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Study of Braided Aramid Fiber Rods for Reinforcing Concrete

Renforcement du béton par des tiges en fibres Aramid tressées

Bewehrung von Beton mit Stäben aus Aramidfaser-Geflecht

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SUMMARY

This paper describes the concrete reinforcing capability of fiber reinforced plastics' rods, FiBRA, which are made by weaving Aramid fibers in braided form. The tensile characteristics and durability of FiBRA were tested. Flexural tests were also performed on concrete beams using FiBRA as the flexural reinforcement, with prestressing tendons. As a result, it was confirmed that FiBRA can be easily put to practical use for reinforcing concrete.

RÉSUMÉ

Cette contribution décrit les possibilités de renforcement du béton par des tiges FiBRA, réalisées en tissant des fibres d'Aramid sous forme de tresses. Les caractéristiques de résistance à la rupture et la durabilité des tiges FiBRA ont été testées. Des essais de flexion ont également été exécutés sur des poutres en béton armées et précontraintes, par des tiges FiBRA. En conclusion il a été confirmé que les tiges FiBRA présentent de nombreuses applications pratiques pour le renforcement du béton.

ZUSAMMENFASSUNG

Dieser Beitrag zeigt die Möglichkeiten, Beton mit FiBRA-Stäben, einem Geflecht aus Aramidfasern, zu bewehren. Die FiBRA -Stäbe wurden auf Zugfestigkeit und auf Dauerhaftigkeit geprüft. Daneben wurden auch Biegeversuche an mit FiBRA-Stäben bewehrten und vorgespannten Betonträgern durchgeführt. Diese Untersuchungen bestätigten, dass FiBRA-Stäbe in grossem Umfang zur Bewehrung von Beton eingesetzt werden können.

1. INTRODUCTION

Recently, research has been going on for utilization of high-performance fibers as concrete reinforcing material with the purpose of improving the durability of reinforced concrete or prestressed concrete. The authors developed rod materials (FiBRA) of continuous fibers woven in braid form as substitutes for reinforcing bars and prestressing tendons, and the performances as structural materials were tested. This report is on tension tests, tensile fatigue tests, relaxation tests, heat resistance tests, and alkali resistance tests performed in particular on a rod material using Aramid fibers to confirm its basic performance, and flexural tests of concrete beams using this rod material as a substitute for reinforcing bars and prestressing tendons to grasp its concrete reinforcing effect.

2. OUTLINE OF FiBRA

The manufacturing process of FiBRA is shown in Fig. 1, while the characteristics of the Aramid fibers (Kevlar® 49) and epoxy resin used are given in Table 1. The manufacturing method consisted of using 6000-denier continuous fibers and weaving them into braids which were impregnated with epoxy resin and hardened. As shown in Photo. 1, a regular pattern of protrusions and depressions unique to the braid is formed on the rod. Weaving in braid form imparts the following two important properties to the FiBRA:

- Tensile force applied to the rod is uniformly transmitted to the entire cross section.
- The bond force to concrete is increased through the protrusions and depressions formed at the surface.

Furthermore, to increase the bond force even more, a FiBRA with a granular material such as sand adhered to the surface was developed.

Table 2 shows the fundamental physical properties of the rods used in the various tests.

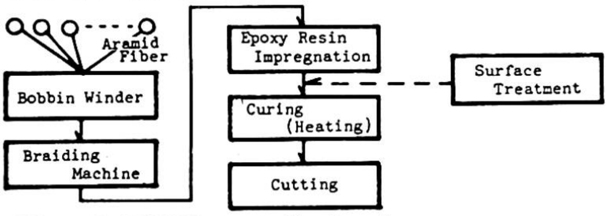


Fig. 1 FiBRA manufacturing process

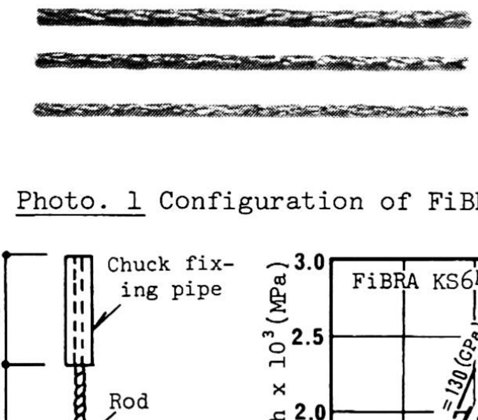


Photo. 1 Configuration of FiBRA

Table 1 Characteristics of Aramid fiber and epoxy resin

Characteristic / Material	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)	Remarks
Aramid fiber	2745	130	2.4	Kevlar® 49.
Epoxy resin	78	1.42	5.5	Epicote 827 + TETA

Table 2 Basic physical properties of FiBRA

Braided material	Av, dia. (mm)	Typical strength		Typical tensile strength (MPa)		Sp. gr. (g/cm^3)
		(KN)	(t)	Full cross section	Aramid fiber	
KS 16	4.0	15.7	1.6	1255	2089	1.29
KS 64	8.0	62.8	6.4			
KS 96	10.0	94.6	9.6			
KS 128	12.0	125.5	12.8			
KS 192	14.0	188.3	19.2			

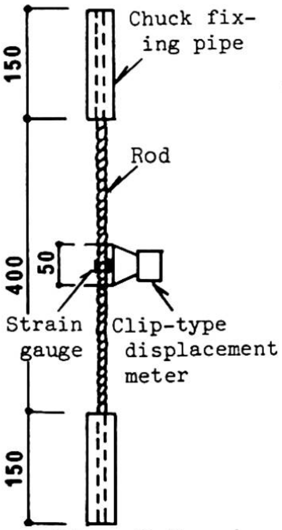


Fig. 2 Tension test method

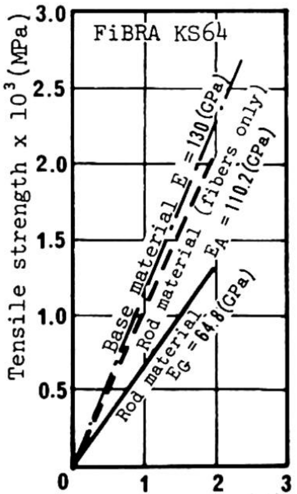


Fig. 3 σ-ε relationship

3. TENSILE CHARACTERISTICS

3.1 Tension Tests

Tension tests were performed on the rods listed in Table 2. The testing method is shown in Fig. 2.

Fig. 3 is an example of the relationship between tensile strength and elongation of KS64. An example of tensile strength distributions of KS64 is shown in Fig. 4. The overall average was 70.1 KN, 85 percent of the theoretical strength calculated from the amount of fibers used, with no case less than the typical tensile strength. The Young's modulus when calculated for the total cross-sectional area (E_G) including epoxy resin was 64.8 GPa, and for cross-sectional area of fibers only 110.2 GPa. Compared based on fibers only, it was 84.5 percent of the Young's modulus of 130.4 GPa of Kevlar® 49.

3.2 Tensile Fatigue Test

Partial pulsating tensile fatigue tests were performed on FiBRA of KS64. The tests were carried out at room temperature varying the stress range with the lower limit load constant at 50 percent of actual rupture and the fatigue limit where rupture would not occur even at 2 million cycles was determined. The results of the tests are shown in Table 3. With stress ranges under 374.6 MPa, rupture did not occur even at 2 million cycles, but in case of 443.3 MPa, rupture occurred at approximately 305,000 cycles.

3.3 Relaxation Test

Relaxation tests were performed under room temperature on KS64 FiBRA. The initial loads were the three levels of 0.7, 0.6, and 0.5 times the tensile strength P_u of KS64. The results of the tests are shown in Fig. 5. The relaxation values of the specimens were 3 to 4 times that of the prestressing steel at 10 hours, and 2 to 2.5 times at 100 hours. With prestressing steel, relaxation value is higher the greater the initial load, but with FiBRA, although there was some amount of scatter, differences depending on initial load were not recognized.

Table 3 Tensile fatigue strength test results

Test	Lower limit		Upper limit		Stress range (MPa)	Cycles to rupture x 10^3
	Load (KN)	Stress (MPa)	Load (KN)	Stress (MPa)		
1	32.26	645.3	46.97	939.5	294.2	> 2090
2	32.26	645.3	42.52	990.5	345.2	>3577
3	32.26	645.3	50.99	1019.9	374.6	> 2063
4	32.26	645.3	54.43	1088.5	443.3	305

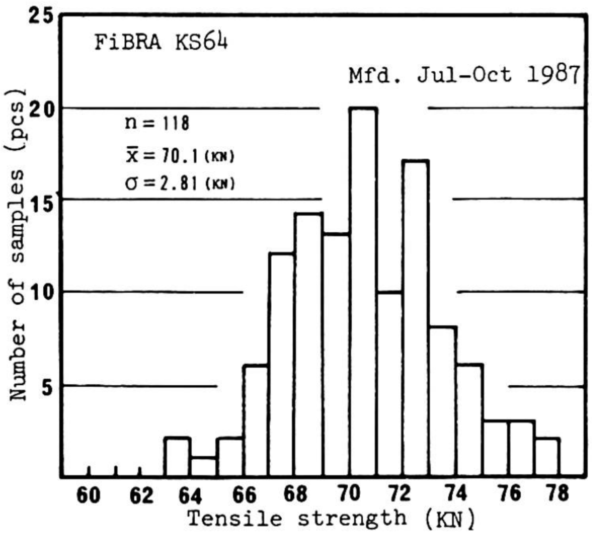


Fig. 4 Tensile strength distribution

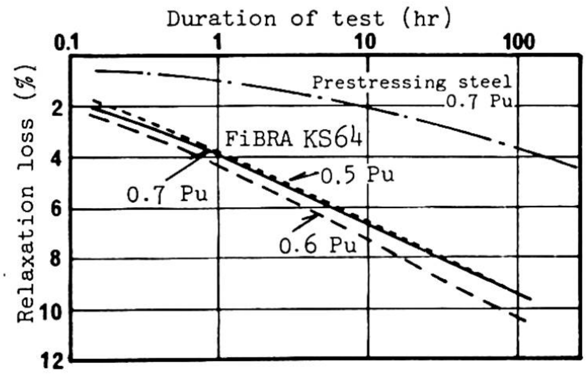


Fig. 5 Relaxation curve

4. DURABILITY

4.1 Heat Resistance Tests

Tests were of the two kinds of dry heat and moist heat tests using small-diameter FiBRA of KS16. Tension tests of the rods were performed for evaluation of heat resistance expressed in terms of ratios of strengths maintained with the strengths for no treatment as 100.

The results of the tests are shown in Fig. 6. In both kinds of testing the ratios of tensile strengths maintained up to treatment temperature of 220°C were high at around 95 percent to indicate very great heat resistance for an organic fiber.

4.2 Alkali Resistance Tests

The tests consisted of immersing KS16 FiBRA in a solution of pH = 13, with temperatures during immersion at the four levels of room temperature, 40, 60, and 80°C. Evaluation of alkali resistance was expressed by ratio of tensile strength maintained with the strength for no treatment as 100.

The results of the tests are shown in Fig. 7. Up to immersion temperature of 40°C strengths were maintained more or less at the values of untreated up to 2000 hours after immersion. For 60°C and 80°C, a tendency for strengths to decline slightly was seen when more than 1400 hours had elapsed, but ratios of strengths maintained were high exceeding 95 percent.

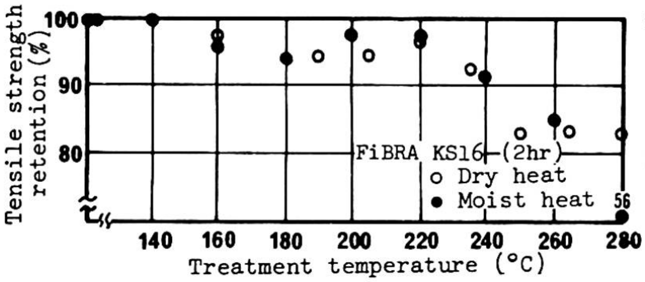


Fig. 6 Heat resistance test results

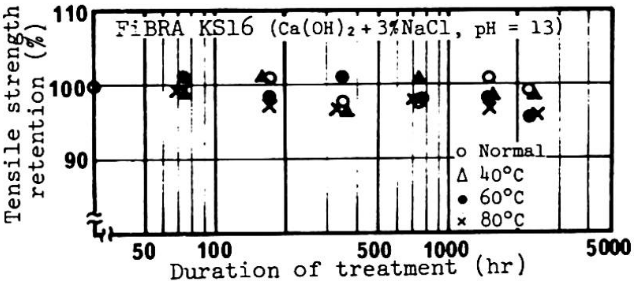


Fig. 7 Alkali resistance test results

5. FLEXURAL TESTS OF PRC (PARTIALLY PRESTRESSED CONCRETE) BEAMS

5.1 Specimens

Flexural tests were performed on PRC beams using FiBRA as main reinforcement and as prestressing tendons in pretensioning. The configuration of specimens was that of a T-beam of beam width 22.5 cm, beam depth 30 cm, and total length 360 cm as shown in Fig. 8. As indicated in Table 4, a total of five specimens were tested with FiBRA used as reinforcing bars the four kinds from KS64 to KS192 listed in Table 2, quartz sand being adhered to the FiBRA surfaces to enhance bonding properties. The parameters of the specimens were the three levels of tensile reinforcement ratio of main reinforcement of 0.13, 0.26, and 0.39 percent, and the three levels of prestress in terms of bottom fiber stress of concrete of 0, 1.47, and 2.94 MPa (0, 15, and 30 kg/cm^2).

5.2 Testing Method

Application of load was by two-point loading with bearing span of 300 cm and loading span of 75 cm, one-way monotonic loading used for the specimen F-26-0, and repeating loadings once at each stage of deformation for other specimens. A view of the testing is given in Photo. 2.

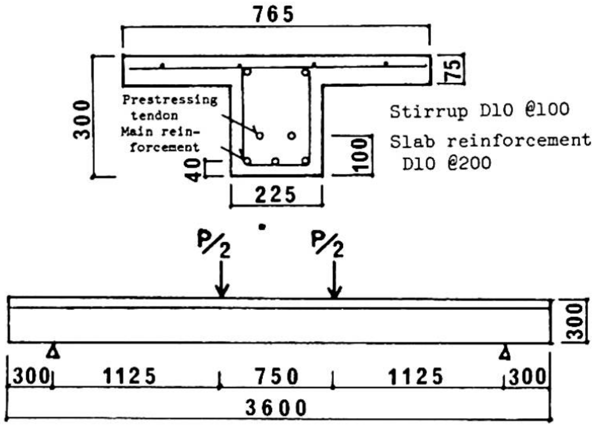
5.3 Test Results

Envelopes of the load-deformation curves of the specimens are shown in Fig. 9. After occurrence of initial cracking, loads and deformations increased in approximately straight lines for all specimens with the gradients dependent on flexural reinforcement quantities. All of the specimens showed adequate deformabilities with ultimate states reached on rupturing of FiBRA. The load-deformation curves of the specimens are shown in Fig. 10. Strength reductions due to repetitive loading were small, while residual deformation was smaller with increased level of prestress. Cracking patterns at 1/100 (D = 3 cm) deformations are shown in Fig. 11. Flexural cracks occurred well-scattered to show that bonding property of FiBRA is good. The test results are given in Table 6. The experimental values of first crack load and calculated values by Eq. (1) agreed well with each other. Consequently, it was thought that the required prestressing force had been adequately transferred. As for ultimate bending load obtained from rupture strength of FiBRA using Eq. (2), it coincided with the experimental value, showing that flexural strength can be estimated with fairly good accuracy.

$$P_{crt} = 2\{Z(0.564\sqrt{F_c} + \sigma_p) - M_o\}/\ell \qquad \text{............... (1)}$$

$$P_{ut} = 2\{0.875 d f_R + (d_p - d/8) f_p\}/\ell \qquad \text{............... (2)}$$

where, Z: section modulus, F_c: concrete strength, σ_p: bottom fiber stress due to prestress, M_o: bending moment due to dead weight, ℓ = 112.5 cm, d = 26 cm, d_p = 20 cm, f_R: rupture strength of main reinforcement, f_p: rupture strength of prestressing tendon.



(Unit of dimensions: mm)

Fig. 8 Specimen configuration

Table 4 Types of flexural specimens

Specimen	Main reinforcement		Prestressing tendon		
	Type	Tensile reinforcement ratio (%)	Type	Tensioning force KN/pc	Bottom fiber prestressing stress MPa
F-13-15	3-KS64	0.13	2-KS96	30.7	1.47 [15.0 kg/cm²]
F-26-15	3-KS128	0.26			
F-39-15	3-KS192	0.39			
F-26-0	3-KS128	0.26		0.0	0.00 (0.0)
F-26-30			2-KS192	61.3	2.94 (30.0)

Table 5 Material characteristics

a) Concrete

	Comp. strength F_c (MPa)	Young's modulus ×10⁴(MPa)
At prestressing	28.5	2.53
At flexural testing	35.4	2.70

b) FiBRA strength

	Theoretical KN	Typical KN	Test value KN
KS64	86.2	62.7	69.1
KS96	123.5	94.1	101.3
KS128	164.6	125.4	132.2
KS192	247.9	188.2	191.6

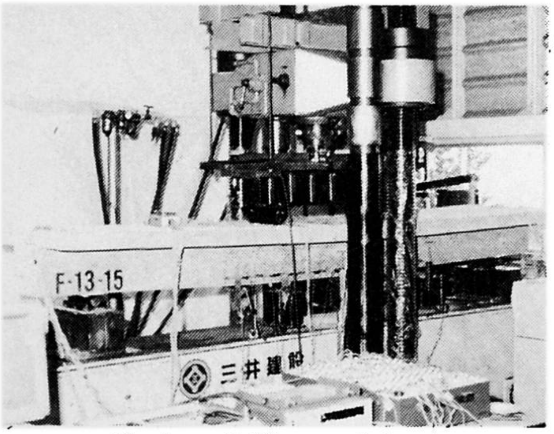


Photo. 2 View of test

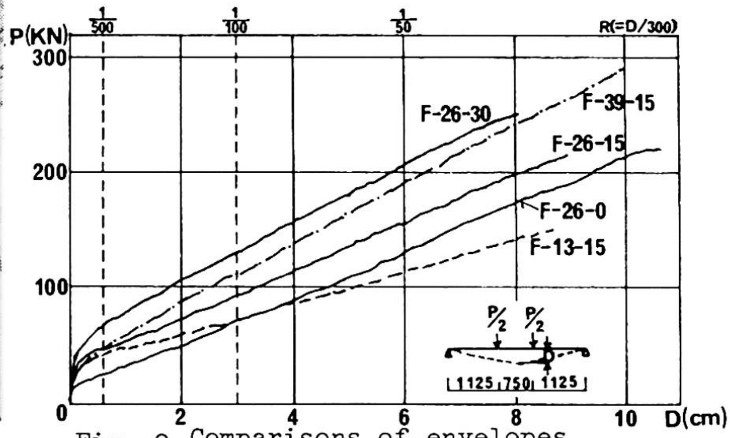


Fig. 9 Comparisons of envelopes of load-deformation curves

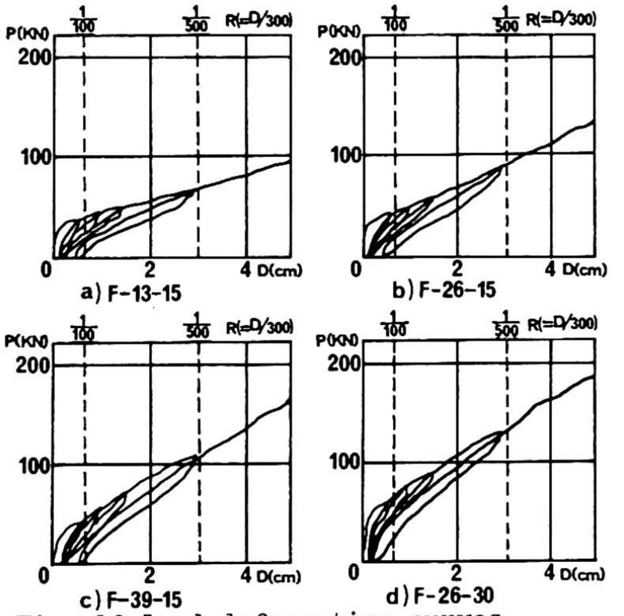


Fig. 10 Load-deformation curves of specimens

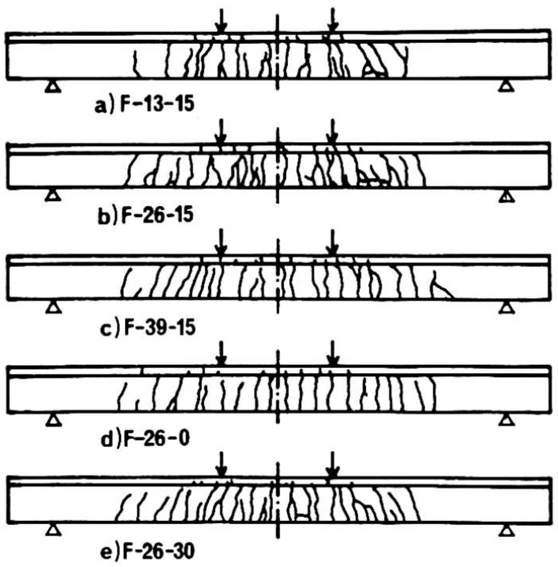


Fig. 11 Cracking patterns at 1/100 (D = 3 cm) deformations

Table 6 Test results

Specimen	At first crack				At ultimate state				
	Test value		Theoretical	$\frac{P_{cr}}{P_{crt}}$	Test value			Theoretical	$\frac{P_u}{P_{ut}}$
	Bending moment Mcr (KN·m)	Load Pcr (KN)	Load Pcrt (KN)		Deflection Du (cm)	Bending moment Mu (KN·m)	Load Pu (KN)	Load Put (KN)	
F-13-15	16.4	29.1	27.9	1.04	8.68	85.5	152	144	1.05
F-26-15	19.7	35.1	27.9	1.25	8.93	121.3	216	221	0.98
F-39-15	16.4	29.1	27.9	1.04	10.1	165.4	294	293	1.00
F-26-0	8.38	14.9	21.3	0.70	10.1	121.3	216	221	0.98
F-26-30	26.4	46.8	44.8	1.05	8.02	140.5	250	274	0.91

6. CONCLUSION

The following were disclosed through the tests carried out:

- According to the results of tension tests, and heat resistance and alkali resistance tests, FiBRA possesses ample practicality as a concrete reinforcing material capable of withstanding long-term use.
- Relaxation loss and tensile fatigue properties of FiBRA are within ranges making possible use as prestressing tendons.
- In concrete beams using FiBRA as flexural reinforcement (main reinforcement and prestressing tendons) the characteristics of FiBRA were amply demonstrated and high strengths and ductilities were indicated.

It is thought concrete members reinforced with FiBRA can be used extensively for durable structures in marine environments and other severe environments requiring chemical resistance.

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