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Strength and Elasticity of Steel Fiber Reinforced Concrete at High Temperatures

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Abstract

Compressive strength and modulus of elasticity of plain and steel fiber reinforced concrete, both before and after exposure to high temperatures were investigated in this study. Two fiber volume fractions of 0.5% and 1.0% were used. Three temperature levels of 150 °C, 350 °C and 500 °C were adopted in addition to room temperature.

The test results showed that compressive strength and modulus of elasticity decreased after high temperatures exposure. At 350 °C, the plain concrete recovered some of the lost strength at 150 °C, while fiber reinforced concrete showed a slight additional decrease in strength at 350 °C as compared to 150 °C.

Only minor loss in modulus of elasticity occurred at 150 °C for both plain and fiber reinforced concrete, which was limited to about 11%. While at 500 °C, significant deterioration occurred. The residual modulus of elasticity at 500 °C was in the range of 31% to 42%.

الخلاصـــــة

في هذا البحث تم دراسة كل من مقاومة الانضغاط ومعامل المرونة للخرسانة المسلحة و الخرسانة غير المسلحة بألياف الحديد قبل وبعد التعرض إلى درجات الحرارة العالية. تم استخدام نسبتين وزنيتين من ألياف الحديد وهما (٠,٥ %و ١,٠ %)، كما تم تبني ثلاثة مستويات من الحرارة وهي (١٥٠ ° س، ٣٥٠ ° س و ٥٠٠ ° س) بالإضافة إلى حرارة الغرفة.

تشير النتائج إلى أن مقادير مقاومة الانضغاط و معامل المرونة تقل بعد التعرض إلى الحرارة العالية. بعد التسخين إلى (٣٥٠ ° س) يلاحظ أن الخرسانة غير المسلحة استعادة بعض من المقاومة التي فقدتها في درجة حرارة (١٥٠ ° س)، بينما لوحظ نقصان إضافي قليل للخرسانة المسلحة بالألياف عند (٣٥٠ ° س) مقارنة مع (١٥٠ ° س).

عند درجة حرارة (١٥٠ ° س) حدث نقصان قليل في مقدار معامل المرونة للخرسانة المسلحة و الخرسانة غير المسلحة بالألياف والذي لا يتعدى (١١ %). أما عند درجة حرارة (٥٠٠ ° س) فقد حصل تدهور ملحوظ في معامل المرونة، حيث كانت نسبة معامل المرونة بعد التسخين إلى معامل المرونة قبل التسخين تتراوح بين (٣١ % و ٤٢ %).

1. Introduction

Exposure to elevated temperatures which is mainly caused by accidental fires, represents one of the more severe exposure conditions of buildings and structures. The fire resistance and post heat exposure behavior of structural members depend on thermal and mechanical properties of the materials composing these members. Elasticity is one of the major material properties which play an essential role in the structural behavior of reinforced concrete members both before and after high temperatures exposure.

The use of spread steel fiber wires can be considered as a solution to control cracking and to increase the strength and ductility of concrete. Since the exposure to high temperature causes different changes in concrete, which lead to the initiation and opening of many cracks, this study was directed to investigate the influence of steel fibers on the elastic modulus of concrete after high temperature exposure.

2. Experimental Work

Three series of concrete mixes were cast using ordinary Portland cement, local sand and local gravel with maximum size of 19 mm. Each series contained the same mix properties of: 1 cement: 1.5 sand: 3 gravel in proportion by weight, and water/cement ratio of 0.5. The main differentiation between the three series is the volume fraction of steel fiber. Series A specimens were cast without using fiber, while (0.5% and 1.0%) by volume was added to series B and C respectively. The used steel fiber was hooked end (Dramix type) with 0.5 mm diameter and 30mm length (aspect ratio L/D=60), and with nominal ultimate strength of 1117 MPa.

Fiber reinforced concrete was mixed according to the fifth mixing procedure of ACI 544 [1]. 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 the age of twenty-eight days.

Cylinders with 150mm diameter and 300mm length were tested for both compressive strength according to ASTM C39-86 [2] and static modulus of elasticity according to ASTM C469-87 [3].

The specimens were heated to three temperatures of (150, 350 and 500 ^{o}C) (302, 662 and 932 F). Three cylinders were tested for compressive strength and three for modulus of elasticity at each temperature from each series. Also, three specimens were used for each test from each series at room temperature as reference specimens. Thus 24 cylinders were tested from each series and totally 72 cylinders were tested in this study.

Using an electrical furnace, the specimens were heated slowly at a constant rate of about (2 ^{o}C/min) to prevent steep thermal gradient [4]. 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 20 to 24 hours later.

3. Results and Discussion

Modulus of elasticity and compressive strength of plain and fiber reinforced concrete, both at normal temperatures and after exposure to elevated temperatures were investigated in this study.

3-1 Concrete Compressive Strength

As shown in **Fig.(1)**, the addition of steel fibers up to 1.0% by volume has no significant effect on compressive strength. The compressive strength increased by about 3% only when 0.5% of fiber was used, where the compressive strength increased from (28.4 to 29.4 MPa). An additional increase of 1% only was gained when 1.0% of fiber was used instead, thus compressive strength increased to 29.7 MPa. These results confirm that fibers usually have only minor effect on the compressive strength, slightly increasing or decreasing the test results [5].

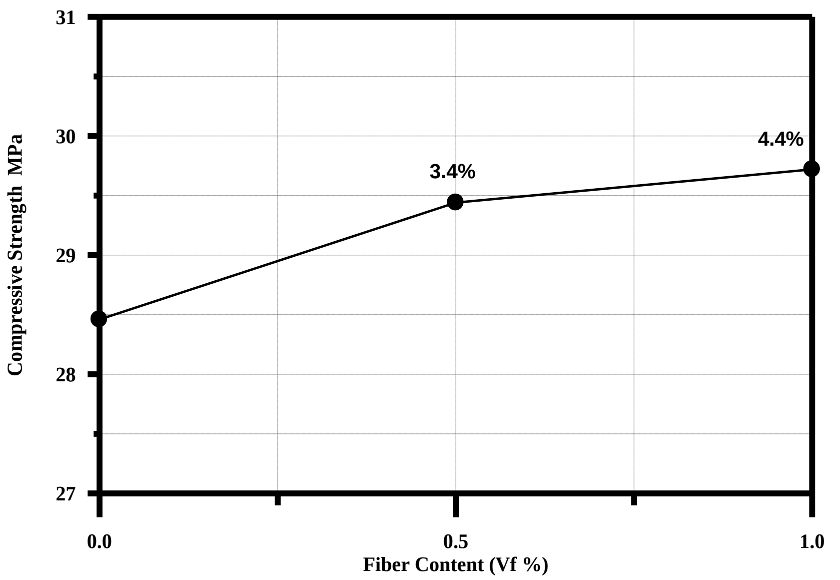

Figure (1) Effect of fiber content on concrete compressive strength

Figure (2) shows the variation of residual compressive strength with temperature. While **Fig.(3)** shows the effect of temperature exposure on the percentage residual compressive strength (the ratio of the maximum compressive strength at a specified temperature to the maximum compressive strength at room temperature).

It is shown that compressive strength decreased after exposure to all the studied range of temperature. From the observation of **Fig.(2)** and **Fig.(3)**, it is noticeable that both plain and fiber reinforced concrete were only slightly affected after exposure to 150 ^{o}C. The percentage residual strength at 150 ^{o}C was about 89% for plain concrete and (90 and 92%) for (0.5 and 1.0%) fiber reinforced concretes. At 350 ^{o}C, the fiber reinforced concrete suffered further minor decrease of about (8 to 10%). While a partial strength recovery occurred for plain concrete. At 500 °C, both concretes decreased at a faster rate to reach percentage residuals ranged between 60% and 66%.

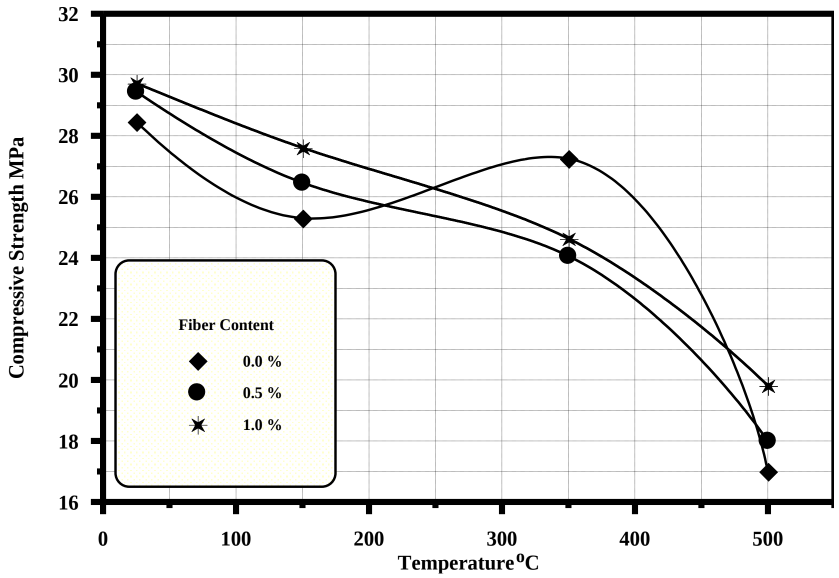

Figure (2) Compressive strength-temperature relationship for different fiber contents

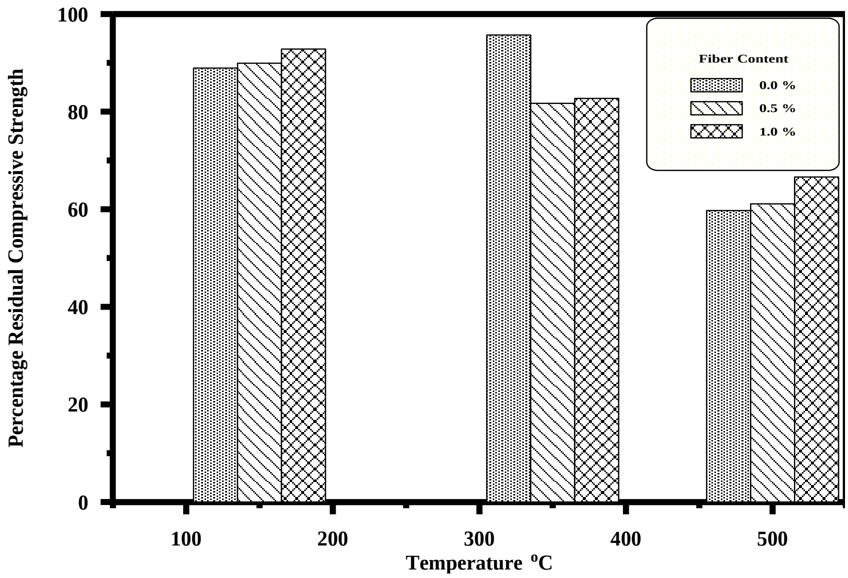

Figure (3) Percentage residual compressive strength for different fiber contents

In an earlier study [6], it was recorded that both plain and fibrous concretes retained higher residual strengths at 350 °C compared to 150 °C. This difference maybe due to the different types of steel fibers and test specimens used in this study. It was recorded that the percentage residual compressive strength curves displayed three different behaviors. First, the strength decreased between room temperature and 150 °C. Then after, a stage of stabilized strength or partial strength recovery occurred between 150 °C and 350 °C. Followed by a continuous higher percentage loss stage beyond 350 °C [7]. The test results of this study confirm these results. However, it is added that the stage between 150 °C and 350 °C is a stage of partial strength recovery, stabilized strength, or minor strength loss.

The slight increase in strength at 350 °C is attributed to the general stiffening of cement gel, or the increase in surface forces between gel particles due to the removal of absorbed water [8,9]. As temperature arises to about 400 °C, one of the changes occurs is the decomposition of calcium hydroxide [10]. Also, the bond between the aggregate and cement paste is weakened due to the different thermal movements (contraction of cement past and expansion of aggregate) [11]. These chemical and physical changes are responsible of the further decrease in strength that occurred at 500 °C.

Another notice is that at 500 °C, the use of steel fiber is somewhat enhanced the compressive strength of concrete. As shown in **Fig.(3)**, the percentage residual strength at 500 °C, increases with the increase of fiber content. Comparing the residual strength values at 500 °C, the use of 1.0% of fiber, increased the compressive strength by about 16.5% as compared to plain concrete at the same temperature.

3-2 Modulus of Elasticity

Figure (4) shows the effect of steel fiber addition on modulus of elasticity of concrete at normal temperatures. It is shown that the addition of 1.0% of spread steel fibers resulted in a noticeable increase in modulus of elasticity. The modulus of elasticity of plain concrete equals to 22.74 GPa, while for 1.0% fiber reinforced concrete, the modulus of elasticity increased to 29.38 GPa with a percentage increase of about 29%. However, only little increase occurred in the modulus of elasticity when 0.5% of fiber was used, where the percentage increase was only about 6%. This enhancement is mainly due to the interlocking action of fibers, where fibers lock the large aggregate together in the matrix and prevent the propagation and the opening of micro cracks, and thus inhibiting crack growth [5].

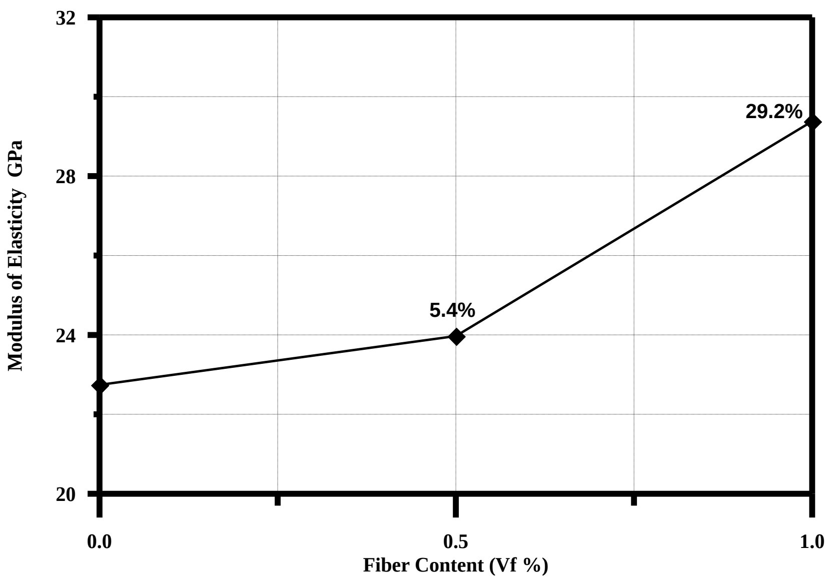

Figure (4) Effect of fiber content on modulus of elasticity of concrete

Early researchers [12,13,14,15] found that modulus of elasticity of concrete decreases as temperature increases. The test results of this study completely confirm this result. The modulus of elasticity of both plain and fiber reinforced concrete decreased as temperature increase by amounts depending on temperature level. The room temperature modulus of elasticity of plain concrete was 22.74 GPa. While, after exposure to (150, 350 and 500 ^{o}C), the modulus of elasticity decreased to (20.24, 15.07, and 9.63 GPa) respectively. Similar sequence of reduction was noticed for fiber reinforced concrete as shown in **Fig.(5)**.

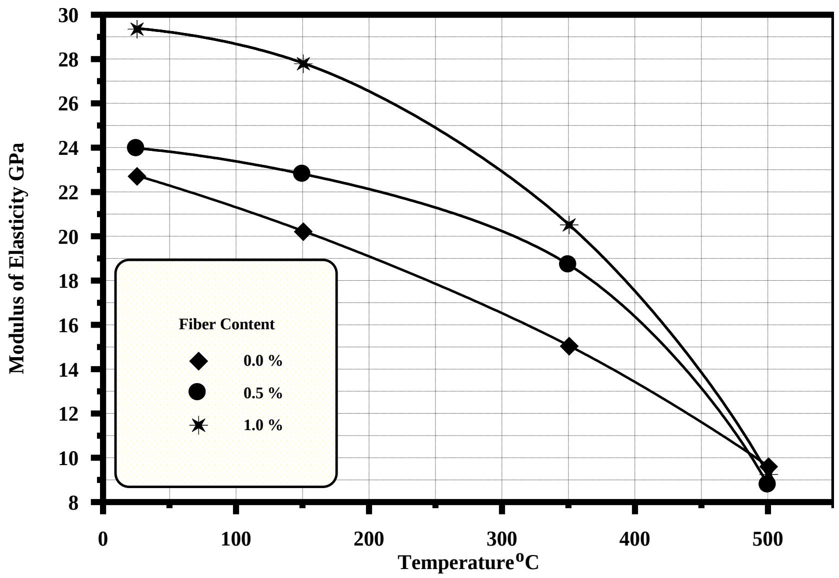

Figure (5) Modulus of elasticity-temperature relationship for different fiber contents

Figure (5) and **Fig.(6)** show the variation of the residual modulus of elasticity and the percentage residual modulus of elasticity with temperature. It is noticed from the observation of **Fig.(6)**, that the percentage loss in modulus of elasticity of both plain and fiber reinforced concrete at 150 ^{o}C is minimal. Where the percentage residual modulus of elasticity was in the range of (89 to 95%) at 150 ^{o}C.

These values are noticeably higher than those obtained by some earlier researchers [14,16,17]. Padevêt [16] , found that modulus of elasticity had a tendency to decrease to about 65% at 125 ^{o}C, but this decrease tendency to stabilized or slightly increased at 150 ^{o}C. Schneider [17], showed similar percentages of decrease for quartzite concrete. While curves obtained by Cruz [14], showed that siliceous aggregate concrete retained about 80% of its original modulus of elasticity at 150 ^{o}C. This difference maybe due to the different definitions of elastic modulus of concrete [18], and the different test procedures, moisture state and rates of heating and cooling.

As shown in **Figs.(5)** and **(6)**, a noticeable loss in modulus of elasticity occurred at 350 ^{o}C. The percentage residual modulus of elasticity at 350 ^{o}C ranged between 66% and

78%. After exposure to 500 ^oC, the modulus of elasticity deteriorated significantly, where a percentage loss in modulus of elasticity ranged between 60% and 70% occurred at 500 ^oC.

Depending on experimental data, Schneider [17] derived curves to represent the influence of temperature on modulus of elasticity for normal and light weight concrete. For normal weight concrete, the proposed percentage residual modulus of elasticity at (150, 200, 400 and 500 ^oC) is (80, 70, 40 and 25%) respectively. The obtained percentage residual modulus of elasticity in this study is higher by about 10% at 150 ^oC and 500 ^oC.

Exposure to high temperatures resulted in many changes in the structure of concrete, which cause much deterioration in concrete properties. Where, during the drying process, which occurs simultaneously with temperature increase, the apparent modulus of elasticity is reduced. This occurs because any movement in moisture results in some bond rupture and consequently in the decrease of stiffness. As temperature increases, the stiffness decreases due to the breakage of bonds in the microstructure of cement paste as well as the short time creep at increasing temperature [18].

Figure (6) shows that at 150 ^oC and 350 ^oC, the percentage residual modulus of elasticity of fiber reinforced concrete is little higher than of plain concrete. While at 500 ^oC, the opposite stands. Similar results were obtained by other researchers [9].

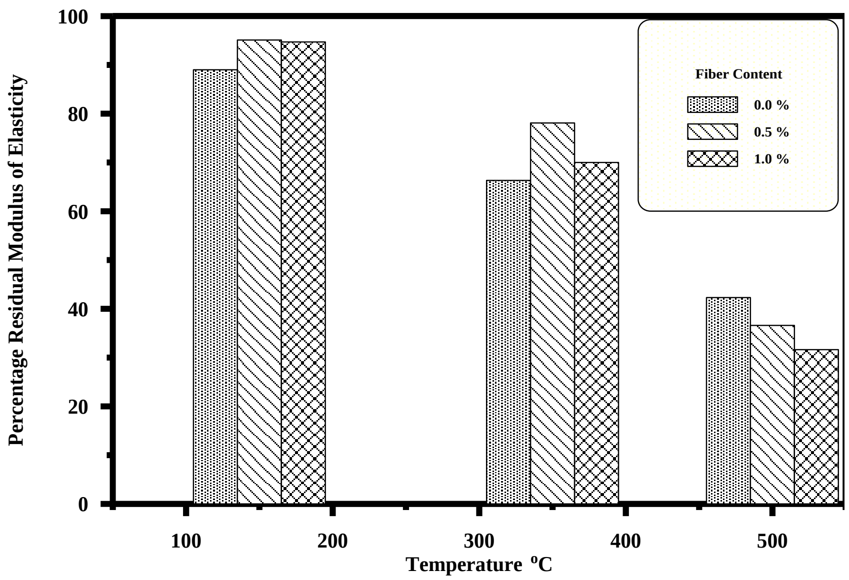

Figure (6) Percentage residual modulus of elasticity for different fiber contents

4. Conclusions

Based on the test results of this study and within the limitations of the test parameters, the following conclusions can be drawn:

1. The compressive strength of both plain and fiber reinforced concretes, decreased in similar fashion after exposure to elevated temperatures. However, the use of 1.0% of steel fibers enhanced the compressive strength at 500 ^{o}C by about 16.5% compared to plain concrete at the same temperature.
2. The use of steel fibers, improved the elastic modulus of concrete at normal temperature. Where the modulus of elasticity increased by about 29% when 1.0% of fiber was used.
3. The modulus of elasticity of both plain and fiber reinforced concrete decreased as temperature increased. The percentage decrease ranged between (5 to 11%) at 150 ^{o}C, while after exposure to 500 ^{o}C, concrete elasticity deteriorated significantly. The modulus of elasticity reduced to about (31 to 42%) from its original values at 500 ^{o}C.

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