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Properties and Applications of Fiber Reinforced Concrete

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ABSTRACT. Fiber reinforced concrete (FRC) is a new structural material which is gaining increasing importance. Addition of fiber reinforcement in discrete form improves many engineering properties of concrete.

Currently, very little research work is being conducted within the Kingdom using this new material. This paper describes the different types of fibers and the application of FRC in different areas. It also presents the result of research about the mechanical properties of FRC using straight as well as hooked steel fibers available in the region.

Introduction

Concrete is weak in tension and has a brittle character. The concept of using fibers to improve the characteristics of construction materials is very old. Early applications include addition of straw to mud bricks, horse hair to reinforce plaster and asbestos to reinforce pottery. Use of continuous reinforcement in concrete (reinforced concrete) increases strength and ductility, but requires careful placement and labour skill. Alternatively, introduction of fibers in discrete form in plain or reinforced concrete may provide a better solution. The modern development of fiber reinforced concrete (FRC) started in the early sixties[1]. Addition of fibers to concrete makes it a homogeneous and isotropic material. When concrete cracks, the randomly oriented fibers start functioning, arrest crack formation and propagation, and thus improve strength and ductility. The failure modes of FRC are either bond failure between fiber and matrix or material failure. In this paper, the state-of-the-art of fiber reinforced concrete is discussed and results of intensive tests made by the author on the properties of fiber reinforced concrete using local materials are reported.

Fiber Types

Fibers are produced from different materials in various shapes and sizes. Typical fiber materials are[2,3]:

Steel Fibers

Straight, crimped, twisted, hooked, ringed, and paddled ends. Diameter range from 0.25 to 0.76mm.

Glass Fibers

Straight. Diameter ranges from 0.005 to 0.015mm (may be bonded together to form elements with diameters of 0.13 to 1.3mm).

Natural Organic and Mineral Fibers

Wood, asbestos, cotton, bamboo, and rockwool. They come in wide range of sizes.

Polypropylene Fibers

Plain, twisted, fibrillated, and with buttoned ends.

Other Synthetic Fibers

Kevlar, nylon, and polyester. Diameter ranges from 0.02 to 0.38mm.

A convenient parameter describing a fiber is its aspect ratio (L/D), defined as the fiber length divided by an equivalent fiber diameter. Typical aspect ratio ranges from about 30 to 150 for length of 6 to 75mm.

Mixture Compositions and Placing

Mixing of FRC can be accomplished by many methods[2]. The mix should have a uniform dispersion of the fibers in order to prevent segregation or balling of the fibers during mixing. Most balling occurs during the fiber addition process. Increase of aspect ratio, volume percentage of fiber, and size and quantity of coarse aggregate will intensify the balling tendencies and decrease the workability. To coat the large surface area of the fibers with paste, experience indicated that a water cement ratio between 0.4 and 0.6, and minimum cement content of 400 kg/m[3] are required. Compared to conventional concrete, fiber reinforced concrete mixes are generally characterized by higher cement factor, higher fine aggregate content, and smaller size coarse aggregate.

A fiber mix generally requires more vibration to consolidate the mix. External vibration is preferable to prevent fiber segregation. Metal trowels, tube floats, and rotating power floats can be used to finish the surface.

Mechanical Properties of FRC

Addition of fibers to concrete influences its mechanical properties which significantly depend on the type and percentage of fiber[2-4]. Fibers with end anchorage and high aspect ratio were found to have improved effectiveness. It was shown that for the same length and diameter, crimped-end fibers can achieve the same properties as straight fibers using 40 percent less fibers[5]. In determining the mechanical properties of FRC, the same equipment and procedure as used for conventional concrete can also be used. Below are cited some properties of FRC determined by different researchers.

Compressive Strength

The presence of fibers may alter the failure mode of cylinders, but the fiber effect will be minor on the improvement of compressive strength values (0 to 15 percent).

Modulus of Elasticity

Modulus of elasticity of FRC increases slightly with an increase in the fibers content. It was found that for each 1 percent increase in fiber content by volume there is an increase of 3 percent in the modulus of elasticity.

Flexure

The flexural strength was reported[2] to be increased by 2.5 times using 4 percent fibers.

Toughness

For FRC, toughness is about 10 to 40 times that of plain concrete.

Splitting Tensile Strength

The presence of 3 percent fiber by volume was reported to increase the splitting tensile strength of mortar about 2.5 times that of the unreinforced one.

Fatigue Strength

The addition of fibers increases fatigue strength of about 90 percent and 70 percent of the static strength at 2×10^6 cycles for non-reverse and full reversal of loading, respectively.

Impact Resistance

The impact strength for fibrous concrete is generally 5 to 10 times that of plain concrete depending on the volume of fiber used[2].

Corrosion of Steel Fibers

A 10-year exposure[2] of steel fibrous mortar to outdoor weathering in an industrial atmosphere showed no adverse effect on the strength properties. Corrosion was found to be confined only to fibers actually exposed on the surface. Steel fibrous mortar continuously immerse in seawater for 10 years exhibited a 15 percent loss compared to 40 percent strength decrease of plain mortar.

Structural Behavior of FRC

Fibers combined with reinforcing bars in structural members will be widely used in the future. The following are some of the structural behaviour[6-8]:

Flexure

The use of fibers in reinforced concrete flexure members increases ductility, tensile strength, moment capacity, and stiffness. The fibers improve crack control and preserve post cracking structural integrity of members.

Torsion

The use of fibers eliminate the sudden failure characteristic of plain concrete beams. It increases stiffness, torsional strength, ductility, rotational capacity, and the number of cracks with less crack width.

Shear

Addition of fibers increases shear capacity of reinforced concrete beams up to 100 percent. Addition of randomly distributed fibers increases shear-friction strength, the first crack strength, and ultimate strength.

Column

The increase of fiber content slightly increases the ductility of axially loaded specimen. The use of fibers helps in reducing the explosive type failure for columns.

High Strength Concrete

Fibers increases the ductility of high strength concrete. The use of high strength concrete and steel produces slender members. Fiber addition will help in controlling cracks and deflections.

Cracking and Deflection

Tests[9] have shown that fiber reinforcement effectively controls cracking and deflection, in addition to strength improvement. In conventionally reinforced concrete beams, fiber addition increases stiffness, and reduces deflection.

Applications

The uniform dispersion of fibers throughout the concrete mix provides isotropic properties not common to conventionally reinforced concrete. The applications of fibers in concrete industries depend on the designer and builder in taking advantage of the static and dynamic characteristics of this new material. The main area of FRC applications are[10]:

Runway, Aircraft Parking, and Pavements

For the same wheel load FRC slabs could be about one half the thickness of plain concrete slab. Compared to a 375mm thickness of conventionally reinforced concrete slab, a 150mm thick crimped-end FRC slab was used to overlay an existing asphaltic-paved aircraft parking area. FRC pavements are now in service in severe and mild environments.

Tunnel Lining and Slope Stabilization

Steel fiber reinforced shortcrete (SFRS) are being used to line underground openings and rock slope stabilization. It eliminates the need for mesh reinforcement and scaffolding.

Blast Resistant Structures

When plain concrete slabs are reinforced conventionally, tests showed[11] that there is no reduction of fragment velocities or number of fragments under blast and shock waves. Similarly, reinforced slabs of fibrous concrete, however, showed 20 percent reduction in velocities, and over 80 percent in fragmentations.

Thin Shell, Walls, Pipes, and Manholes

Fibrous concrete permits the use of thinner flat and curved structural elements. Steel fibrous shortcrete is used in the construction of hemispherical domes using the inflated membrane process. Glass fiber reinforced cement or concrete (GFRC), made by the spray-up process, have been used to construct wall panels. Steel and glass fibers addition in concrete pipes and manholes improves strength, reduces thickness, and diminishes handling damages.

Dams and Hydraulic Structure

FRC is being used for the construction and repair of dams and other hydraulic structures to provide resistance to cavitation and severe errosion caused by the impact of large waterborn debris.

Other Applications

These include machine tool frames, lighting poles, water and oil tanks and concrete repairs.

Comparative Study of the Mechanical Behavior of FRC Using Local Materials

Researches are being carried out in the Civil Engineering Department of King Abdulaziz University about the mechanical properties of fibrous concrete and the structural behaviour of fibrous concrete beams with and without prestressing subjected to different combinations of bending, shear, and torsion. A study of the mechanical behavior of fibrous concrete using local materials is presented in this section.

Materials

Table 1 shows the different properties of the straight and the hooked fibers used in this study. The hooked fibers are glued together into bundles with a water-soluble adhesive. The collating of the 30 fibers creates an artificial aspect ratio of approximately 15. The plain fibers were obtained by cutting galvanized steel wires manually. Type I portland cement, 10mm graded crushed stone aggregate, desert sand of fineness modulus 3 .1, and a 3 percent super plasticizer were used for all the mixes. The mix proportion was 1.0:2.0:1.6 and the water-cement ratio was 0.44.

TABLE 1. Properties of straight and deformed steel fibers.

	Straight fiber	Hooked fiber
Material	Galvanized Steel	Carbon Steel
Length (mm)	53.00	60.00
Diameter (mm)	0.71	0.80
Aspect ratio (L/D)	75.00	75.00
f_y(MPa)	260.00	660.00

Workability

The conventional slump test is not a good measure of workability of FRC. The inverted slump cone test (2.4) devised especially for the fibrous concrete is recommended. The time it takes an inverted lamp cone full of FRC to be emptied after a vibrator is inserted into the concrete is called the inverted-cone time. It should vary between 10 and 30 seconds.

The conventional slump test (ASTM C143-78) and the inverted slump cone test (ASTM C995-83) were conducted to compare the performance of the plastic concrete reinforced with the two different types of fibers. The hooked fibers performed well during mixing because no balling occurred even though the fibers were added to the mixer along with the aggregate all at one time. The straight fibers had to be sprinkled into the mixer by hand to avoid balling. It took approximately 2 minutes to add the straight fibers to the mix, resulting in a 2 minutes extra mixing time. Figure 1 shows the effect of fiber content on both slump and inverted cone time. It is clearly seen that as the fiber content increased from 0.0 to 2.0 percent, the slumps value decreased from 230 to 20mm, and the time required to empty the inverted cone time increased from 20 to 70 seconds. For the highest fiber volume percentage used (V_f = 2.0 percent) it was noticed that the FRC in the test specimens was difficult to consolidate using the internal vibrator.

Compressive Strength

Sixty concrete cylinders (1500 × 300mm) were cast and tested in compression (ASTM C39) at the end of 7, 28 and 90 days. Figure 2 shows the effect of the hooked fiber content on the compressive strength values and shows the stress-strain relationship. The fiber addition had no effect on the compressive strength values. However, the brittle mode of failure associated with plain concrete was transformed into a more ductile one with the increased addition of fibers. Figure 3 presents the effect of

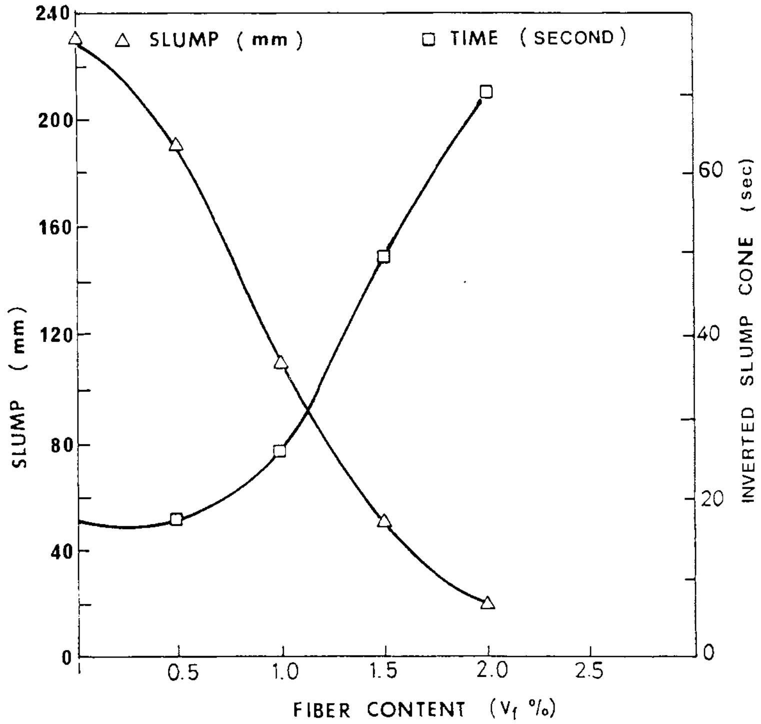

FIG. 1. Effect of fiber content on workability.

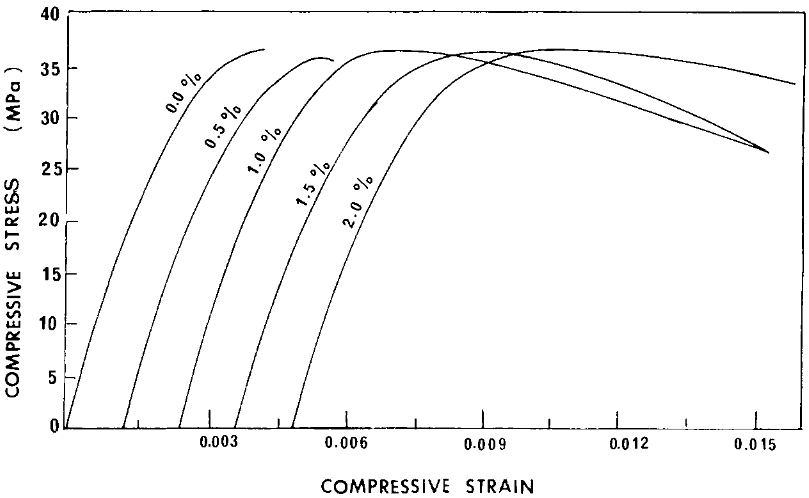

FIG. 2. Effect of hooked fiber content on compressive stress-strain curves (28 days).

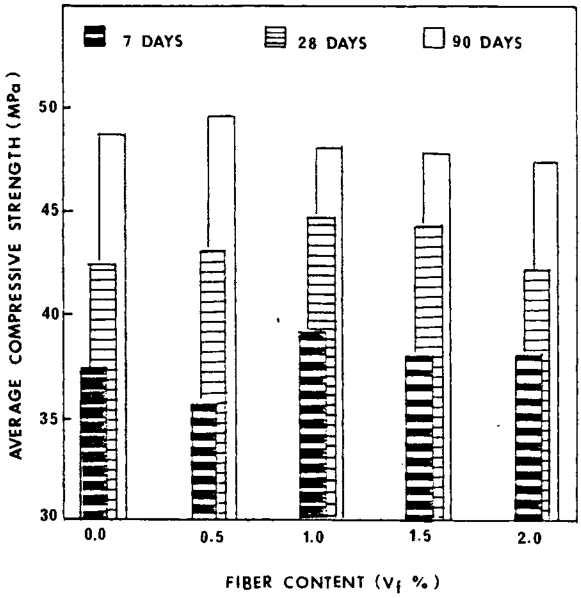

FIG. 3. Effect of hooked fiber content on compressive strength at different ages.

hooked fiber content on the compressive strength after 7, 28 and 90 days. It is observed that although slight scatter exists, the percentage of fiber volume content has practically no influence on the compressive strength of concrete either at early or later stage of its life. Table 2 and Fig. 4 present a comparison of the strength for hooked and straight fibers which indicates that the fiber types and content have little effect on the compressive strength. The results are similar to those of other investigators[2,3].

TABLE 2. Comparison of strengths using hooked and straight fibers (7 days).

V_f(%)	Compressive Strength		Modulus of Rupture		Split Tensile Strength	
	Hooked (MPa)	Straight (MPa)	Hooked (MPa)	Straight (MPa)	Hooked (MPa)	Straight (MPa)
0.0	37.3	37.3	6.15	6.15	3.43	3.43
0.5	35.8	37.0	7.68	6.60	4.21	3.60
1.0	39.1	37.9	9.81	6.97	5.26	4.72
1.5	38.0	39.2	10.20	7.78	5.15	4.91
2.0	38.2	40.8	8.70	8.35	5.15	5.10

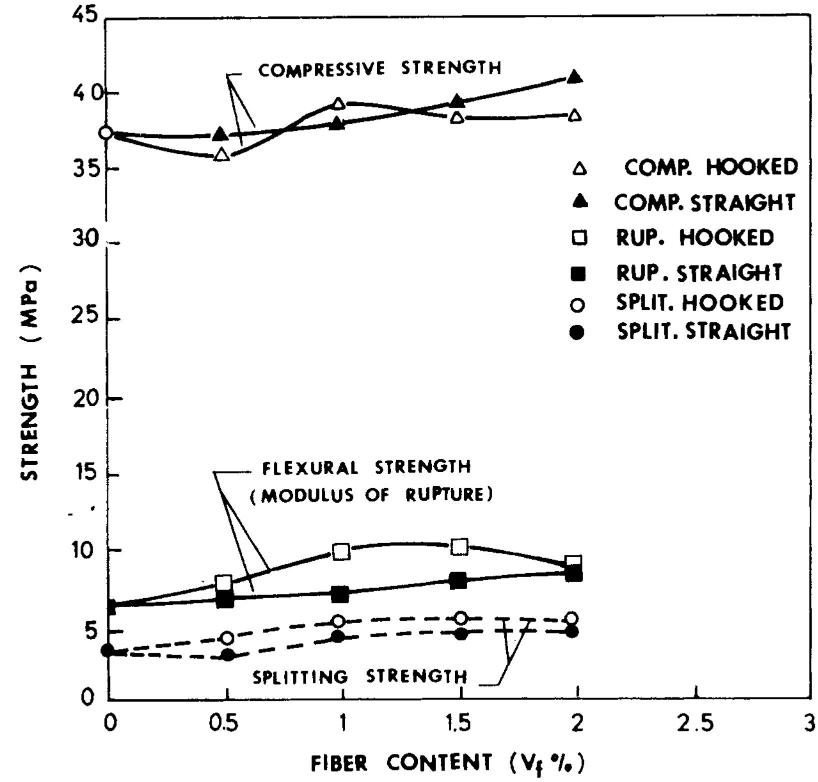

FIG. 4. Compressive, flexural and splitting strengths for hooked and straight fibers (7 days).

Modulus of Elasticity

Figure 2 shows that the initial slope of the stress-strain curve is practically the same for all mixes and equal to 31,900 MPa compared to 30,400 MPa obtained using the ACI formula. This indicates that the modulus of elasticity does not change much by the addition of fibers.

Flexural Test - Modulus of Rupture

Sixty concrete beams (100 × 100 × 350mm) were tested in flexure (ASTM C78-75) after 7, 28 and 90 days. Figures 5 and 6 show the load-deflection curves for hooked and straight fibers with different volume content. The load-deflection curve for plain as well for fibrous concrete is linear up to point A (Fig. 5) and the strength at A is called the first cracking strength. For plain concrete beams, cracking immediately leads to failure. Beyond point A, the curve is non-linear due to the presence of fibers and reaches the ultimate strength at B. After reaching the peak value, the flexural strength drops and attains a steady value of 60 to 70 percent of the peak

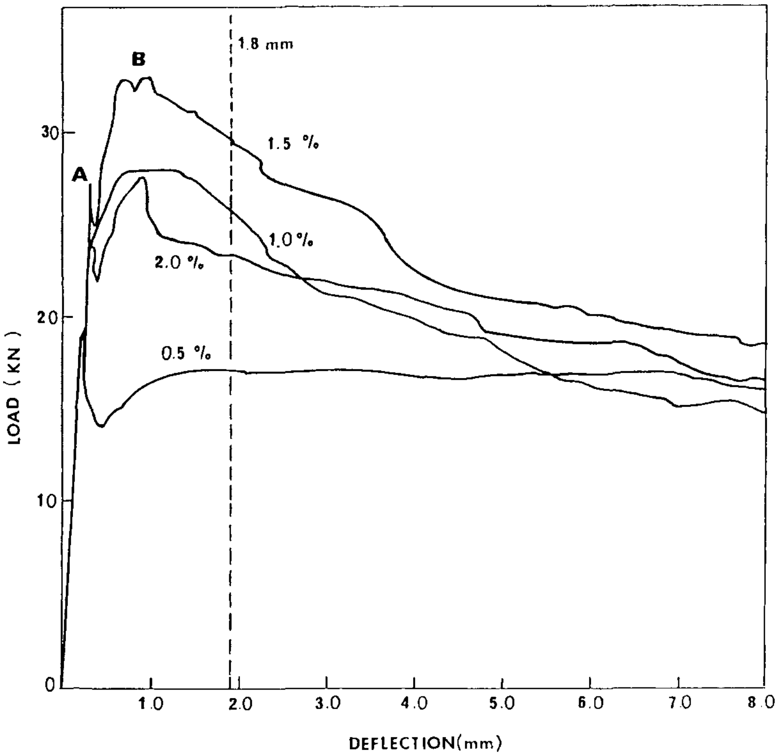

FIG. 5. Load-deflection curves for hooked fibers.

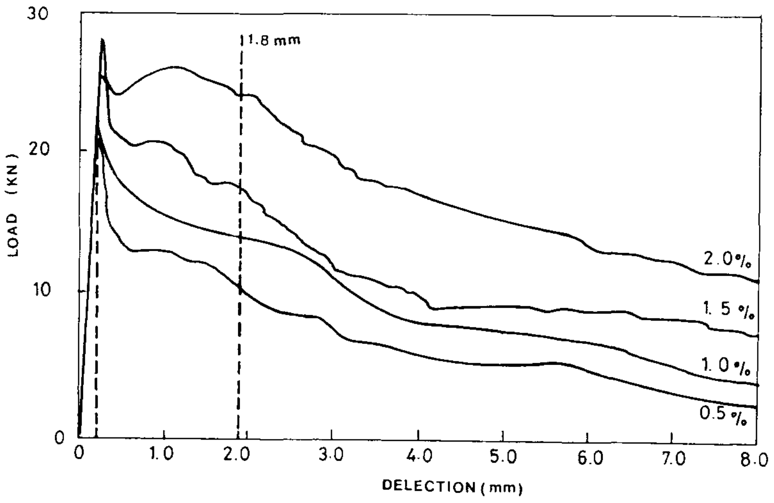

FIG. 6. Load-deflection curves for straight fibers.

value in the case of hooked fibers. For straight fibers, the flexural strength goes on dropping until failure, showing continous slippage of the straight fiber. This behaviour can be explained as follows. For the fibrous concrete, once cracks are initiated, the fibers start working as crack arresters. Use of fiber produces more closely spaced cracks and reduces crack width. Additional energy is required to extend the cracks and debond the fibers from the matrix. The deformed ends of the hooked fibers contributed significantly to the increase in the bond between fiber and matrix and extra energy is required for straightening the deformed ends before a complete debonding can take place.

Figure 7 shows the effect of hooked fiber content on flexural strength after 7, 28 and 90 days. The addition of 1.5 percent of hooked fibers gives the optimum increase of the flexural strength. It increased the flexural strength by 67 percent, whereas the addition of 2.0 percent straight fiber gives the optimum increase of the flexural strength by 40 percent more than that of the plain concrete (compared to the 250 percent increase given in literature[2] using 4 percent fibers). At a high dosage of hooked fiber (2 percent), the test specimens were difficult to consolidate and fibers were probably not randomly distributed. This caused a slight reduction in strength. Table 2 and Fig. 4 show the comparison between the two fibers.

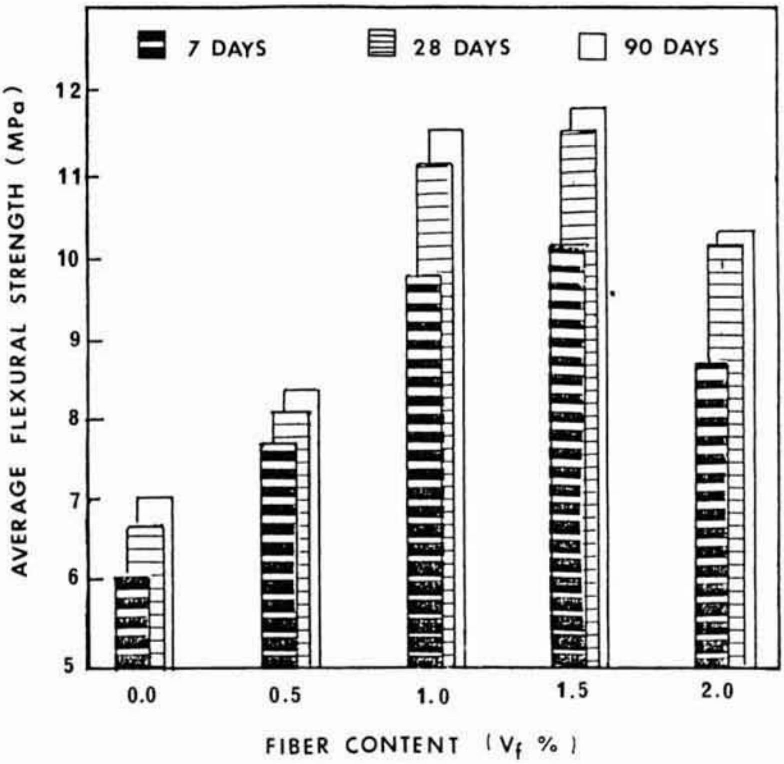

FIG. 7. Effect of hooked fiber content on flexural strength at different ages.

Splitting Tensile Strength

Sixty concrete cylinders (150 × 300mm) were tested for splitting strength (ASTM C496) after, 7,28 and 90 days. Fig. 8 shows the effect of hooked fiber addition on the splitting tensile strength. It is clear that the highest improvement is reached with 1.5 percent fiber content (57 content more than plain concrete). Table 2 and Fig. 4 show the comparison between hooked and straight fibers.

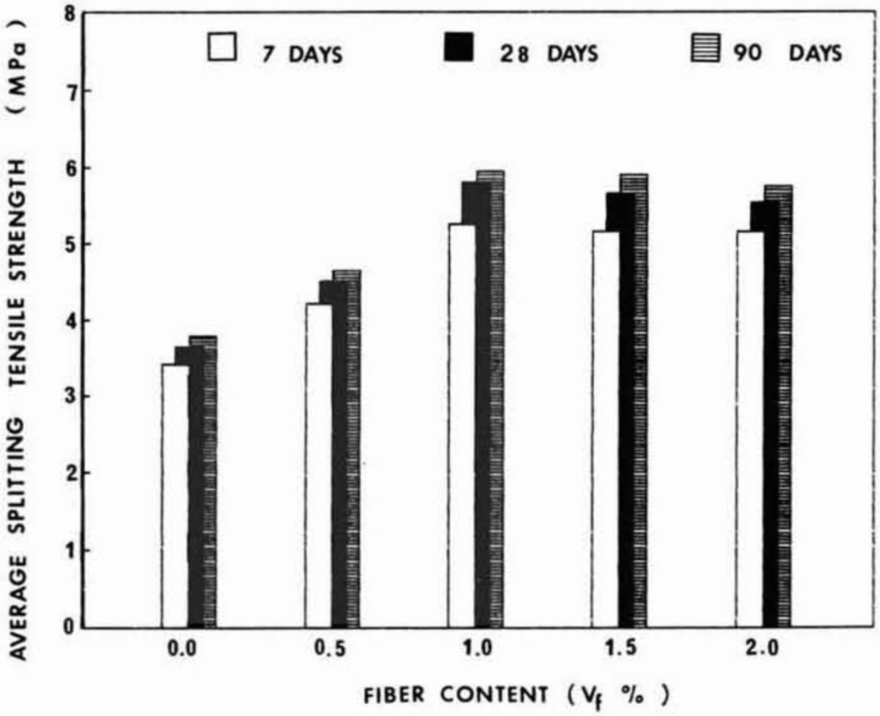

FIG. 8. Effect of hooked fiber content on splitting tensile strength at different ages.

Toughness (Energy Absorption)

Toughness as defined by the total energy absorbed prior to complete separation of the specimen is given by the area under load-deflection curve. Toughness or energy absorption of concrete is increased considerably by the addition of fibers. The toughness index is calculated as the area under the load deflection curve (Fig. 5) up to the 1.8mm deflection divided by the area up to the first crack strength (proportional limit). The calculated toughness index for each mix is given in Table 3. All specimens made of plain concrete failed immediately after the first crack and, hence, the toughness index for these specimens is equal to 1. The addition of fiber increases the toughness index of hooked and straight fibers up to 19.9 and 16.9, respectively. The average toughness index for specimens reinforced with hooked fibers was 25 to 65 percent greater than that for specimens reinforced with straight fibers.

TABLE 3. Effect of fiber content on the toughness index.

Fiber content (%)	Toughness Index	
	Hooked fibers	Straight fibers
0.0	1.0	1.0
0.5	11.4	9.2
1.0	18.0	11.1
1.5	19.9	13.6
2.0	16.7	16.9

Impact Strength

Fifteen short cylinders (150mm diameter and 63mm thick) were cast and tested for impact[4] after 28 days. The results of impact test are given in Fig. 9. The rest results show that the impact strength increases with the increase of the fiber content. Use of 2 percent hooked fiber increased the impact strength by about 25 times compared to 10 times given in literature[2].

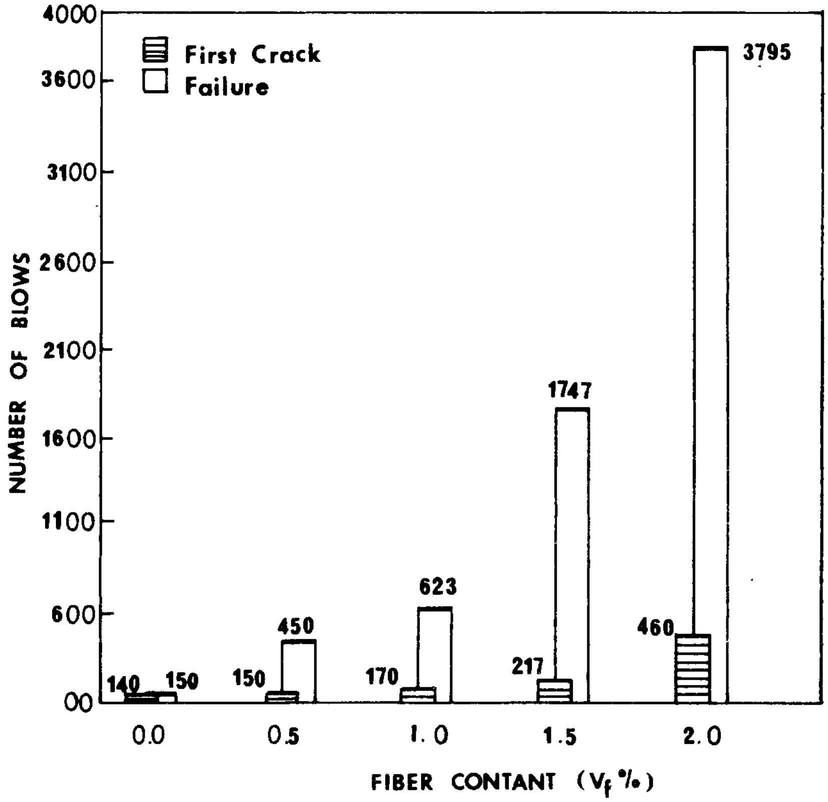

FIG. 9. Effect of hooked fiber content on the impact strength.

Conclusion

Based on the test of one hundred and ninety five specimens made with the available local materials, the following conclusions can be derived:

1. No workability problem was encountered for the use of hooked fibers up to 1.5 percent in the concrete mix. The straight fibers produce balling at high fiber content and require special handling procedure.

2. Use of fiber produces more closely spaced cracks and reduces crack width. Fibers bridge cracks to resist deformation.

3. Fiber addition improves ductility of concrete and its post-cracking load-carrying capacity.

4. The mechanical properties of FRC are much improved by the use of hooked fibers than straight fibers, the optimum volume content being 1.5 percent. While fibers addition does not increase the compressive strength, the use of 1.5 percent fiber increase the flexure strength by 67 percent, the splitting tensile strength by 57 percent, and the impact strength 25 times.

5. The toughness index of FRC is increased up to 20 folds (for 1.5 percent hooked fiber content) indicating excellent energy absorbing capacity.

6. FRC controls cracking and deformation under impact load much better than plain concrete and increased the impact strength 25 times.

The material covered by this investigation mainly is concerned with the mechanical properties of FRC using local materials. Researches are being conducted in the Civil Engineering laboratory of King Abdulaziz University on the structural behavior of FRC members.

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خـــواص الخرسانـــة المسلحـــة بالأليـــاف وتطبيقاتهـــا

فيصل فؤاد وفا
أستاذ مشارك ، قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك عبد العزيز
جـــدة ، المملكة العربية السعودية

تعتبر الخرسانة المسلحة بالألياف مادة إنشائية جديدة تزداد أهميتها مع مرور الزمن . تُحسِّن إضافة ألياف تسليح على هيئة قطع قصيرة منفصلة العديد من الخواص الهندسية للخرسانة العادية . مازالت الأبحاث الجارية في المملكة حول استخدام هذه المادة وتطويرها محدودة . تساهم هذه الورقة في زيادة المعرفة في هذا المجال ، إذ تصف أنواع الألياف المختلفة وتطبيقات الخرسانة المسلحة بالألياف في مختلف المجالات . كما تعرض الورقة نتائج بحث عن الخواص الميكانيكية للخرسانة المسلحة بالألياف استخدمت فيه ألياف فولاذية مستقيمة وأخرى ذات أطراف معقوفة جميعها موجودة بوفرة في المنطقة .