Influence of High Temperature on Steel Fiber Reinforced Concrete

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Abstract

This investigation includes an experimental study of the changes in compressive strength, splitting tensile strength, modulus of rupture and static modulus of elasticity after exposure to high temperature ranging between 250 to 750°C of plain and steel fiber reinforced concrete (SFRC) in comparison with ordinary temperature (25°C). Hooked and straight steel fibers with aspect ratio of 60 and two different percentages by volume (0.5% and 1%) were used.

Each group of specimens was heated to a specified temperature and kept at that temperature for one hour before being gradually cooled to room temperature, and then they were tested. The results show an appreciable decrease in compressive strength, splitting tensile strength, modulus of rupture and elastic modulus after exposure to temperature higher than 350°C of both plain and SFRC. The inclusion of fibers very slightly affects the compressive strength of concrete at temperature below 350°C, while the loss in compressive strength for SFRC is lower relative to plain concrete after exposure to temperature higher than 350°C. The results also show that the loss in splitting tensile strength and modulus of rupture for SFRC is appreciably lower in comparison with that of plain concrete for all heating temperatures up to 750°C. The volume content of fiber slightly affects the compressive strength of concrete; also the type and volume content of fibers slightly affect the elastic modulus of concrete at elevated temperature, while the type and volume content of fibers have appreciable effect on tensile strength and modulus of rupture of concrete.

Generally, the results show that SFRC resists high temperature more than plain concrete and SFRC with 1% hooked end fibers has a superior behaviour after exposure to high temperature.

الخلاصـــــــة

يشتمل البحث دراسة مختبرية للتغيرات الحاصلة في مقاومتي الانضغاط والشد الانشطاري ومعامل المرونة ومعاير الكسر بعد التعرض لدرجات الحرارة العالية بين ٢٥٠ إلى ٧٥٠مْ للخرسانة الغير مسلحة والخرسانة المسلحة بالألياف، بالمقارنة مع درجة الحرارة الاعتيادية(٢٥مْ). أستخدم نوعان من الألياف الفولاذية، الألياف الفولاذية الملساء والمعقوفة النهاية بنسبة نوعية (٦٠) وبنسب حجميه (٠،٥%، ١%) من حجم الخليط.

سخنت كل مجموعة من النماذج إلى درجة الحرارة المحددة وتم الإبقاء على هذه الدرجة لفترة ساعة واحدة قبل تبريدها تدريجياً إلى درجة الحرارة الاعتيادية ثم أجريت الفحوصات المختلفة على النماذج. أظهرت نتائج الفحوصات حصول انخفاض واضح في مقاومتي الانضغاط والشد الانشطاري و معاير الكسر ومعامل المرونة بعد التعرض لدرجات حرارة تزيد على ٣٥٠ مْ للخرسانة المسلحة وغير المسلحة بالألياف، وأن استخدام الألياف له تأثير ضئيل جداً في مقاومة الانضغاط للخرسانة عند درجة حرارة اقل من ٣٥٠ مْ ولكن بعد التعرض لدرجات حرارة تزيد على ٣٥٠ مْ فأن الفقدان الحاصل في مقاومة الانضغاط للنماذج المسلحة بالألياف يكون أقل بالمقارنة مع نماذج الخرسانة الغير مسلحة بالألياف. كذلك أظهرت النتائج، أن الفقدان الحاصل في مقاومة الشد الانشطاري ومعاير الكسر للخرسانة المسلحة بالألياف كان أقل وبشكل واضح بالمقارنة مع الخرسانة الغير مسلحة بالألياف لجميع درجات الحرارة ولحد ٧٥٠ مْ، وأن نسبة الألياف لها تأثير قليل على مقاومة الانضغاط للخرسانة بعد التعرض لدرجات الحرارة العالية، كذلك فأن تأثير النسبة الحجمية ونوع الألياف يكون ضئيلاً على معامل المرونة للخرسانة بعد تعرضها لدرجات الحرارة العالية، في حين ظهر تأثير النسبة الحجمية ونوع الألياف واضحاً على مقاومة الشد الانشطاري ومعاير الكسر للخرسانة.

بصورة عامة فأن الخرسانة المسلحة بالألياف تقاوم درجات الحرارة العالية بشكل أفضل من مقاومة الخرسانة الغير مسلحة بالألياف، وأن الألياف الفولاذية المعقوفة النهاية وبنسبة حجمية ١% يكون لها سلوكاً متفوقاً بعد التعرض لدرجات الحرارة العالية.

1. Introduction

Concrete structures may be exposed to high temperatures at which deterioration of concrete occurs. Exposing concrete to high temperature causes strength deterioration, increase in drying shrinkage, reduction in bond strength with reinforcement [1] and increase in the risk of reinforcement corrosion due to high permeability and cracks.

Previous studies [2-5] indicate that the mechanical properties of concrete deteriorate at high temperatures. The amount of residual strength depends on many factors such as: temperature level, heating duration, method of recooling, type of aggregate and cement-aggregate ratio. Recent interest has been shown in the use of SFRC since the tensile strength of the composite is higher than that of plain concrete and the use of fibers may lead to reduction in the amount of cracking under serviceability conditions.

Little investigations have been noticed to provide experimental results about the effect of fibers on the properties of concrete at high temperature [6-8], so it becomes necessary to make additional studies on the effect of elevated temperature on properties of SFRC using different types of steel fibers. In this study an investigation is carried out on the effect of high temperature on the compressive strength, splitting tensile strength, modulus of rupture and static modulus of elasticity of different types and volume contents of SFRC.

2. Experimental Work

2-1 Materials

The materials used in this investigation were, ordinary Portland cement which conforms to the provisions of Iraqi Specification No.5-1984, natural sand brought from Al-Ukhaider region which conforms to Iraqi Specification No.45-1984, its grading lying in zone 2 and gravel of maximum size 10mm, used to avoid undue interference between the aggregate and the fibers and thus a more uniform distribution of fibers was obtained. The gravel confirms to Iraqi Specification No.45-1984.

The mix used was 1: 1.5: 2.5 of cement: sand: gravel by weight with water-cement ratio of 0.47. Two types of steel fibers were used: straight steel fibers of 0.4mm diameter and 24mm length with aspect ratio = 60, and hooked end steel fiber of 0.5mm diameter and 30mm length with aspect ratio = 60 with volume fraction (0.5% and 1%) considered for the straight and hooked end fibers.

Mixing was carried out according to ACI Committee 544 recommendation for FRC [9]. All materials were proportioned by weight. After casting the specimens were demoulded after 24 hours, cured in water for 28 days and then dried in oven at temperature of 60°C for at least 48 hours before testing to avoid the explosive spalling [10].

2-2 Details of the Tests

An electric furnace was used for heating the specimens; the maximum furnace temperature was 1000°C. The temperature was controlled by an electronic controller. The specimens were exposed to different temperatures of 250, 350, 450, 550 and 750°C. They were heated to the test temperature, allowed to remain at that temperature for one hour then allowed to cool gradually in air at room temperature for a period of 24 hours before being tested. The following tests at each temperature level were carried out:

1. Three 100mm cubes were heated to evaluate the residual compressive strength.
2. Three cylinders of 100×200mm were heated and their residual splitting tensile strengths were evaluated.
3. Three prisms of 100×100×400mm were heated to determine the residual modulus of rupture and static modulus of elasticity.

3. Results and Discussion

3-1 Effect of Temperature on Compressive Strength

Table (1), **Table (3)** and **Fig.(1)** shows the relationship between temperature and the residual compressive strength in relation to the original strength prior to heating of plain concrete and SFRC. Generally, it can be seen that all mixes whether plain or steel fiber mixes exhibited compressive strength loss as temperature increases. There is a considerable decrease in compressive strength as the temperature increases above 350°C, this is due to the loss of cement paste plasticity at high temperatures [11].

SFRC at 25°C exhibited slightly higher compressive strength relative to plain concrete; the enhancement was greater when hooked steel fiber was used in comparison with straight steel fiber. This is due to the fact that the presence of steel fibers increases strainability in compressive failure [12], and hence the compressive strength increases. It can be observed that fiber content has no effect on the residual compressive strength after exposure to temperature below 350°C; On the other hand the incorporation of steel fiber has a significant effect on residual compressive strength as the temperature increases above 350°C. The residual strength for all mixes was (80 to 82%) of the corresponding initial strength when the concrete was heated to temperature of 250°C. As the temperature was increased to 550°C the residual strength for reference concrete was about 11%; On the other hand the residual strength for hooked end steel fiber reinforced concrete (HSFRC) with volume fraction (0.5 and 1%) was about (34 and 37%), while for straight steel fiber reinforced concrete (SSFRC) with volume content (0.5 and 1%) was about (27 and 32%) respectively. Beyond 550°C the strength continued to drop and at 750°C the residual strength for reference concrete was about 7%, while for HSFRC with volume fraction of (0.5 and 1%) the residual strength was about (31 and 32%). On the other hand for SSFRC with volume content of (0.5 and 1%) the values were about (20 and 21%) respectively.

Table (1) Effect of high temperature on compressive and splitting tensile strengths of FRC (hooked end steel fiber)

Temperature °C	Volume fraction %	Compressive strength (f'_c)		Splitting tensile strength (f_t)	
		f'_c N/mm^2	Residual (f'_c) %	f_t N/mm^2	Residual (f_t) %
25	0	35.1	100	3	100
	0.5	39.9	100	4	100
	1	38.7	100	4.7	100
250	0	28.1	80.1	2.1	70
	0.5	32.5	81.5	3.5	87.5
	1	31.6	81.7	4.5	95.7
350	0	16.9	48.1	1.75	58.3
	0.5	15.9	39.8	3.2	80
	1	17.8	46	4.17	88.7
450	0	4.8	13.7	1.5	50
	0.5	14.2	35.6	2.5	62.5
	1	15.3	39.5	3.8	80.9
550	0	3.9	11.1	0.96	32
	0.5	13.7	34.3	2	50
	1	14.2	36.7	3.5	74.5
750	0	2.31	6.6	0.43	14.3
	0.5	12.2	30.6	1.33	33.2
	1	12.5	32.3	3.2	68.1

Table (3) Effect of high temperature on compressive and splitting Tensile strengths of FRC (straight steel fiber)

Temperature °C	Volume fraction %	Compressive strength (f'_c)		Splitting tensile strength (f_t)	
		f'_c N/mm^2	Residual (f'_c) %	f_t N/mm^2	Residual (f_t) %
25	0	35.1	100	3	100
	0.5	36.8	100	3.5	100
	1	35.9	100	3.8	100
250	0	28.1	80.1	2.1	70
	0.5	29.7	80.7	3.1	88.6
	1	29.3	81.6	3.5	92.1
350	0	16.9	48.1	1.75	58.3
	0.5	16	43.5	2.66	76
	1	16.8	46.8	3.35	88.2
450	0	4.8	13.7	1.5	50
	0.5	11.9	32.3	2.13	60.9
	1	12.6	35.1	2.72	71.6
550	0	3.9	11.1	0.96	32
	0.5	9.78	26.6	1.36	38.9
	1	11.52	32.1	1.97	51.8
750	0	2.31	6.6	0.43	14.3
	0.5	7.2	19.6	0.88	25.1
	1	7.65	21.3	1.36	35.8

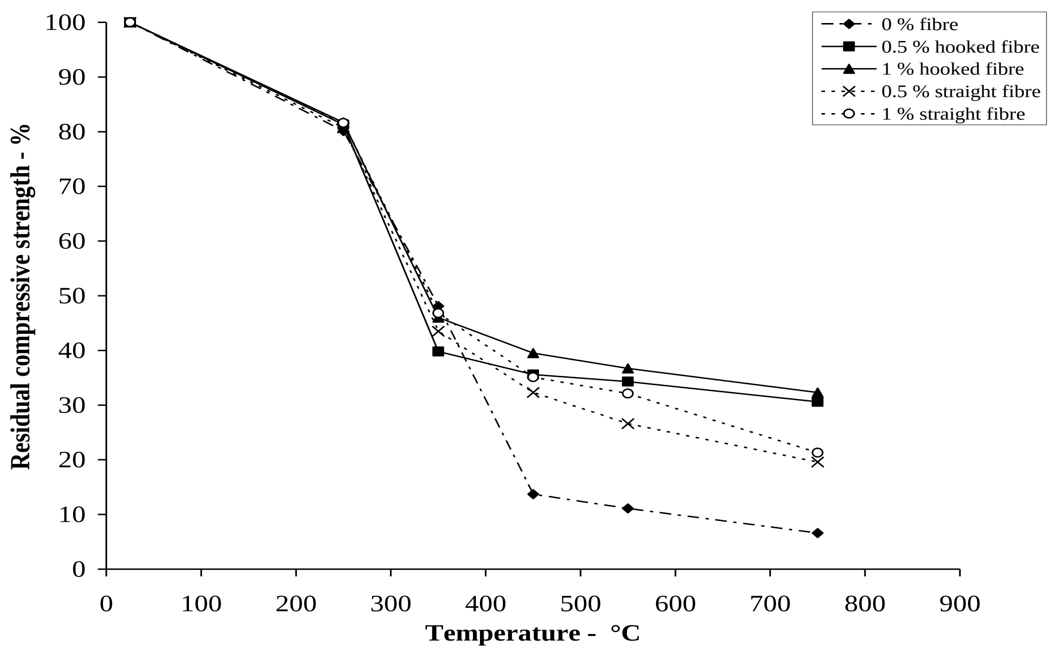

Figure (1) Relationship between residual compressive strength and temperature of plain and SFRC

Figure (2) shows the variation in compressive strength ratio (i.e: strength of SFRC mix to strength of plain mix for the same temperature level) with temperature. It can be observed that the compressive strength ratio is the same as that of plain concrete at temperature below 350°C. The compressive strength ratio for SFRC significantly increases at temperature higher than 350°C. The volume content of the fiber very slightly affects the compressive strength ratio. At temperature 750°C the compressive strength ratio was 5.3 and 5.4 for HSFRC, while for SSFRC the compressive strength ratio was 3.1 and 3.3 as volume content of fiber increased from (0.5 to 1%) respectively.

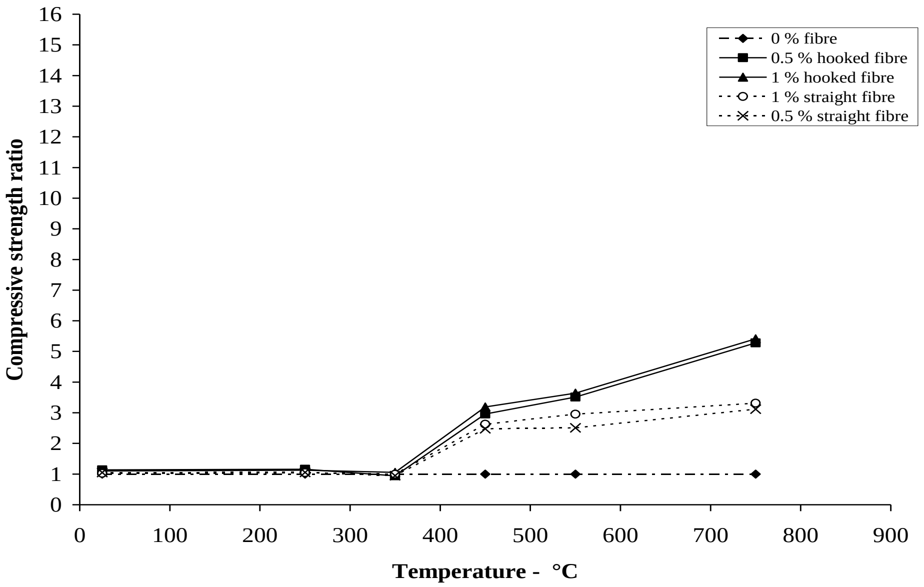

Figure (2) Compressive strength ratio versus temperature of SFRC

3-2 Effect of High Temperature on Splitting Tensile Strength

The relationship between the temperature and the residual splitting tensile strength of plain concrete and SFRC is shown in **Fig.(3)**, **Table (1)** and **Table (3)**. The splitting tensile strength clearly decreases with temperature for all mixes and the percentage of reduction increases as the temperature increased. Generally, it can be seen that the fiber significantly increases the residual tensile strength after exposure to high temperature. At temperature of 750°C the residual tensile strength for plain concrete was 14%, while for SSFRC with volume content of (0.5 and 1%) was about (25 and 36%) respectively. On the other hand the residual tensile strength for HSFRC with volume fraction (0.5 and 1%) was about (33 and 68%) respectively. This is attributed to the role of fibers in controlling crack propagation which begins only after matrix cracking [13] and the excellent mechanical anchorage of hooked end steel fibers at their ends which leads to high fiber matrix bond strength compared with that reinforced by straight steel fiber [14,15].

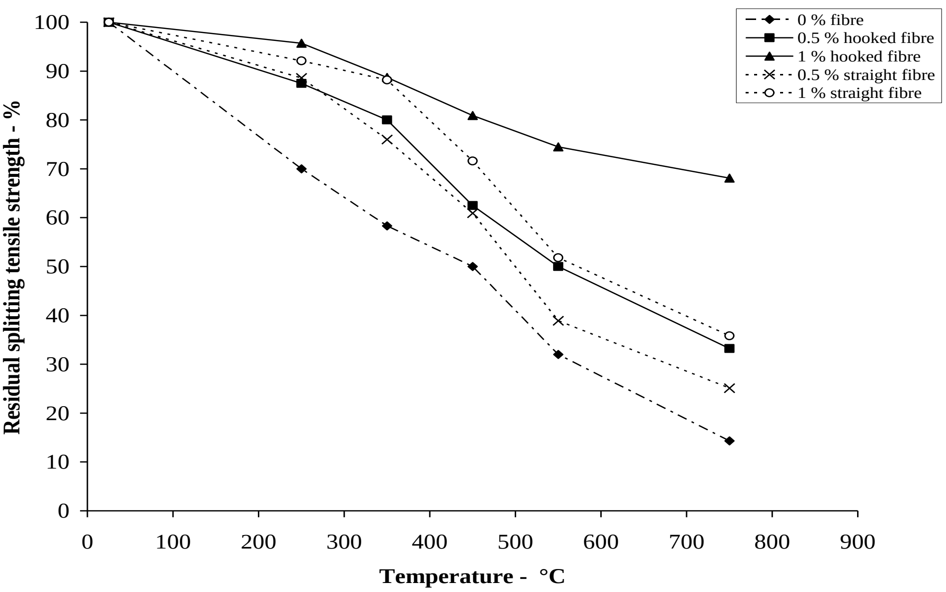

Figure (3) Relationship between residual splitting tensile strength and temperature of plain and SFRC

Figure (4) shows the relationship between the splitting tensile strength ratio and temperature. Generally, it can be seen that volume content of fiber at temperature below 450°C slightly affects the splitting tensile strength ratio. At temperature above 450°C the hooked end steel fibers with 1% volume content significantly increase the strength ratio. It can be observed that after exposure to 750°C the splitting tensile strength ratio of SSFRC with volume content 0.5% and 1% was 2 and 3.2, while of HSFRC with volume content 0.5% and 1% the strength ratio was 3.1 and 7.4 respectively.

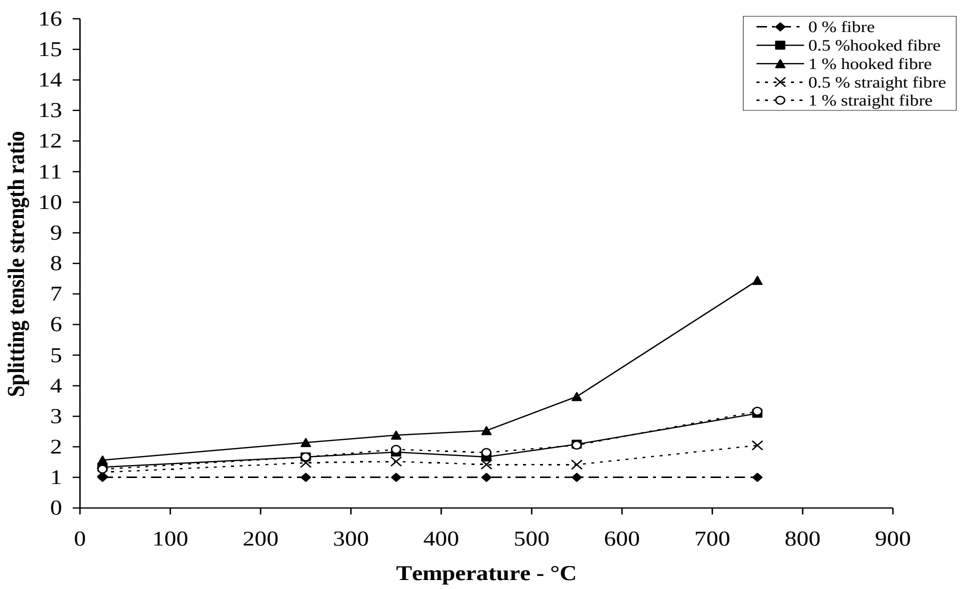

Figure (4) Splitting tensile strength ratio versus temperature of SFRC

3-3 Effect of High Temperature on Modulus of Rupture

Table (2), **Table (4)** and **Fig.(5)** shows the residual modulus of rupture for plain concrete and SFRC as a function of the maximum temperature. Similar to compressive and splitting tensile strengths of plain concrete and SFRC, the modulus of rupture decreases with temperature. It can be seen that SFRC has higher residual modulus of rupture relative to plain concrete after exposure to high temperature, hooked end steel fibers appear to have much greater influence on improving the modulus of rupture than straight steel fiber. This is because the modulus of rupture is influenced by the geometry of the fiber, and these fibers as mentioned before, have excellent mechanical anchorage at their ends [13,14]. This leads to high fiber matrix bond strength compared with that reinforced by straight steel fibers. Also it can be noted that fiber content has a significant effect on the residual modulus of rupture after exposure to high temperature. The residual modulus of rupture after exposure to 750°C for plain concrete was about 4%, while it was about 14% and 20% for SSFRC with volume content 0.5% and 1% respectively. On the other hand the residual modulus of rupture for HSFRC with volume fraction 0.5% and 1% was about 20% and 33% respectively.

Table (2) Effect of high temperature on modulus of rupture and static modulus of elasticity of FRC (hooked end steel fiber)

Temperature °C	Volume fraction %	Modulus of rupture (f_r)		Modulus of elasticity (E_s)	
		f_r N/mm^2	Residual (f_r) %	E_s Gpa	Residual (E_s) %
25	0	5.5	100	30	100
	0.5	9.36	100	32.8	100
	1	9.32	100	39.4	100
250	0	3.5	63.6	26.6	88.7
	0.5	6.8	72.6	29.3	89.3
	1	7.7	82.6	32.4	82.2
350	0	1.35	24.5	22.8	76
	0.5	2.91	31.1	25.7	78.4
	1	5.37	57.6	26.75	67.9
450	0	0.82	14.9	16.7	55.7
	0.5	2.42	25.9	19.3	58.8
	1	4.2	45.1	16.7	42.4
550	0	0.3	5.5	8.17	27.2
	0.5	2.26	24.1	10.5	32
	1	3.63	38.9	14.2	36.1
750	0	0.22	4	3.14	10.5
	0.5	1.84	19.7	6.77	20.6
	1	3.1	33.3	12.57	31.9

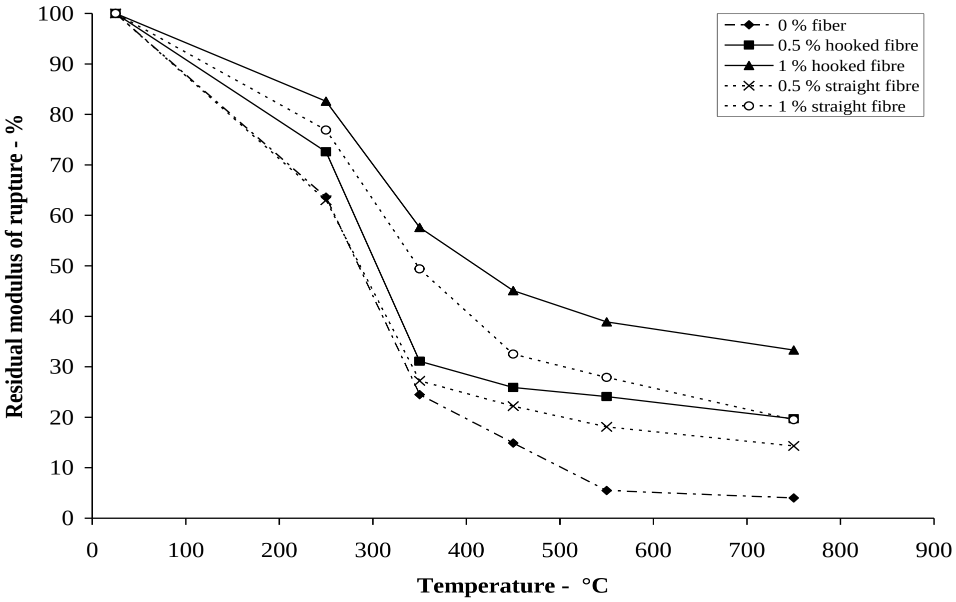

Figure (5) Relationship between residual modulus of rupture and temperature of plain and SFRC

Figure (6) shows the variation in modulus of rupture ratio with temperature. From this Figure it can be seen that the modulus of rupture for SFRC is higher than that of plain concrete for all temperature levels. There is a very considerable increase in the modulus of rupture ratio at temperature above 450°C especially for HSFRC with volume content 1%. The modulus of rupture ratio at temperature 750°C was 5.3 and 7.1 for SSFRC while for HSFRC it was 8.4 and 14.1 as volume fraction of fiber increased form 0.5% to 1% respectively.

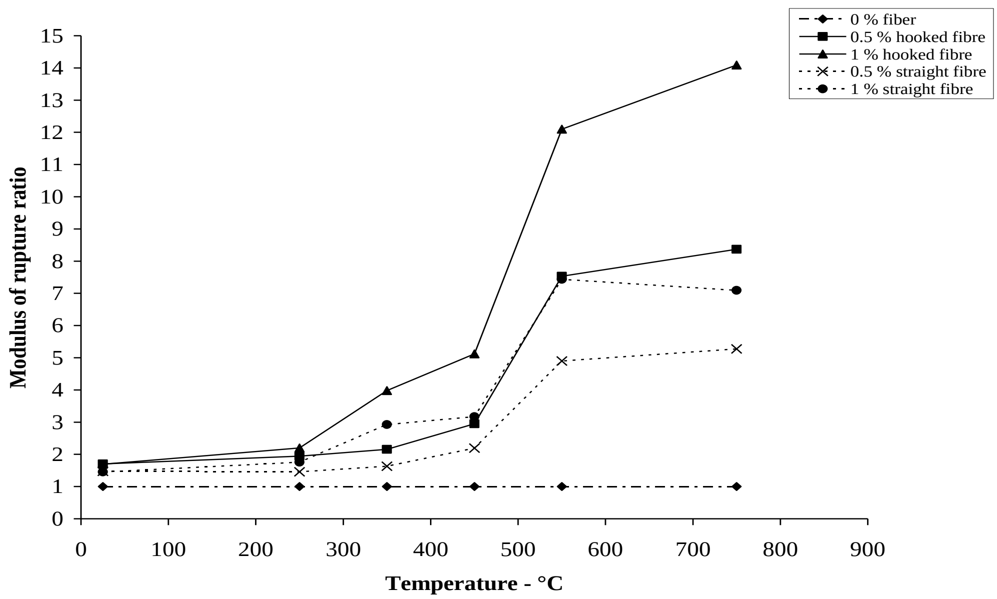

Figure (6) Modulus of rupture ratio versus temperature of SFRC

3-4 Effect of High Temperature on Static Modulus of Elasticity

Table (2), **Table (4)** and **Figure (7)** shows the residual modulus of elasticity of plain concrete and SFRC as a function of the maximum temperature. Similar to the strengths, elastic modulus was decreased with the increase in temperature. It can be observed that fibers slightly affect the elastic modulus after exposure to high temperature and it is clear that the elastic modulus is independent of fiber content at all exposed temperatures.

Table (4) Effect of high temperature on modulus of rupture and static modulus of elasticity of FRC (straight steel fibre)

Temperature °C	Volume fraction %	Modulus of rupture (f_r)		Modulus of elasticity (E_s)	
		f_r N/mm^2	Residual (f_r) %	E_s Gpa	Residual (E_s) %
25	0	5.5	100	30	100
	0.5	8.1	100	33.5	100
	1	8	100	40.2	100
250	0	3.5	63.6	26.6	88.7
	0.5	5.1	63	28.98	86.5
	1	6.15	76.9	36.3	90.2
350	0	1.35	24.5	22.8	76
	0.5	2.2	27.2	24.96	74.5
	1	3.95	49.4	31.6	78.6
450	0	0.82	14.9	16.7	55.7
	0.5	1.8	22.2	19.6	58.5
	1	2.6	32.5	24	59.7
550	0	0.3	5.5	8.17	27.2
	0.5	1.47	18.1	12	35.8
	1	2.23	27.9	14.9	37.1
750	0	0.22	4	3.14	10.5
	0.5	1.16	14.3	5.63	16.8
	1	1.56	19.5	7.5	18.7

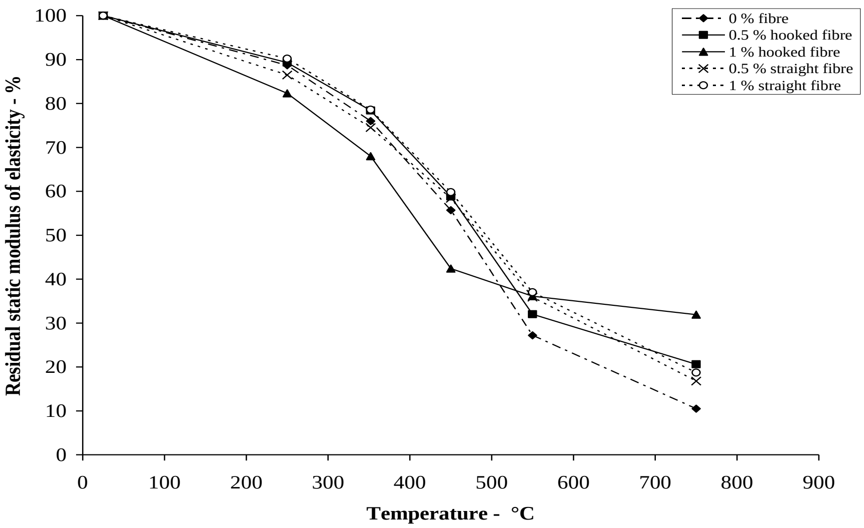

Figure (7) Relationship between residual static modulus of elasticity and temperature of plain and SFRC

4. Conclusions

1. The compressive strength, splitting tensile strength, modulus of rupture and static modulus of elasticity of plain concrete and SFRC are reduced by an amount depending on the exposed temperature.
2. The behaviour of SFRC at elevated temperature is similar to that of the plain concrete.
3. Steel fibers very slightly affect the residual compressive strength of concrete after exposure to temperature below 350°C.
4. The residual compressive strength of SFRC is higher than that for the plain concrete at all heating temperatures above 350°C.
5. The residual splitting tensile strength and modulus of rupture of SFRC are higher than that of plain concrete for all heating temperatures up to 750°C.
6. The type and volume content of fiber slightly affect the elastic modulus of concrete after exposure to a high temperature.
7. The type and volume content of fiber have a significant effect on splitting tensile strength and modulus of rupture at all exposed temperatures.
8. Steel fiber reinforced concrete resists high temperature more than plain concrete, SFRC with 1% hooked end fibers has a superior behaviour after exposure to a high temperature.

5. References

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