ملم) وارتفاع (٢٠٠ملم). تم تعريض النماذج إلى أربعة مستويات من الحرارة وهي (١٥٠، ٣٥٠، ٥٠٠، و ٧٠٠ ° س). تم استخدام خلطة خرسانية موحدة لجميع النماذج مع ثلاثة نسب وزنية مختلفة من ألياف الحديد (٠.٠، ٠.٥ و١.٠ %).

تشير النتائج العملية لهذا البحث إلى تحسن في الطبيعة الهشة للخرسانة عند الفشل قبل وبعد التعرض إلى درجات الحرارة العالية كما تشير إلى أن التعرض إلى درجات الحرارة العالية يؤثر على كل خواص الخرسانة ولكن بمقادير مختلفة تعتمد بالدرجة الأساس على نوع الإجهادات في كل فحص وعلى درجة حرارة التعرض. كما تشير النتائج إلى أن استخدام الألياف الحديدية أدى إلى تحسن ملحوظ في مقاومة الإنفلاق و مقاومة الإنثناء ومعامل المرونة الديناميكي للخرسانة بينما كان أقل تأثيراً أو غير مؤثر على مقاومة اللاإنضغاط وسرعة الأمواج فوق الصوتية.

1. Introduction

One of the problems of cement-based matrix is the inherently brittle type of failure, which occurs under tensile stress systems, and the low tensile and flexural strength of plain concrete. Therefore, the use of spread steel fiber wires can be consider as a solution to control cracking and to alter the mode of failure to more ductile failure type by increasing the post-cracking ductility, and consequently improve concrete properties, especially tensile and flexural strengths.

Exposure to elevated temperature as in the case of accidental fires is known to deteriorates concrete properties by the initiation of thermal cracks and propagation of these cracks and the previously existed cracks in concrete members, which leads to a decrease in concrete strength and causes further deterioration in concrete members. Therefore, this study was directed to investigate the ability of steel fiber to improve concrete properties at high temperature exposure.

2. Experimental Work

In this study three types of specimens were used to investigate the behavior of five concrete properties. 100mm Cubes were used to obtain compressive strength and ultra sonic pulse velocity (UPV), (100x100x500 mm) prisms to study the flexural strength (modulus of rupture) and the dynamic modulus of elasticity (ED), and finally (100mm) diameter by (200mm) length cylinders were used to investigate splitting tensile strength. A single concrete mix of (1: 1.5: 3) (cement: sand: gravel) in proportion by weight, and water/cement ratio of (0.5) was used in this study. Two main variable were investigated, the first was the steel fiber content, where three fiber contents (Vf %) of 0.0, 0.5 and 1.0 % by weight were used. The second variable was temperature, where four temperature levels of 150, 350, 500 and 700 ^{o}C were investigated. Concrete mixes were mixed according to the fifth mixing procedure recommended by ACI committee [1]. Three specimens were tested at each temperature level; therefore fifteen specimens were tested for each fiber content. A total of forty-five cubes, forty-five prisms and forty-five cylinders were used in this study to investigate compressive strength, UPV, flexural strength, ED and splitting tensile strength.

The cement used in this investigation was ordinary Portland cement (type I) manufactured in Kubaisa factory according to (IQS:5). Locally graded fine aggregate and graded rounded river gravel with maximum size of aggregate of (19mm) were used. The used steel fiber was crimped 0.5mm diameter, 30 mm length and 1050 MPa yield strength.

Twenty-four hours after casting, the specimens were stripped from the moulds and placed in water containers to be cured for fourteen days. Then after, the specimens were removed from the water containers and left in the laboratory environment until the time of heating at age of twenty-eight days. The specimens were heated slowly at a constant rate of about (2 ^{o}C/min) using electrical furnace. Once the required temperature was attained, the specimens were thermally saturated for one hour at that temperature, and then air cooled until the time of testing about twenty hours later.

3. Results and Discussion

The effects of steel fiber content on some destructive and nondestructive properties of concrete at normal temperatures and after exposure to elevated temperature were investigated in this study.

3-1 Concrete Properties at Normal Temperatures

The effect of fiber addition on the studied concrete properties, at normal temperatures is discussed in this section.

The addition of fibers up to (1%) by volume was observed to cause a slight enhancement on some concrete properties, while some other properties were significantly affected by the fiber addition. On the other hand, the ultra sonic pulse velocity showed a very little decrease after steel fiber addition.

A significant notice is that for all destructive tests, the addition of fibers altered the mode of failure of the test specimens, from brittle failure for plain concrete to a more ductile failure in the presence of fiber.

3-1-1 Concrete Compressive Strength

Figure (1) shows the effect of addition of steel fibers on concrete compressive strength. It is shown that the addition of fiber volume fraction (Vf %) of (0.5 %) increased compressive strength from (34 to 34.2 MPa), while after the addition of (1.0 %) of steel fiber, compressive strength reached (36.6 MPa) with a percentage increase of about (8%). Thus it can be concluded that the addition of fibers up to (1.0 %) by volume, causes only a little increase in concrete compressive strength. These results confirm that fibers usually have only minor effect on the compressive strength, slightly increasing or decreasing the test results [2].

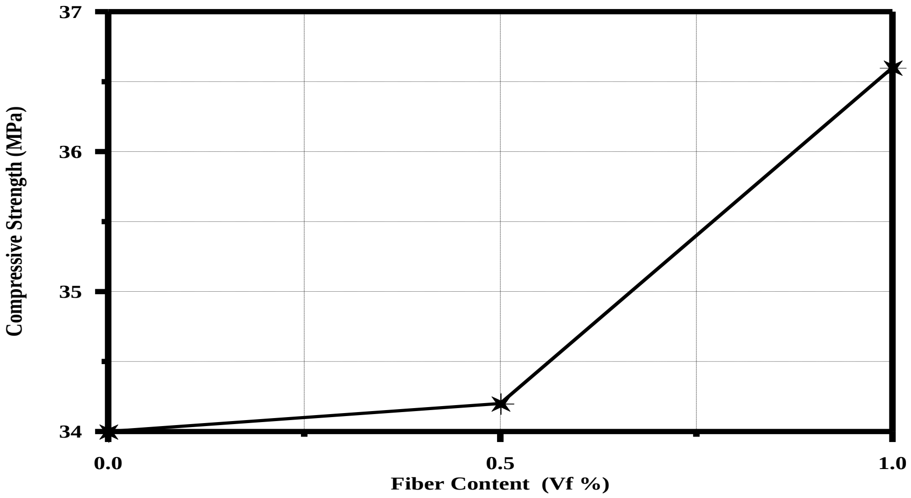

Figure (1) Effect of fiber content on concrete compressive strength

3-1-2 Splitting Tensile Strength

When (0.5%) by volume of fiber was added, there was no gain in splitting tensile strength of concrete, while when (1.0 %) fiber was used, the splitting tensile strength increased from (2.7 to 3.18 MPa), with a percentage increase of (17.8 %), as shown in **Fig.(2)**. This increase in tensile strength is expected, since steel fiber wires work as a spread reinforcing elements in the matrix, which means that fibers inhibit crack propagation in the matrix, and consequently enhance the behavior and the strength of concrete.

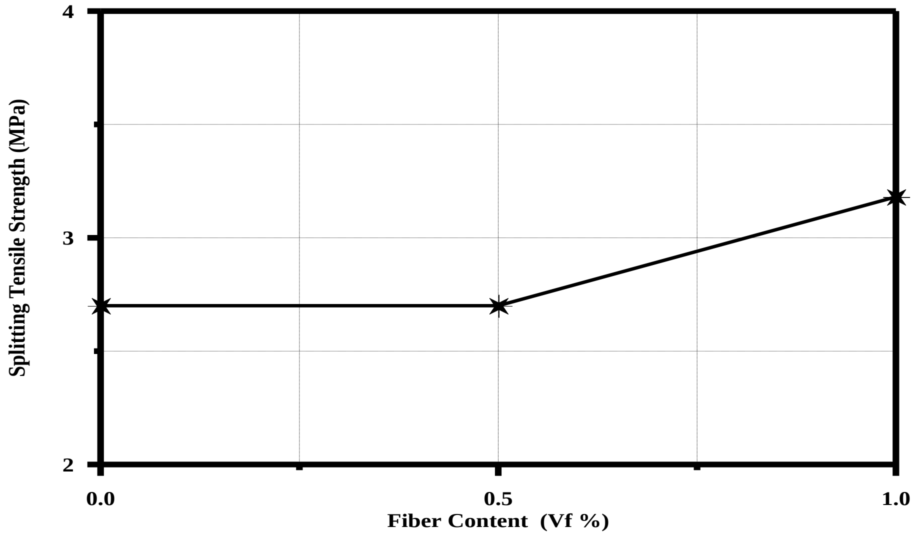

Figure (2) Effect of fiber content on splitting tensile strength

3-1-3 Flexural Strength

Since flexural strength (modulus of rupture) depends mainly on the tensile capacity of the concrete matrix, fiber addition influenced flexural strength significantly, as shown in **Fig.(3)**. The flexural strength of concrete increased from (3.15 MPa) for plain concrete to (3.67 MPa) for a concrete matrix containing (0.5 %) by volume of steel fiber. While when (1.0 %) of fiber was used, the flexural strength increased to (5.06 MPa). This means that when (0.5 and 1.0 %) by volume of steel fiber was used, the flexural strength of the matrix was increased by (16.5 and 60.6 %) respectively. This result confirms that the influence of steel fiber on flexural strength of concrete is much greater than that for direct tension or compression [3].

3-1-4 Ultra Sonic Pulse Velocity (UPV)

Figure (4) shows the changes on UPV before and after fiber addition to the concrete matrix. It is shown that there was a very slightly decrease in UPV, which did not exceeded (2 %) in the worst case. UPV behavior after fiber addition differs from other investigated properties of concrete. It is known that as the density of concrete increases, UPV readings increase. And since steel fibers are more dense than plain concrete, where its specific gravity is about (7.84), and then the expected result is that the steel fiber reinforced concrete is more dense than plain concrete and consequently, UPV for the steel fiber reinforced concrete is higher. An explanation of this result, is the difficulty of mixing of the used type of steel fibers (crimped wire fibers), which makes the concrete mix less homogeneous and leads to the existence of some air voids near and between the collected wires in the matrix, and consequently the pulse wave will be retarded by these voids, which results in less enhancement or even some decrease in UPV.

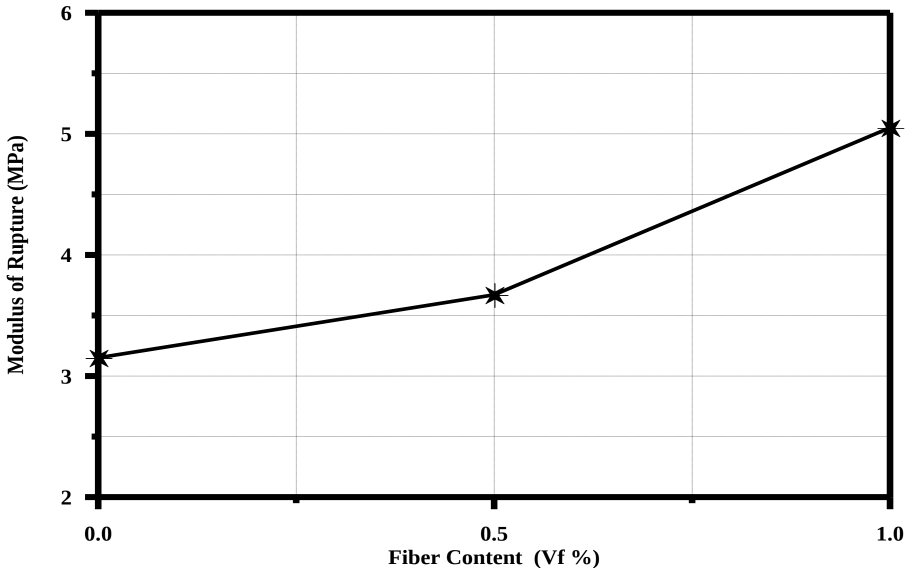

Figure (3) Effect of fiber content on flexural strength

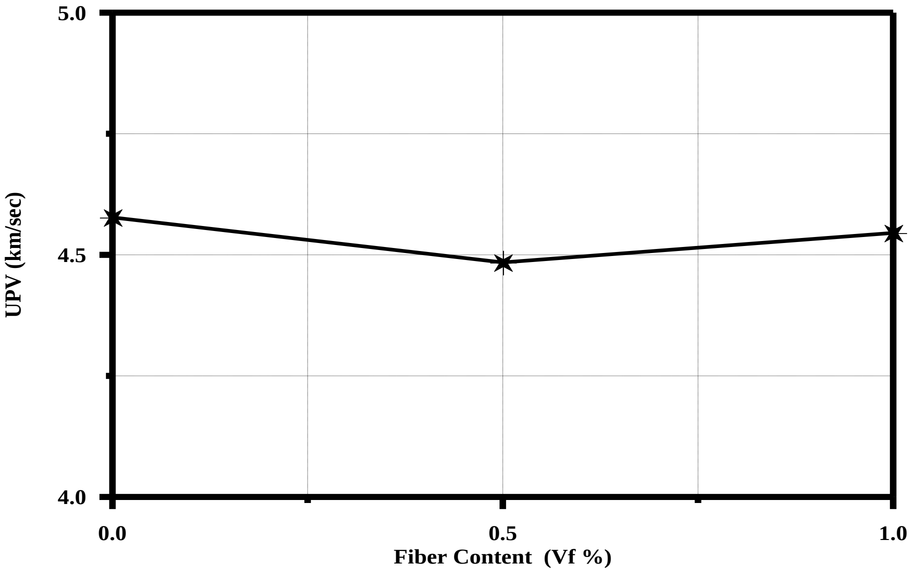

Figure (4) Effect of fiber content on UPV

3-1-5 Dynamic Modulus of Elasticity (ED)

Figure (5) shows the effect of the use of steel fibers in concrete on the dynamic modulus of elasticity. The test results of this study showed that for plain concrete, the dynamic modulus of elasticity (ED) was (26 GPa). For the concrete mix with (0.5 %) by volume of steel fiber, ED increased by (15.4 %) to reach (30 GPa). While the addition of (1.0 %) by volume of steel fiber, increased the dynamic modulus of elasticity to (36.6 GPa), with a percentage increase of (36.6 %).

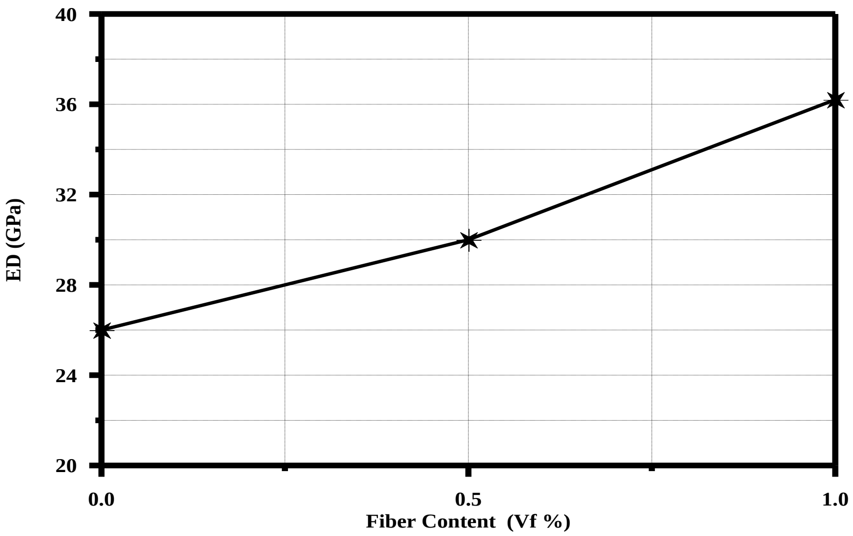

Figure (5) Effect of fiber content on ED

3-2 Concrete Properties after High Temperature Exposure

After exposure to (150, 350, 500 and 700 °C), it was noticed that the investigated concrete properties for both plain concrete and steel fiber reinforced concrete suffer a lot of changes. These changes ranged from limited loss in strength up to extreme deterioration, and even jump in strength over the original strength values in some cases. But, it can be recorded that the exposure to temperatures above (350 °C) causes a noticeable decrease in strength, for plain concrete and for steel fiber reinforced concrete. However, the enhancement of steel fiber on concrete is clear in most cases. Where the steel fiber reinforced concrete gained higher residual strength than plain concrete. On the other hand, the mode of failure was very different between plain concrete and steel fiber reinforced concrete. The plain concrete specimens showed very brittle failure at high temperature, while the steel fiber reinforced concrete specimens were significantly more ductile at the same temperature levels.

3-2-1 Concrete Compressive Strength

A lot of information is available about the behavior of concrete compressive strength for plain concrete after exposure to elevated temperatures. In some earlier investigations [4,5,6], it was found that the behavior of compressive strength of plain concrete with temperatures could be summarized in three stages. First, between normal temperature and about (150 °C) compressive strength shows some decrease, however, this decrease does exceed (20 %) in most cases. Then in the second stage, the strength tends to increase to recover some or even the full lost strength in the previous stage. The strength recovery stage was noticed to be between (250 °C) and (400 °C) [4,5,6]. Followed by the third and final stage, where compressive strength shows a noticeable decrease as temperature increase.

The results of this study completely confirm this behavior. Where for the plain concrete, the compressive strength decreased from (34 MPa) at room temperature to (29.5 MPa) at (150 °C), then the strength was increased to (31.7 MPa) after exposure to (350 °C). Beyond this temperature, compressive strength showed continuous noticeable decrease, where the residual compressive strengths at (500 and 700 °C) were only (20.5 and 12.1 MPa), respectively. Thus the percentage residual compressive strength after exposure to (150, 350, 500 and 700 °C) were about (86.8, 93.2, 60.3 and 35.6 %), respectively.

The behavior of the compressive strength of the steel fiber reinforced concrete with temperature was similar to that of plain concrete. Where similar sequence of reduction was noticed for the steel fiber reinforced concrete as shown in **Fig.(6)**. The residual compressive strength for concrete with fiber percentage volume fraction of (0.5 %) were (27.5, 32.8, 25.5 and 12.4 MPa) after exposure to (150, 350, 500 and 700 °C) respectively. Similarly for the steel fiber reinforced concrete with percentage fiber content of (1.0 %) by volume, the sequence was (33.3, 35.05, 29.19 and 12.8 MPa) respectively. **Figure (7)** shows the percentage residual compressive strength of the three groups of specimens. It is noticeable that there is only minor deviation between the percentage residual compressive strength of the three groups at (150, 350 and 700 °C). At (500 °C), the superior behavior of the steel fiber reinforced concrete is noticeable. Where the percentage residual compressive strength for concrete mix with (1.0 %), (0.5 %) of fiber and for plain concrete were (79.6, 74.6 and 60.3 %) respectively.

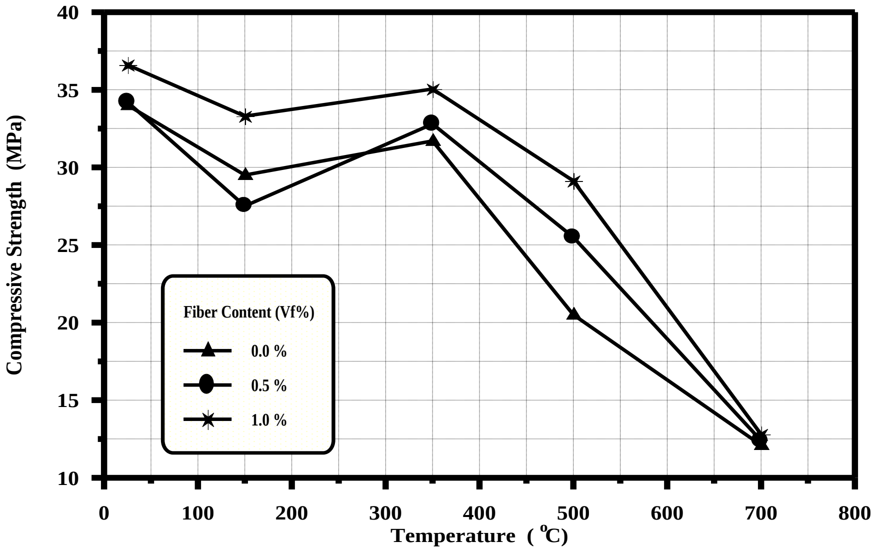

Figure (6) Compressive strength-temperature relationship for different fiber contents

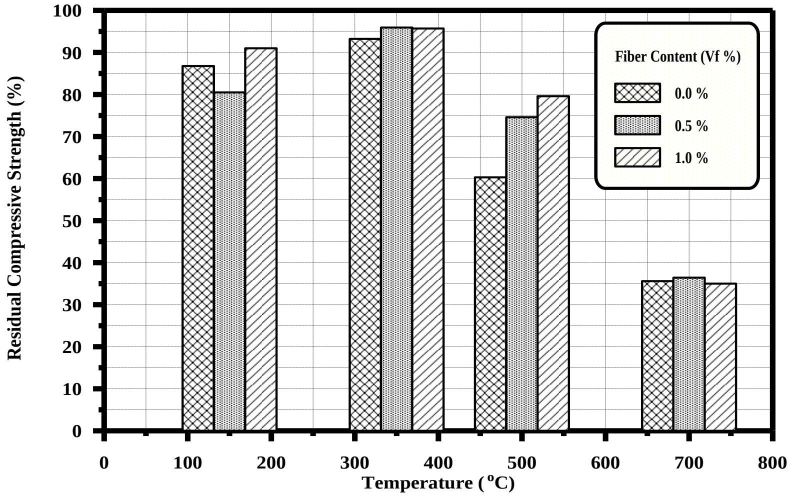

Figure (7) Percentage residual compressive strength for different fiber contents

3-2-2 Splitting Tensile Strength

Figure (8) shows the behavior of the residual splitting tensile strength with temperature. It shown that the behavior of the splitting tensile strength with temperature differs from the behavior of compressive strength, where there was no existence to the three stages that were recognized for compressive strength, instead there was a continuous decrease in strength as temperature increased. The residual splitting tensile strength after exposure to (150, 350, 500 and 700 ^{o}C) were (2.62, 1.62, 1.22 and 0.83 MPa), respectively. For the steel fiber reinforced concrete, the behavior of the splitting tensile strength with temperature was somewhat different. Where at (150 ^{o}C) the splitting tensile strength jumped to values above the original splitting tensile strength. For steel fiber reinforced concrete with (1.0 %) of fiber, the splitting tensile strength increased from (2.7 MPa) to (2.95 MPa). Similarly for concrete with (1.0 %) of fiber, the strength increased from (3.18 MPa) to (3.56 MPa). This result can be noticed in **Fig.(9)**. Where the percentage residual splitting tensile strength for concrete mixes with (0.5 and 1.0 %) were (109.7 and 112 %) respectively.

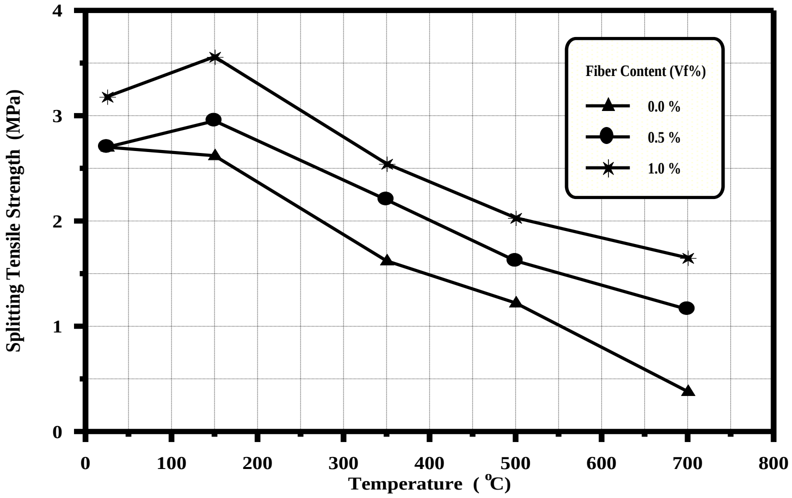

Figure (8) Splitting strength-temperature relationship for different fiber contents

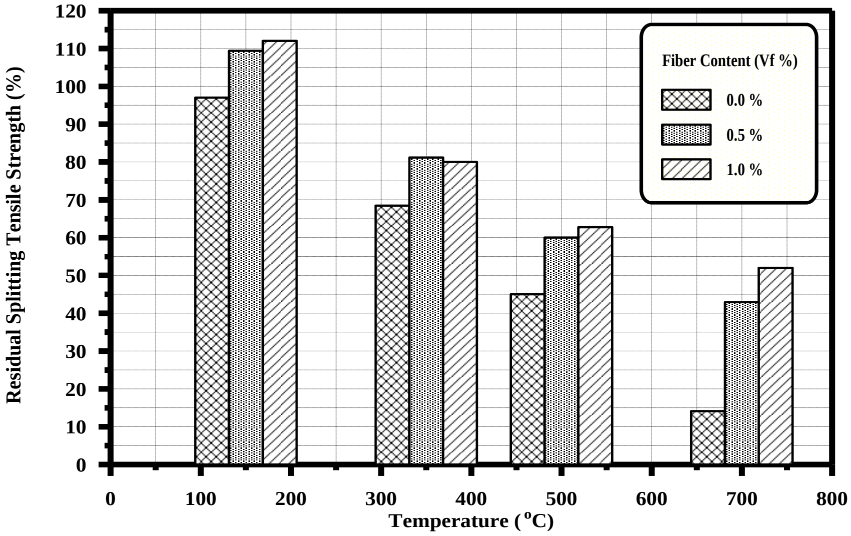

Figure (9) Percentage residual splitting strength for different fiber contents

The effect of the steel fiber presence on the behavior of the splitting tensile strength, after exposure to elevated temperatures is shown in **Figs. (8)** and **(9)**. It is noticeable that steel fiber presence enhanced the splitting tensile strength behavior after high temperature exposure. Where for all the studied temperature range, the splitting tensile strength was higher for the higher steel fiber content as shown in **Fig.(8)**. Also, the percentage reduction in strength was lower for concrete with the higher content of steel fiber. For concrete with percentage fiber content of (0.0, 0.5, and 1.0 %) by volume, the percentage reductions in splitting tensile strength were about (55, 40 and 36.3 %) respectively at (500 ^oC), and (85.9, 57.1 and 48 %) respectively at (700 ^oC), as shown in **Fig.(9)**.

These results can be attributed to the reinforcing action of the steel fiber wires, which improve the strength because of the prevention of the propagation of the cracks that occurred due to the heating process. Where a rapid drop in strength occurs beyond (350 ^oC) reflects the changes taken place with concrete due to loss of moisture (dehydration of calcium silicate hydrated in the cement paste) and thermal movement between cement paste and aggregate particles (i.e. shrinkage of cement paste and expansion of aggregate). Also, the inversion of $\propto$ quartz to β quartz causes a sudden volume change in the aggregate particles at about (573 ^oC), which also, leads to further failure in bond between cement paste and aggregate particles, in addition to the splitting of aggregate particles it selves. All these thermal processes lead to initiation and propagation of more thermal cracks, which makes the concrete more brittle and decreases the strength significantly. Thus, the presence of spread steel wires prevents or at least limits crack propagation and consequently improve both the ultimate strength and failure mode.

3-2-3 Flexural Strength

The behavior of flexural strength with temperature was the same both for plain concrete and steel fiber reinforced concrete. As shown in **Fig.(10)**, the flexural strength for the three groups showed continuous decrease as temperature increase. The residual flexural strength at (150 °C) was in the range of (2.0 to 3.4 MPa), and it was between (1.71 MPa) and (2.89 MPa) at (350 °C), while it was in the range of (1.26 to 2.35 MPa) and (0.28 to 0.73 MPa) at (500 and 700 °C) respectively. **Figure (10)** and **(11)** summarize the effect of steel fiber on the flexural strength of concrete. **Figure (10)** shows that at each particular temperature, the flexural strength of concrete with higher percentage of fiber is still higher than of the lower percentage fiber content and of plain concrete. This results, reflects the improvement occurred in flexural strength with the presence of steel fiber, both in normal temperatures and after exposure to temperatures up to (500 °C). However, the exposure to (700 °C) was very disruptive, and the little enhancement in strength with the presence of steel fiber was insignificant. Where the flexural strength deteriorated strongly to reach very low values, and to lose about (90 %) of it's original strength as shown in **Fig.(11)**.

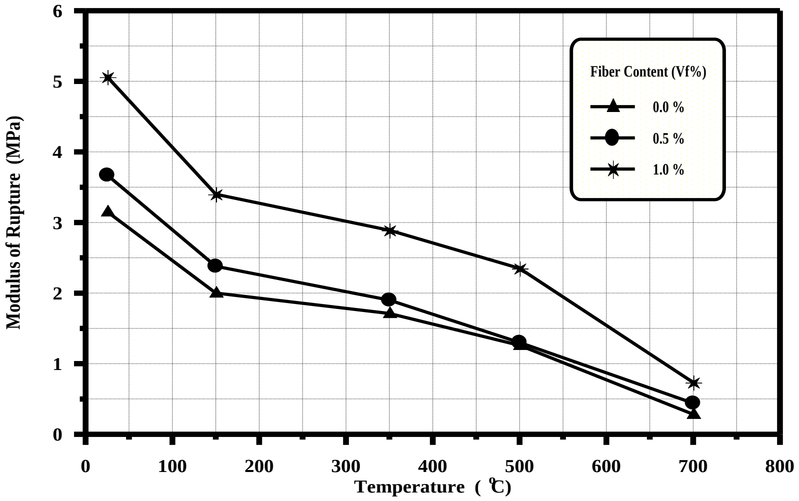

Figure (10) Flexural strength-temperature relationship for different fiber contents

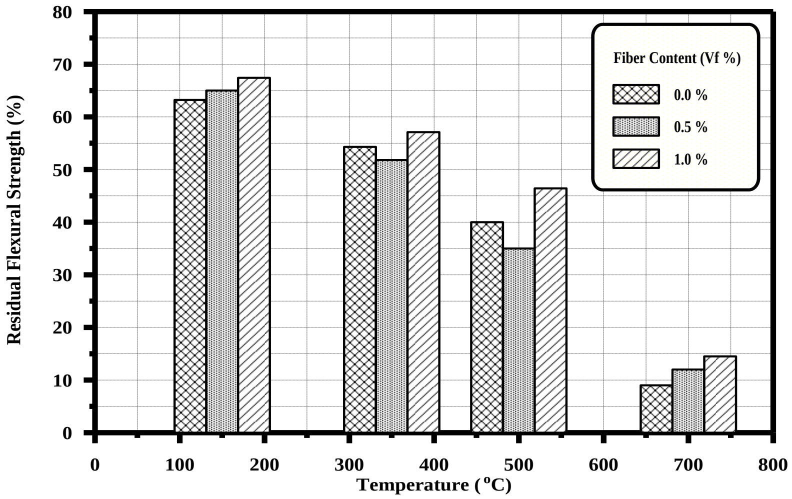

Figure (11) Percentage residual flexural strength for different fiber contents

3-2-4 Ultra Sonic Pulse Velocity (UPV)

The effect of fiber addition on the ultra sonic pulse velocity was insignificant at normal temperature, at high temperature, the same stands. Where after exposure to high temperatures, the presence of steel fiber was less important. As shown in **Fig.(12)**, UPV shows continuous decrease as temperature increase for the three groups of specimens. The sequence of UPV after elevated temperature exposure was the same with and with out steel fiber addition. For plain concrete the residual UPV values were (4.27, 3.22, 2.57 and 0.637 km/sec) after exposure to (150, 350, 500 and 700 °C) respectively. For concrete with (0.5 %) of fiber, the sequence at the same temperatures was (4.2, 3.01, 1.95 and 0.714 km/sec) respectively. Similar sequence was recorded to concrete with (1.0 %) of steel fiber. **Figure (13)** shows the percentage residual UPV with temperature. The observation of this figure confirms that the influence of steel fiber on UPV after high temperature exposure is insignificant.

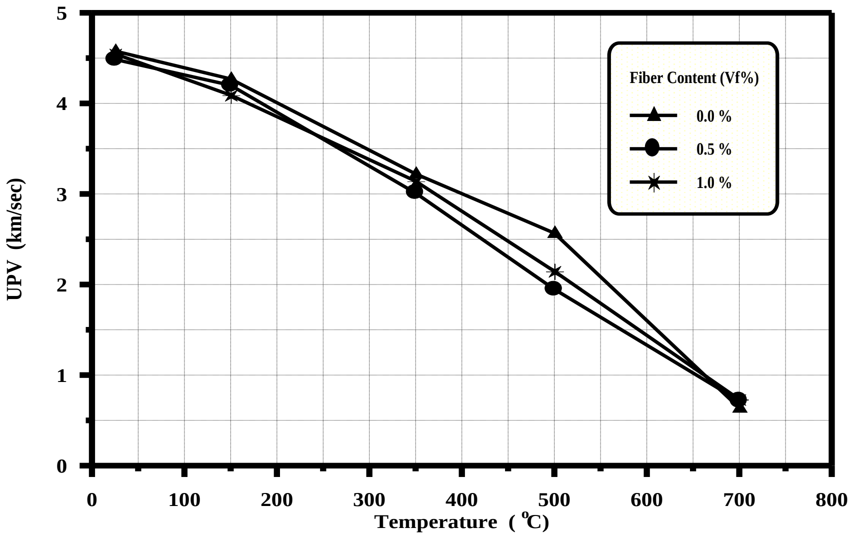

Figure (12) UPV-Temperature relationship for different fiber contents

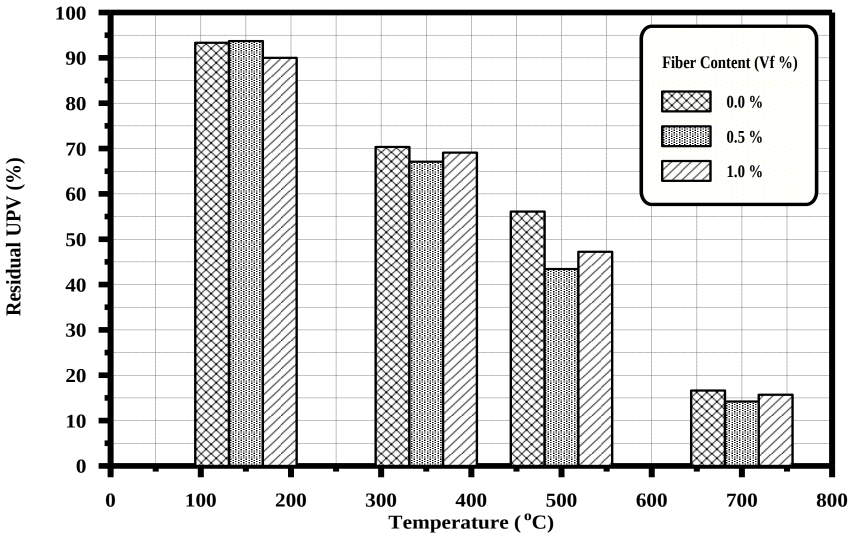

Figure (13) Percentage residual UPV for different fiber contents

3-2-5 Dynamic Modulus of Elasticity (ED)

Figure (14) shows the relationship between ED and temperature for the three groups. It is obvious that ED shows further decrease as temperature increase. The residual dynamic modulus of elasticity values after exposure to (150, 350, 500 and 700 °C) were about (18.2, 12.9, 12 and 3.2 GPa) respectively for plain concrete. While for concrete with (1.0 %) of steel fiber, the percentage ED values were (26.9, 18, 15 and 6.21 GPa) after exposure to the same temperatures. As shown in **Fig.(14)**, the effect of steel fiber addition on the behavior of ED after high temperature exposure was very limited when only (0.5 %) of steel fiber was used. But the concrete with (1.0 %) of fiber was superior to plain concrete. Where for each particular temperature, the residual ED values were higher than those of plain concrete. However, this superiority attributed to the higher original ED values for the steel fiber reinforced concrete and could not be consider as an enhancement in the behavior of ED after high temperature exposure. **Figure (15)** confirms this conclusion, where as shown in the figure there is only minor deviation between the percentages residual ED for the three groups at each temperature.

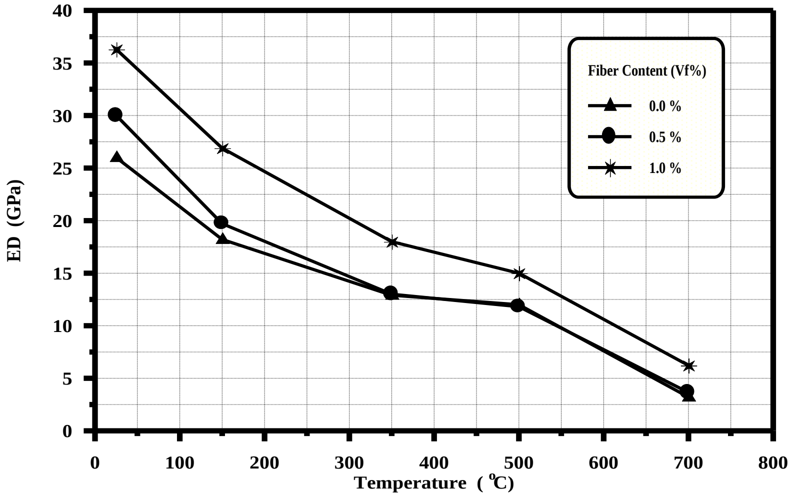

Figure (14) ED-Temperature relationship for different fiber contents

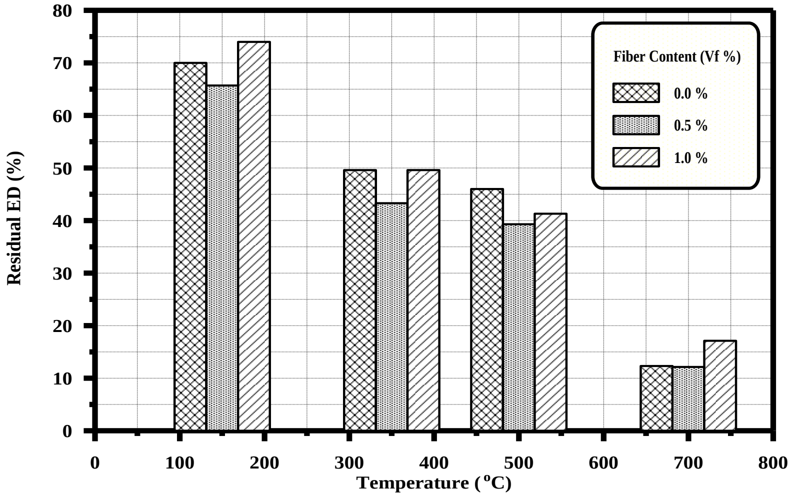

Figure (15) Percentage residual Ed for different fiber contents

4. Conclusions

Based on the test results of this study and within the limits of the investigated variables, the following conclusions can be obtained:

1. The addition of steel fibers to concrete changes the mode of failure for all tests, from sudden brittle failure to more ductile failure, both before and after exposure to elevated temperatures.
2. Exposure to elevated temperatures affects concrete strength significantly. The strength decrease depends mainly on the temperature level and the type of stresses in concrete in each test.
3. Steel fiber in concrete has no significant effect on compressive strength, before and after exposure to elevated temperatures. Also, the compressive strength-temperature behavior of the steel fiber reinforced concrete was similar to that of plain concrete.
4. The use of steel fibers improves splitting tensile strength of concrete, both before and after exposure to high temperatures. Where at normal temperature the splitting tensile strength increased by (17.8 %) when fiber was used by (1.0 %) by volume. After exposure to (700 ^{o}C), the residual splitting tensile strength for concrete with fiber content of (0.0, 0.5 and 1.0 %) by volume was (14.1, 42.9 and 52 %) respectively.
5. The effect of steel fibers on flexural tensile strength is very significant at normal temperatures, where the flexural strength increased by (60.6 %) when (1.0 %) of steel fiber was used. However, after exposure to high temperature the presence of steel fiber was less significant.
6. The effect of steel fiber on UPV was found to be insignificant, before and after exposure to elevated temperatures.
7. The addition of (1.0 %) steel fiber enhanced the dynamic modulus of elasticity (ED) at normal temperature by about (39.6 %). However, after exposure to high temperature no significant effect of steel fiber on ED was noticed.

5. References

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